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Economic Impact of Climate Change: Simulations with a Regionalized Climate-Economy Model

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Abstract:

Climate change affects the physical and biological system in many regions of the world. The extent to which human systems will suffer economically from climate change depends on the adaptive capabilities within a region as well as across regions. We use an economic General-Equilibrium model and an Ocean-Atmosphere model in a regionally and sectorally disaggregated framework to analyze adaptation to climate change in different regions of the world. It turns out that vulnerability to climate impacts differs significantly across regions and that the overall adjustment of the economic system quite reduces the direct climate impacts.

Keywords: Climate Change, Computable General Equilibrium Model, Integrated Assessment Framework, Impact Modelling, Ocean-Atmosphere Model.

JEL classification: D58, O13, O41, Q17, Q24, R53.

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3 INTRODUCTION

In its latest report the Working Group I of the IPCC concludes that in the 20th century the globally averaged surface temperatures have increased by 0.6°C ± 0.2°C. The report also predicts that during the 21st century this warming trend will continue and temperatures will by 2100 be 1.4°C to 5.8°C higher than in 1990. This trend would vary by region and would – combined with changes in precipitation – lead to changes in the variability of climate and to changes in the frequency and intensity of some extreme climate phenomena (IPCC/WG-I 2001). Similarly, the sea-level is projected to rise by 0.09 to 0.88 meters by 2100.

These climate changes have already affected a diverse set of physical and biological systems in many regions of the world and this process is expected to continue (IPCC/WG-II 2001). The working Group II of the IPCC then concludes that – although with much lower confidence – human systems are also sensitive to these changes. The vulnerability of these systems depends on their geographic location as well as on their social, economic and environmental conditions. Among the negative impacts are

- a reduction in crop yields mostly in tropical and subtropical zones,
- a decrease in the availability of water in many regions
- an increase in vector-borne and water-borne diseases, and
- an increase in the risk of flooding.

These negative effects contrast with potential improvements in some regions, especially higher yields in agriculture and forestry in the mid-latitudes.

The extent to which human systems will suffer economically from climate change depends on the adaptive capabilities within a region as well as across regions. So far there are very few studies trying to translate climate change into its impact on human welfare (see e.g. Tol et al. 2000 or Tol 1999). The welfare effects of climate change have usually been estimated in monetary terms at the local level and have then been aggregated to regional and even global scales. These estimates present a first approximation to the range of welfare effects that can be expected from climate change. At the same time, they face a number of methodological problems whose impact on the overall costs of climate change is as yet not clear.

At the core of the problem for assessing the welfare effects of climate change is the question as to how much the economies of the different regions of the world will be able to adapt to the changing conditions for producing and consuming goods and services. Such adaptation takes place at the individual level of the consumer – e.g. when he/she changes his/her demand for energy for heating or cooling, – the producer – e.g. when a farmer adjusts his crop mix to new climatic conditions. It also affects the national level and even the international division of labor when trade flows and foreign direct investment react to emerging scarcities of goods and factors. The main drivers of such adaptation processes are price changes which reflect scarcities of goods and services whose provision becomes more costly through climate change. Monetary estimates of climate impacts are commonly based on existing prices thus underestimating the welfare effect. On the other hand they often do not take into account the adjustments in the production and consumption structure at the regional and international scale, hence they tend to overestimate the costs of climate change.

Another difficulty in estimating the welfare effects of climate change is connected with the long time scales over which the impacts are expected to occur. The model simulations of natural scientists commonly extend to the end of this century. It would not be especially meaningful to value climate impacts occurring in the second half of this century at current technologies, factor endowments and prices for goods and factors. Instead, it would be preferable to model physical impacts within an economic scenario in which future supply and demand conditions can be adequately represented. Such an approach is presented here.

It is clear that the full range of climate impacts over the next century cannot be represented in such a modeling framework, firstly because the impact data often are not available, and secondly because many impacts can not be integrated in the structure of the economic model. Therefore, in this paper only the climate impacts on agriculture and due to sea-level rise are incorporated in the analysis. The effects are modeled within a regionally and sectorally disaggregated framework.

The basic structure is the following: Historic and future CO_2-emissions as output from an economic growth model are fed into an Ocean-Atmosphere-Model which computes regional changes in temperature and precipitation as well as sea-level rise. These climate parameters are then translated into regional impacts by adjusting the productivity of land used in agriculture. Sea-level rise scales the investment necessary to prevent increased levels of flooding.

These impacts are then used as an input in the regionally and sectorally disaggregated economic growth model in order to assess how the economic system reacts and adapts to such climate change. In the economic model the direct effect on agriculture without intersectoral and interregional adjustment can be compared to the production and welfare effects when the different regional economies have adjusted to the new situation. It turns out that the overall adjustment of the economic system significantly reduces the direct climate impacts on agriculture. Because of the long time lags between emissions and climate impacts and the minor influence of climate impacts on emissions it is not necessary to completely couple the economic model with the climate model.

The paper is organized as follows: First the structure of the economic growth model is illustrated and it is shown how a possible benchmark development of the world economy could look like. In Chapter 3 the reduced Ocean-Atmosphere model is presented and the regional climate changes are shown. In Chapter 4 the climate change is translated into changes in land productivity through impact functions and the projected sea-level rise is used to determine the investment necessary for the prevention of increased flooding. The simulation results are presented in Chapter 5 and conclusions are drawn in Chapter 6.

4 THE ECONOMIC SYSTEM – A COMPUTABLE GENERAL EQUILIBRIUM MODEL

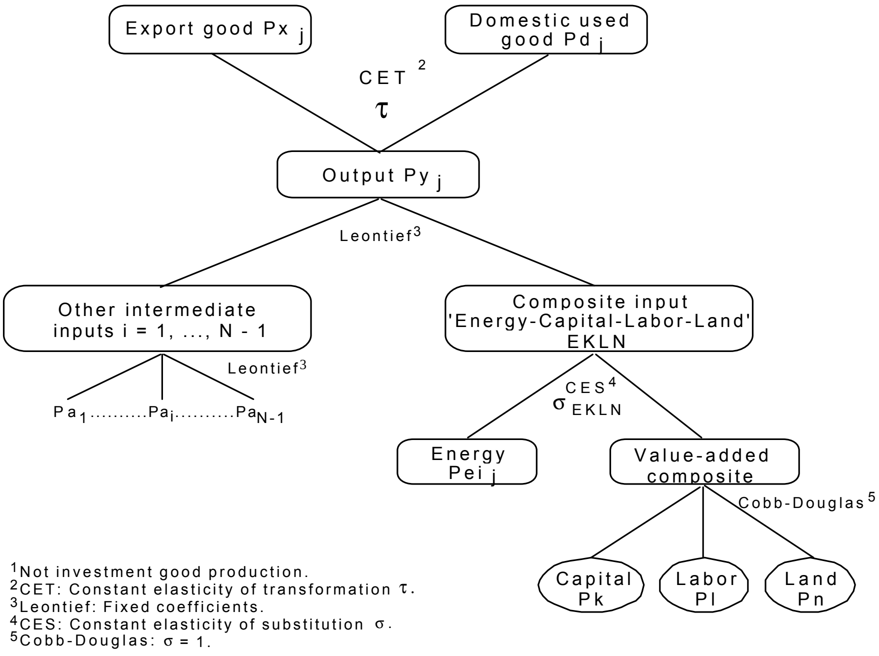
4.1 The Basic DART-Model

The DART-model is a multi-region, multi-sector, recursive dynamic Computable General Equilibrium (CGE) model. The economic structure is fully specified for each region and covers production, consumption, investment and governmental activity. Each market is perfectly competitive. Output and factor prices are fully flexible. For each region, the model incorporates three types of agents: the producers, distinguished by production sectors, the representative private household and the government.

PRODUCER BEHAVIOR

Producer behavior is characterized by cost minimization for a given output. All industry sectors are assumed to operate at constant returns to scale. Output of each production sector is produced by the combination of energy, non-energy intermediate inputs, and the primary factors labor, capital and agricultural land.[1] For each industry, a multi-level nested separable constant elasticity of substitution (CES) function describes the technological substitution possibilities in domestic production.[2] Figure 1 shows the nested production structure.

Figure 1 — Production Structure of Industry Sector j in Region r



[1] Not investment good production.
[2] CET: Constant elasticity of transformation τ.
[3] Leontief: Fixed coefficients.
[4] CES: Constant elasticity of substitution σ.
[5] Cobb-Douglas: $\sigma = 1$.

Agricultural output is produced with the same nested production function as above. However, one distinguishing feature of the agricultural sector is that only this sector uses land as a primary input in production.

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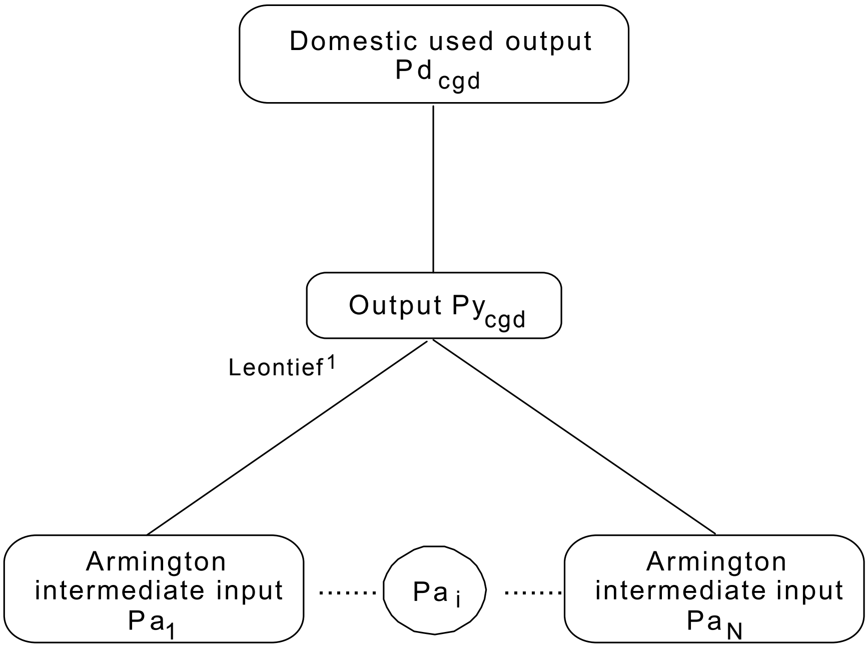
[1] The differentiation between energy and non-energy intermediate products is useful in the context of climate change policy. Energy use in production and consumption produces varying amounts of the greenhouse gas (GHG) carbon dioxide (CO_2) depending on the fossil source and the policies assumed to be in place. Carbon dioxide, with large emission levels and a long lifetime in the atmosphere is the largest single contributor to the greenhouse effect. Other GHGs as methane, nitrous oxide, ozone, and halocarbons, as well as emissions of CO_2 from deforestation are not considered in this model.

[2] The nesting structure and nest elasticities of the production cost functions are based on the ETA-MACRO model (See Manne and Richels 1992, pp. 130).

In each region, composite investment is a Leontief aggregation of Armington inputs by each industry sector. There is no sector-specific investment activity in the basic version of the model. The DART-model does not contain cross border investment activities, i.e. investment goods are treated as non-tradables. Investment does not require direct primary factor inputs. Figure 2 shows the production structure of the investment activity. Producer goods are directly demanded by regional households, governments, the investment sector, other industries, and the export sector.

Figure 2 — Production Structure of the Investment Good Sector cgd



[1] Leontief: Fixed coefficients.

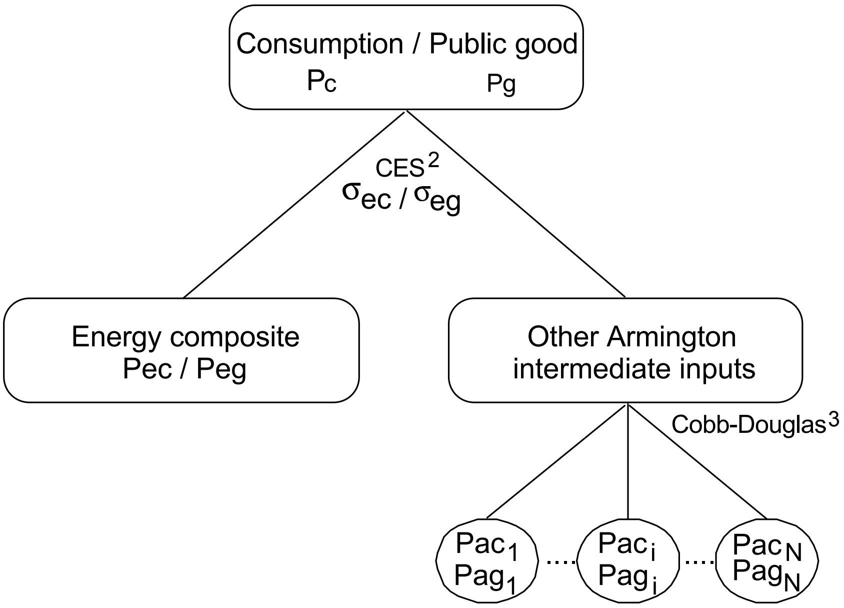
CONSUMPTION, AND GOVERNMENT EXPENDITURE

The representative household receives all income generated by providing primary factors to the production process. Disposable income is used for maximizing utility by purchasing goods after taxes and savings are deducted. The consumer decides between different primary energy inputs and non-energy inputs depending on their relative prices in order to receive this consumption with the lowest expenditures. The consumer saves a fixed share of income in each time period. These savings are invested in the production sectors.

The expenditure function of the representative household is assumed to be a CES composite which combines consumption of an energy aggregate and a non-energy bundle. Within the non-energy consumption composite, substitution possibilities are described by a Cobb-Douglas function of Armington goods. Figure 3 shows the structure of household and government behavior.

The third agent, the government, provides a public good which is produced with commodities purchased at market prices. Public goods are produced with the same two level nesting structure as the household “production” function (see Figure 3). The public good is financed with tax revenues.

Figure 3 — Household / Government Production Structure[1]



[1] Lower case roman letter *c* stands for household and *g* for government.

[2] CES: Constant elasticity of substitution σ_{ec}/σ_{eg}.

[3] Cobb-Douglas: $\sigma = 1$.

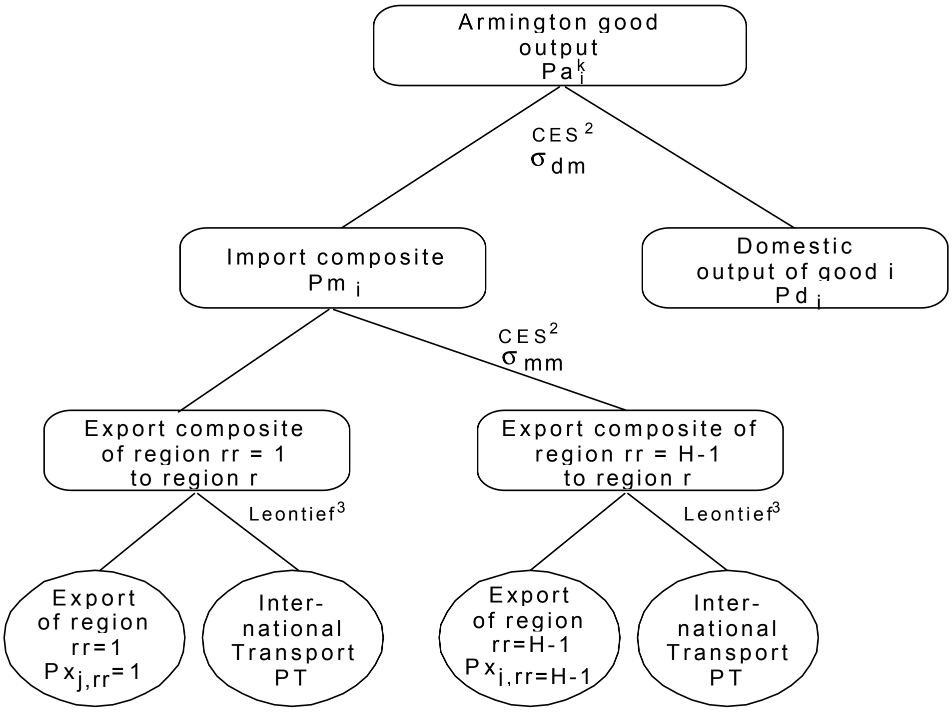
FOREIGN TRADE

The world is divided into economic regions, which are linked by bilateral trade flows. All goods are traded among regions, except for the investment good. Following the proposition of Armington (1969), domestic and foreign goods are imperfect substitutes, and distinguished by country of origin.

Import demand is derived from a three stage, nested, separable CES cost or expenditure function respectively and distinguishes between imported and domestically produced goods as well as between the country of origin of the import goods. The structure of foreign trade is shown in Figure 4. The imports of one region *r* are equivalent to the exports of all other regions *rr* into that region *r* including transport. Transport costs, distinguished by commodity and bilateral flow, apply to international trade but not to domestic sales. The exports are connected to transport costs by a Leontief function. International transports are treated as a worldwide activity which is financed by domestic production proportionately to the trade flows of each commodity. There is no special sector for transports related to international trade.

On the export side, the Armington assumption applies to final output of the industry sectors destined for domestic and international markets. Here, produced commodities for the domestic and for the international market are no perfect substitutes. Exports are not differentiated by country of destination.

Figure 4 — Structure of Foreign Trade (Armington Good Production of Good i in Region r)



[1] Armington output is distinguished by agent with k = {Y, C, G}
[2] CES: Constant elasticity of substitution.
[3] Leontief: Fixed coefficients.

FACTOR MARKETS

Factor markets are perfectly competitive and full employment of all factors is assumed. Hence, factor prices adjust so that supply equals demand. Labor is assumed to be a homogenous good, mobile across industries within regions but internationally immobile. The equilibrium condition of the solution requires that the sum of all sectoral demands for labor is equal to the exogenous labor supply in each region. In the basic version of the DART-model capital is inter-sectorally but not internationally mobile. There is no sector-specific capital. Capital stock is given at the beginning of each time period and results from the capital accumulation equation. In every time period the regional capital stock, Kst_r, earns a correspondent amount of income measured as physical units in terms of capital services, K_r. The supply of the primary factor land is exogenously given. Land is only employed in agricultural sectors.

CO_2-EMISSIONS

Carbon Dioxide emissions result from the combustion of fossil fuels, i.e. crude oil, natural gas and coal. Different emission coefficients for the various types of fossil fuels are considered. CO_2-emissions depend thus on the economic activities by firms, private households, and government in each region, and therefore on the speed of economic development. Parameters influencing the dynamic development are described in the next section. The CO_2-emission path resulting from the economic activity serves as an input for the climate model which determines then the according changes in climatic variables such as change in global mean temperature, precipitation and sea-level.

In the empirical analysis below two different energy supply and, thus, emission scenarios are distinguished. The base case constitutes Scenario B. In this scenario the carbon emissions of coal, natural gas, and crude oil are calibrated on the emissions as projected by the scenario B of the World Energy Council and IIASA (Nakicenovic et al. 1998). This scenario reflects the most likely development of the fossil fuel market within the next century. The resulting carbon emissions, as predicted by the economic model, start from 6 Gt carbon per year in 1993 and reach 9.7 Gt carbon per year in 2030. As an input for the climate model this emission path in the benchmark. i.e. without considering climate change impacts, was extrapolated to the year 2100 with 19 Gt carbon emissions in the final year.

Furthermore, the model was calibrated to a second emission scenario, a kind of Worst-Case-Scenario, in order to check the sensitivity of the results of Scenario B. This second scenario is called the Back-to-Coal-Scenario and is based on the dirtiest emission scenario by the World Energy Council and IIASA (Nakicenovic et al. 1998). It is characterized by a different composition of fossil fuel consumption with a larger share of coal, lower energy prices, and thus, higher greenhouse gas emissions compared to Scenario B. Therefore, the Back-to-Coal-Scenario leads to emissions of 6 Gt carbon in 1993 which increase to about 12 Gt carbon per year in 2030. Again, these results of the economic model were extrapolated up to 2100 with yearly emissions of 22.5 Gt carbon in 2100.

4.2 Dynamics of the DART-Model

The DART-model is recursive-dynamic, meaning that it solves for a sequence of static one-period equilibria for future time periods connected through capital accumulation, population growth, human capital accumulation, savings, and technical progress. The dynamics of the DART-model are defined by equations which describe how the endowments of the primary factors evolve over time. The major driving exogenous factors in the model are population change, the rate of labor productivity growth, the change in human capital, the savings rate, the gross rate of return on capital, and thus the endogenous rate of capital accumulation. The DART-model is recursive in the sense that it is solved stepwise in time without any ability to anticipate possible future changes in relative prices or in constraints.

The agents have myopic expectations which is consistent with the in principle static nature of the DART-model. The savings behavior of regional households is characterized by a constant savings rate over time.[3] This rather ad-hoc assumption seems consistent with empirical observable, regional different, but nearly constant savings rates of economies, which adjust according to income developments over very long time periods (for savings rates cf. Schmidt-Hebbel and Servén, 1997).

SUPPLY OF LABOR AND AGRICULTURAL LAND

In the DART-model, the labor supply in efficiency units, $L_{r,t}$, evolves exogenously over time. Therefore, exogenous labor supply $\overline{L}$ for each region r at the beginning of time period $t+1$ is given by:

$$(1) \quad \overline{L}_{r,t+1} = \overline{L}_{r,t} * \left(1 + gp_{r,t} + ga_r + gh_r\right)$$

An increase of effective labor implies either growth of human capital accumulated per physical unit of labor, gh_r, population growth, gp_r, or total factor productivity improvement, ga_r, or the sum of all.

In the basic version of the DART-model we assume constant, but regionally different labor productivity improvement rates, ga_r, constant but regionally different growth rates of human capital, gh_r, which stem from Hall and Jones (1999), and declining population growth rates over time, $gp_{r,t}$, according to the

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[3] The savings rate is allowed to adjust to income changes in regions with extraordinarily high benchmark savings rates.

World Bank population growth projections (Bos et al., 1994). For the derivation of the growth rates of human capital see Springer (1998). Because of the lack of data for the future evolution of the labor participation rate the growth rate of population is used instead of labor force. This implies a constant labor participation rate over time.

In the basic version of the DART-model the supply of the sector-specific primary factor land is held fixed to its benchmark level over time. The assumption of a fixed land endowment over time is relaxed when impacts of climate change on the agricultural sector are incorporated into the model (see Chapter 4.2).

CAPITAL FORMATION

Current period's investment augments the capital stock in the next period. The aggregated regional capital stock, Kst, in each time period t is updated by an accumulation function equating the next-period capital stock, Kst_{t+1}, to the sum of the depreciated capital stock of the current period and the current period's physical quantity of investment, $Iq_{r,t}$, given by $Iq_{r,t} = Inv_{r,t} / Pi_{r,t}$ where $Inv_{r,t}$ is the value of investment in region r in period t and $Pi_{r,t}$ denotes the costs of constructing a unit of capital. The equation of motion for capital stock $Kst_{r,t+1}$ in region r is given by:

$$(2) \quad Kst_{r,t+1} = Kst_{r,t} * (1 - d_t) + Iq_{r,t} \qquad t \geq 1$$

where d_t denotes the exogenously given constant depreciation rate in period t. The allocation of capital among sectors follows from the intra-period optimization of the firms. Capital accumulation changes when sea-level rise due to climate change is considered. In case of sea-level rise, part of the annual investment is earmarked for protection measures of sea-level rise (see Chapter 4.3)

5 TRANSLATING CARBON DIOXIDE EMISSIONS INTO CLIMATE CHANGE – PROJECTIONS FROM AN OCEAN-ATMOSPHERE MODEL

This chapter, about the climate modelling part, gives a brief outline of the model technique, a short description of the scenario-specific input to the climate model, and a listing of the scenario-specific output from the climate model.

The climate model is a fast and nevertheless accurate aggregate representation of state-of-the-art three-dimensional global climate circulation and carbon cycle models. It is specially designed for the purpose of translating CO_2-emission scenarios into scenarios of climate change for assessment of climate change impacts. Input to the climate model are historic and future emissions of carbon dioxide from combustion of fossil fuels, according to two scenarios of CO_2-emission treated with the economic CGE model and one additional scenario for illustrative purposes. The output from the climate model is later used to introduce the impact of climate change into the economic model. The output variables are the annual and regional mean changes in near-surface air temperature (T), precipitation (P), and sea-level (S). The changes are computed for each regions at each (simulation) time period, in response to the scenario-specific history of anthropogenic CO_2-emissions.

5.1 The Climate Model

The most reliable instruments currently available for the estimation of anthropogenic climate change are coupled models of the general three-dimensional (3D) circulation of ocean and atmosphere models (GCMs). However, for multi-scenario investigations, these models are prohibitively expensive in computation time. Ideally, a climate model designed for application in integrated assessment and climate impact studies should provide the desired climate-change information without excessive computational cost, while nevertheless approaching the reliability and detail of sophisticated, top-of-the-line climate models.

The simplified model used in this study, the Nonlinear Impulse response representation of the coupled Carbon Cycle-Plus-Climate-system (NICCS; Hooss et al. 2001), meets these requirements. The NICCS model is based on impulse-response representations of a 3D ocean carbon cycle model and a current coupled ocean-atmosphere model. It is an extended version of the impulse response function (IRF) climate model used in the Structural-Integrated-Assessment-Model (SIAM) by Hasselmann et al. (1997), augmented by nonlinear ocean carbon chemistry, a simple IRF representation of the land vegetation in the carbon cycle adapted from Joos et. al. (1996), a logarithmic formulation of the radiative greenhouse forcing, and spatial patterns of change in four impact-relevant climate variables. The most straightforward application of NICCS is the fast computation at maximum available credibility of the response of atmospheric CO_2-concentration and climate to given emission scenarios.[4]

5.2 Impulse Response Technique

While in a GCM the 3D ocean-atmosphere system is described by large amounts of data, only the time-dependent response of three variables $x(t)$ to a time-

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[4] The model has also been applied in combination with, and as part of, other models like integrated assessment studies (cf. Bruckner et al. 1998, Petschel-Held 1999, Füssel and van Minnen 1999, Bruckner et al. 2001), investigations of climate change feedbacks onto the terrestrial carbon cycle (Joos et al. 1999, 2001), or an educational tool developed for the EXPO 2000 World Exhibition.

dependent, one-dimensional perturbation (anthropogenic CO_2-emissions) is required in this study to assess the impact of climate change. Provided that the change relative to a reference climate state is small, the response of $p_v(t)$ to an arbitrary (but small) forcing $f(t')$ may be computed simply by convolution with the system's linear impulse response function (IRF) R:

$$(3) \quad x(t) = \int_{-\infty}^{t} f(t') * R(t-t') * dt'$$

Once the IRF R has been extracted from the outcome of a single GCM calibration run, the simple convolution model which is hereafter called the IRF model can be applied to any time-dependent forcing scenario without further reference to the GCM it is based upon, serving as an exact substitute, provided that the perturbations to the system remain relatively small (within the linear response regime). IRF models may be calibrated to reproduce, without loss of information, any output from sophisticated models. They provide a highly efficient method of computing credible time-dependent climate change scenarios, with CPU times in the order of seconds on a workstation.

The linear range to which IRF models may be applied is constrained to CO_2-concentrations less than about twice the preindustrial value of 280 ppm, corresponding to an equilibrium warming of less than about 2.5 °C (Maier-Reimer and Hasselmann 1987). Outside that range, substituting GCMs by their linear IRF representation becomes inaccurate. Apart from possible catastrophic instabilities of the global climate system when forced with very high CO_2-concentrations, the linear response becomes inaccurate for elevated CO_2-levels even inside the stable domain because of the following main nonlinearities:

First, the solubility of additional CO_2 in the ocean surface water decreases with rising concentrations. Thus, also the relative oceanic uptake is reduced at higher concentrations. Second, the land vegetation may serve as an additional medium-term sink for anthropogenic carbon. Third, the radiative greenhouse forcing grows only logarithmically with increasing CO_2-concentrations, as the infrared absorption is already close to saturation in most bands. These nonlinearities are explicitly treated in our IRF-based climate module. The applicability range has thus been substantially widened.

The NICCS model consists of two modules: firstly, the global carbon cycle module that translates CO_2-emissions into the time evolution of its atmospheric concentration, and secondly, the regionalized global climate change module that translates the changing concentrations into climate change.

5.3 The Global Carbon Cycle Model

The IRF model describing the oceanic uptake of fossil-fuel carbon has been calibrated in a recent experiment (Hooss et al. 2001) using the atmospheric response of the Hamburg model of the oceanic carbon cycle (HAMOCC, Maier-Reimer and Hasselmann 1987).

To include the nonlinear effect of the sea water's carbonate chemistry on CO_2-solubility, the IRF model has been translated into an equivalent box-type differential representation, which in turn could be physically interpreted to the degree necessary for the treatment of the chemical equilibria governing the CO_2-solubility. The model is thus capable of reproducing the HAMOCC carbon uptake even at very high concentrations up to several thousand ppm. The approximation holds as long as the ocean circulation does not change drastically. The carbon cycle module is augmented by a land-vegetation carbon-uptake IRF module adapted from Joos et al. (1996).

5.4 The Atmosphere-Ocean Climate Module

Climate change is computed in response to rising CO_2-concentrations by impulse-response models of the coupled atmosphere-ocean model ECHAM3-LSG (cf. Vooss et. al 1998). Spatial patterns of change and the IRFs characterizing the time evolution of change have been obtained by an Empirical Orthogonal Function (EOF) / Principal Component (PC) analysis of the outcome of a transient 850-year experiment (Voss and Mikolajewicz 2000).

Let x denote the geographic coordinates of some given point of the model Earth's surface, and let t denote some given simulated time point. The spatiotemporal evolution of each climate variable $v(x,t)$, e.g. near-surface air temperature, can then be described as the product of the time-dependent global mean climate change signal $p_v(t)$ and a spatial pattern $f_v(x)$ of relative weights:

$$(4) \quad v(x,t) = f_v(x) * p_v(t)$$

The spatial patterns of change in the three output variables, $f_T(x)$, $f_P(x)$, $f_S(x)$ are shown in the Figures 5, 6 and 7[5]. The patterns have been normalized to unity mean. Thus, where the pattern values are greater than unity, the changes are stronger than in the global mean, and vice versa.

Some main climatological aspects of change should be briefly mentioned: First, most notable in the temperature pattern is the land-sea contrast: continents warm faster than oceans. However the strongest warming appears in the arctic where the melting of sea ice exposes more open water to the cold arctic air, increasing the release of heat from the ocean. The weakest warming is in the Antarctic

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[5] The figures are shown in the Appendix B.

circumpolar current where deep convection mixes the greenhouse heat down into the cold abyss. Second, the precipitation change pattern reflects the (unperturbed) climatological precipitation in the different climatic zones (from the equator to the poles: wet tropics, dry subtropics, moist midlatitudes, dry polar regions). Thus climate change is expected to further increase these contrasts: in general, wet regions will become wetter and dry regions might become even drier. Third, the changes in sea-level are fairly evenly distributed over the globe, ranging only from 0.7 to 1.3 times the global mean rise, at least at the coarse resolution of the parent 3D GCM.

The global-mean time series of the climate signals $p_v(t)$ in the three output variables (temperature, precipitation, and sea-level) from the above mentioned 850-year CGCM experiment have been used to calibrate appropriate IRF models. Through logarithmic response to the CO_2-concentration, the three substitute models account for the sublinear increase of the radiative forcing at rising concentrations.

These IRF models have then been applied, as an exact substitute of the parent GCM, to the emission scenarios from the economic model. For each scenario, they generated global mean time series of climate change in the three output variables (cf. Figures 9 and 10).

5.5 Regional Climate Change

A map showing the economic regions in the resolution of the GCM grid is given in Figure 8[6]. The three spatial patterns of change $f_v(x)$ are averaged over the

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[6] See Appendix B.

eleven regions of the economic CGE model, yielding region-specific weighting factors $f_{v,r}(x)=\langle f_v(x)\rangle_r$, where v is one of T, P, S and "$\langle\ \rangle_r$" denotes the spatial average over region r. Likewise, the spread of the pattern values in each region is measured by their standard deviation $s_{f,v,r}=\sqrt{\left\langle\left(f_v(x)-f_{v,r}\right)^2\right\rangle_r}$.

One of the impact functions of the economic CGE model requires relative changes of precipitation (i.e. in percent instead of mm/day). To achieve this, the local (grid-cell) values of the precipitation change pattern are divided through the local absolute precipitation values from the control run of the GCM. They were furthermore multiplied by 100 and bear thus the dimension [% / (mm/day)]. From the resulting relative-change pattern, regional averages and spreads were computed.

The regional averages and spreads of the sea-level change pattern have been taken over a belt of two to three grid cells width along the coastlines of the respective economic regions. This is a compromise between, on the one hand, staying as close to the region itself (as defined over land only) and, on the other hand, including as many grid cells as possible for statistical reasons. Fortunately, the results are insensitive to the width of the belts as the global pattern is fairly homogeneous, with spatial standard deviations in the order of only some percent of the pattern values.

The eleven regional pattern averages and spreads are compiled into Tables A1, A2 and A3 in the appendix. In addition to the regions, each table has one row with global data (As mentioned above, the patterns are normalized such that the global pattern averages are always unity).

The regional means $f_{v,r}$ and spreads $s_{f,v,r}$ of the time-independent patterns are then used as weighting factors for multiplication with the global mean time series of change from the IRF models, to yield regional mean time series of change and time series of the regional spread of the change:

$$\Delta_{v,r}(t) = p_v(t) * f_{v,r} \tag{5}$$

$$s_{v,r}(t) = p_v(t) * s_{f,v,r} \tag{6}$$

5.6 Uncertainty Assessment

We analyze three main sources of systematic uncertainty. First, several economic regions cover more than one climatic zone (e.g., WEU, FSU, NAM, LAM, especially ROW). In those regions, precipitation changes with opposite sign tend to cancel out in the respective regional averages. Thus local climate change may be severely underestimated in the averages over those regions. A measure of the spread within the regions is provided by the regional standard deviations. For example, although the absolute mean precipitation slightly increases in Western Europe (WEU), the mean of the relative changes is negative, seemingly paradoxically. The reason is that there are a moistening in the North and a drying in the South. These almost cancel out, leaving only a small net increase in the region; only the much larger spread indicates the underestimation. The decreases in the semiarid Mediterranean climate are larger in relation to the poor total precipitation, than increases of the same magnitude in the humid north are in relation to the moister climate there. This explains the small negative average of the relative changes in Western Europe.

A second problem of regionalization is the coarse spatial resolution of the GCM (roughly 500 km), which does not permit quantitative interpretation of sub-continental-scale structures in the patterns. Therefore, climate change in the smaller regions (like Pacific Asia or Western Europe) is estimated with greater uncertainty than in the larger regions. To obtain as robust statistics as possible, we tried to keep the regions as large as possible. Accordingly, some border grid cells are assigned to more than one region. Such overlap cells are drawn in black on the map.[7]

Third, we note the main source of uncertainty in our sea-level projections. The modeled sea-level changes are exclusively caused by thermal expansion of the water masses. The thermal effect is probably the most important effect, but at least two more effects are expected to give significant contributions: Melting or accumulating land ice may increase or decrease the total amount of liquid water in the oceans, leading to sea-level changes in the order of some centimeters to meters. Changing circulation patterns may also contribute to considerable local changes of the sea-level along some coast lines. Both effects are to our knowledge not yet modeled satisfactorily. Thus, we have to keep in mind that our model may well under- or overestimate regional changes by 100 percent, although our estimate is the among best ones available.

Given these limitations, we are aware that our regional averages are – although among the most reliable predictions possible today – still rather coarse first-order estimates of regionalized climate change.

5.7 The Scenarios: Input and Output

Two different emission scenarios have been treated with the economic CGE model (cf. Section 2), the Scenario B and the Back-to-Coal-Scenario, which are fed into the climate model. For illustrative purposes, the climate model has been run on an additional third scenario (labeled “Constant emissions”) where the emissions are kept constant at the 1990 value of 6 GtC / yr.

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[7] Due to a problem with the graphics software, some overlap cells also happen to appear white in the plot.

In all scenarios, the carbon cycle and climate model is spun up by a period of historical emissions from 1800 to 1990 (reasonably approximated by exponential growth). This spinup period is necessary because of the inertia of carbon cycle and the ocean-atmosphere climate system; both are still responding to the historic emissions throughout and beyond the entire 40-year period. For each of the three emission scenarios, the resulting changes in atmospheric CO_2-concentration and the annual-and-global-mean changes in the three output variables are shown in Figure 9 and 10. The complete result consists in 3 x 11 regional climate change scenarios, each in 3 climate variables and their regional spreads, computed as described above through simple multiplication of the global-mean changes with the respective regional pattern averages. For illustration, the regional climate change projections for the Scenario B (ScB), the Back-to-Coal-Scenario (BTC) have been compiled into three tables of regional averages of change in the year 2030 (cf. Tables 1, 2 and 3)[8].

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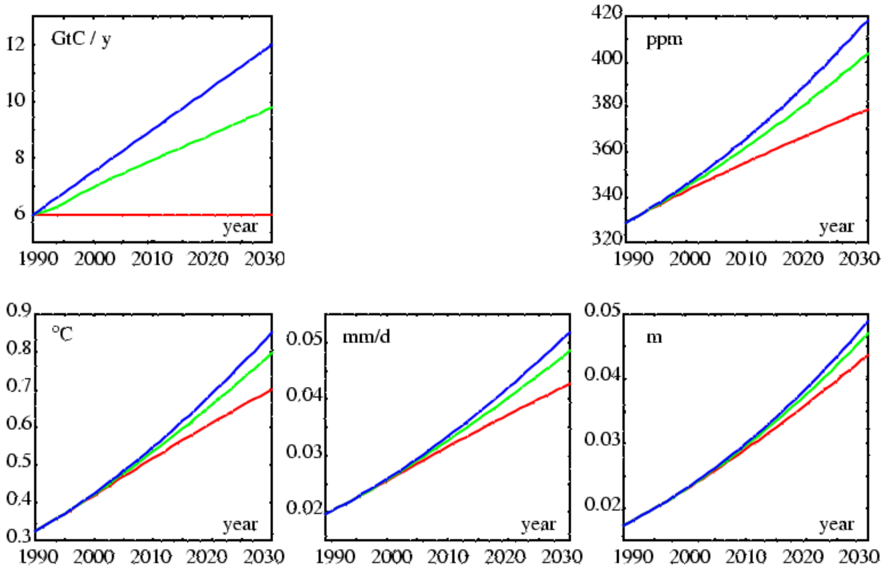
[8] For completeness, the climate model output for temperature, precipitation, and sea-level rise is given in the Appendix tables A1-A4.
In the Worst-Case-Scenario the Back-to-Coal Emission profile is used and the sum of two times the regional spread (cf. equation 6) is added to the regional mean change (cf. equation 5). This is done in order to illustrate something like an “worst-case” reaction of climate variables to a strong increase in CO_2-emissions. For precipitation in WEU, the sum is consequently subtracted since the regional mean is negative.

Figure 9 — CO_2 Emissions (Upper Left Panel) and Atmospheric Concentration (Upper Right Panel), and Global Mean Signal of Change in Near-Surface Air Temperature (Lower Left Panel), Precipitation (Lower Middle Panel), and Sea-Level (Lower Right Panel).



Each signal of change computed for the three scenarios (Scenario B labeled "BAU", Back-to-Coal-Scenario "BTC", and Constant Emissions "COE").

Figure 10 — CO_2 Emissions (Upper Left Panel) and Atmospheric Concentration (Upper Right Panel), and Global Mean Signal of Change in Near-Surface Air Temperature (Lower Left Panel), Precipitation (Lower Middle Panel), and Sea-Level (Lower Right Panel) 1900 to 2100

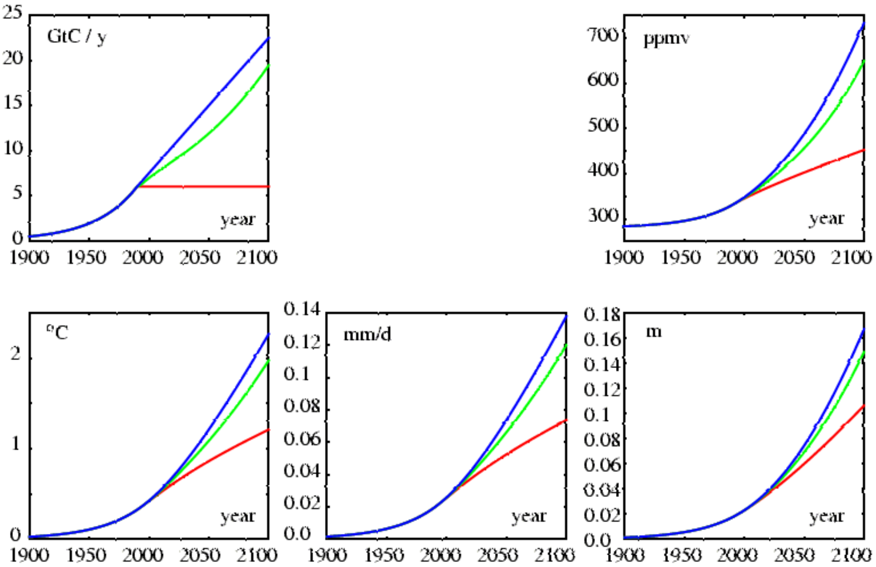


Table 1 — Regional Mean of Near-Surface Temperature Change in (°C) in the Year 2030

Region (r)	Scenario B	Worst-Case-Scenario
North America	0.73	1.12
Western Europe	0.59	0.83
Former Soviet Union	0.72	1.01
Pacific Asia OECD	0.52	0.71
Pacific Asia	0.46	0.70
China	0.64	1.00
India	0.50	0.80
Middle East & N'africa	0.69	1.02
Subsaharan Africa	0.53	0.75
Latin America	0.51	0.76
Rest of the World	0.57	0.93
GLOBE	0.44	0.90

Table 2 — Regional Mean of Relative Changes (in %) in Precipitation in the Year 2030

Region (r)	Scenario B	Worst-Case-Scenario
North America	0.83	4.47
Western Europe	-0.44	-5.64
Former Soviet Union	1.52	6.65
Pacific Asia OECD	1.95	5.98
Pacific Asia	1.62	5.12
China	1.44	5.54
India	4.61	11.44
Middle East & N'africa	17.44	73.78
Subsaharan Africa	1.08	5.21
Latin America	1.27	5.72
Rest of the World	4.13	27.12
GLOBE	1.66	16.19

Table 3 — Regional Mean of Sea-Level Changes (in Centimeters) in the Year 2030 to 1993

Region (r)	Scenario B	Worst-Case-Scenario
North America	2.78	3.27
Western Europe	2.75	3.24
Former Soviet Union	2.98	3.48
Pacific Asia OECD	3.03	3.54
Pacific Asia	3.03	3.54
China	3.01	3.51
India	3.15	3.66
Middle East & N'africa	2.75	3.24
Subsaharan Africa	2.84	3.33
Latin America	2.67	3.15
Rest of the World	2.81	3.30
GLOBE	2.81	3.30

5.8 Climatological Discussion of the Scenarios

Within the time frame under investigation, the climate response is remarkably similar over the whole spectrum of possible emissions scenarios – from staying constant at 6 GtC/y to doubling the rate in only 40 years. The total changes in atmospheric CO_2 and climate remain moderate until the end of the simulation period in year 2030. However, the trends are unmitigated. The steepness of the increase suggests larger changes if extrapolated beyond the simulation time window (see also Figure 10 for extrapolations to the entire century). This holds for all three scenarios, despite the wide range of emissions considered. From the similarity of the climate responses to considerably different emission scenarios it becomes evident that drastic emission reductions, although important in the long-term evolution, cannot be expected to yield a clearly distinguishable influence on short-term climate change during, say the coming half century.

Having in mind the response time lag of the planetary system (that is long compared with both individual human time perception and economic or political planning horizons) and with that the planetary changes expected for the coming centuries, it must be concluded that the costs computed for the next few decades cannot adequately reflect the historical and planetary significance of global change.[9]

6 CONSIDERING THE IMPACT OF CLIMATE CHANGE IN THE ECONOMIC MODEL

Translating changes in climate parameters such as temperature, precipitation, and sea-level rise into the effects on economic activity and economic welfare requires a large amount of integrated modelling. This area is not yet well researched due to conceptual as well as informational problems. The conceptual problem for modelling climate impacts in an economic model originates from several sources:

- Many climate impacts on the economy materialize only indirectly or are difficult to measure and integrate into market models. Examples are changes in health or impacts on non-market values such as landscapes or aesthetics of the biosphere.
- If impacts are measured in terms of monetary damages the evaluation of such damages needs to be derived from existing price systems. These price systems, however, may change in the moment the damage actually occurs.
- Contrary to natural systems whose reaction to external shocks follow certain rules of nature, the reaction of humans to climate change is difficult to model. Adaptation to changing climate conditions occurs from the

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[9] Two idealized 1000-year scenarios studied with the NICCS model demonstrate that the use of all currently estimated fossil fuel resources would carry the Earth's climate far beyond the range of climate change for which reliable quantitative predictions are possible today, and that even a freezing of emissions to present-day levels would not be sufficient to prevent a major global warming in the long term (cf. Hooss et al. 2001).

individual to the societal level. But these adaptations do not follow pre-described rules.

- Since adaptation occurs on different levels of decision making in a society it is important to decide which part of the adaptive capacities are modeled as exogenous and which part will be endogenous. For example, adaptation of individual decision makers may be endogenous whereas adaptation policies imposed by a government may be treated as exogenous. Hence, the aggregation level of the economic model determines the degree of impacts depending on the share of adaptation which is endogenous to the economic model.
- There are also severe data problems for assessing the impact of climate change on important economic variables. Many non-market goods are already difficult to evaluate; it is even more difficult to assess their change in values as the climate system slowly changes. Even seemingly easier changes in the quality and quantity of natural and environmental resources which enter production and/or consumption processes suffer from a lack of regionally disaggregated data.

In this paper we have therefore chosen a limited approach for which little but at least some impact data can be derived and can be integrated into an economic simulation model. We include the impact of climate change on agriculture and the investment necessary to prevent damages from sea-level rise. Although this is only a small part of the wide spectrum of climate impacts it gives an indication of the size and the regional variability of the economic damages imposed by climate change. It also highlights the adjustments in the economic system to such climate change.

6.1 General Methodical Considerations

We introduce the impact of climate change into the economic model by means of region-specific impact functions. The impact functions relate projections of climate parameters for each year to the impact they have on the factor endowments or decisions of actors in the economy.

The climate parameters for each year are obtained from the climate model which itself uses the CO_2-emission paths resulting from projections of economic activity in the economic model. The climate model computes region-specific paths of temperature, precipitation and sea-level for each CO_2-emission scenario that we consider. In order to specify region-specific impact functions the changes of the climate parameters temperature, precipitation and sea-level as computed in the climate model must be connected to the economic activities which are sensitive to changes in the climate.

We specify the region-specific impact functions on the basis of studies which examine the physical impact of climate change on the economy since prices and therefore economic damages are endogenous in the economic model. The majority of studies on physical impacts deals with the agricultural sector which is especially climate-sensitive. There exist very few quantitative studies which analyse the impact of climate change on other sectors or on final demand. Therefore we concentrate on the agricultural sector. Given the discussion about the consequences of sea-level rise and the availability of a variety of regional studies we also consider the impact of sea-level rise in the economic model.

Adaptation to climate change is a complex process which simultaneously takes place on different time as well as geographical scales. First of all, there is the impact of the climate system on the biosphere in which plants will adapt to. However, it is usually claimed that the speed of climate change is too fast for a smooth transition. These processes are ignored in the present modelling context, mainly because our focus is on agricultural production where the adaptation by humans through adjustments in the production process by far dominates natural adaptation.

But in farming activities different scales of adaptation can be identified as well. Changes in temperature and precipitation patterns through climate change will both be adapted to by farmers through a variation of inputs, through different cultivation activities, or through a change in crops grown which are more suited to the new situation. They are done even without a change in agricultural input or output prices. Such adjustments take place at the farm level and as this is a much smaller scale than the aggregation level of the CGE-model it can not satisfactorily be included in the analysis. Ideally, one would like to use information of climate impacts at the farm level with the adaptation by farmers included. However, such data is not available to our knowledge. Therefore, we are forced to ignore effects such as shifts in cultivation or in crops grown at the farm level.

A further data problem arises because many studies on the impact of climate change on agricultural productivity have attempted to identify a point estimate. The benchmark most often used is a CO_2-doubling compared to pre-industrial times. We therefore need to downscale these estimates since a doubling of CO_2-concentrations will most likely not take place until the year 2030. The functional form for this downscaling can only be chosen on an ad-hoc basis.

These considerations show that the modelling of climate impacts within a CGE-framework can only give a rough guide as to what the overall repercussions of climate change are when agricultural land productivity is affected and actions against sea-level rise need to be taken. The following sections describe how we derive impact functions for the agricultural sector and for sea-level rise on the basis of impact studies and how we introduce the impact functions into the CGE model.

6.2 Impacts on the Agricultural Sector

The impacts of climate change on agriculture will differ by region. While in some regions agricultural production may decrease, e.g. due to decreasing crop productivity or losses in acreage, the agricultural sector in other regions may benefit from a warmer and more humid climate (Fischer et al. 1996, IPCC 1996). Producers will respond to climate-induced changes in production conditions by changing their behavior, and therefore, lessen direct negative effects (respectively strengthen direct positive effects) of climate change (Parry 1990).

Within a CGE-framework, such adaptation measures take place on a scale which cannot be integrated into the model. However, there remain climate-induced changes in production possibilities which need to be taken into account in the CGE model. Such direct climate impacts affecting the supply side of the economy can be modeled as changes in parameter values of production functions or as changes in factor endowments (cf. Kurtze and Springer 1999). Information on the magnitude of qualitative and quantitative changes in the production function of the agricultural sector can be derived from physical impact studies.

In the following, the methods and the results of agricultural impact studies are briefly described. Furthermore, we look at the characteristics of an impact function and the requirements when integrating the function into the model. Finally, numerical values are assigned to the parameters of the impact function which incorporate the information of the impact studies.

PHYSICAL IMPACT STUDIES

The studies of climate impacts on agriculture deal with different issues, such as shifts of cropping zones, the assessment of changes in crop yields or the analysis of the effects on income and employment in the agricultural sector (Feenstra et al. 1998). Since adaptation to climate change on a sectoral level is endogenously determined in the CGE framework, only those impact studies which deal with yield changes and which do not consider overall economic reactions are appropriate for determining the impact functions. For the analysis of crop yield changes, empirical-statistical models, process-based crop growth models and analogue studies are applied (Feenstra et al. 1998).

All types of crop models rely on information of possible changes in climate. These climate data are derived from meteorological simulation models, the General Circulation Models (GCMs). Most of the impact studies refer to climate change scenarios which have been run at the meteorological institutes GFDL, GISS and UKMO. The published results of the GCMs mainly document changes in annual mean temperature in degrees and percentage changes of the annual amount of precipitation. Using different scenarios on temperature and precipitation changes derived from each of the mentioned GCMs, changes in crop yields are finally determined as percentage changes in annual average yield per hectare in these studies.

THE IMPACT FUNCTION

When modelling the impact of climate change in a CGE framework, a continuous functional relationship between the yield change, temperature change and change in precipitation has to be established. We have chosen a simple linear relationship between the impact of changes in temperature and percentual changes in precipitation on yield[10].

$$\frac{dq}{q} = a_1 * dT + a_2 * \frac{dP}{P} \qquad (7)$$

$\frac{dq}{q}$	relative changes in yield per hectare (%)
dT	absolute changes in temperature (T) (°C)
$\frac{dP}{P}$	relative changes in precipitation (P) (%)
a_i	climate impact parameter

The impact function (7) shows certain properties which shall be briefly discussed.

First, a linear relationship between changes in yields and climate implies that the more temperature and precipitation vary, the more are crop yields affected. This specification can only hold for small perturbations since it can be observed, that yields of certain crops sometimes decrease dramatically after a previously

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[10] One may expect that the interaction of temperature and precipitation has an impact on yield changes. To verify this assumption, we have performed an econometric analysis using data from impact studies for the US and Canada. However, a least-square estimation has revealed that the estimated coefficient for an interaction term of temperature and precipiation on yield changes is not significant. Thus we argue that a linear relationship between changes in crop yields and changes in climate variables prevails. Moreover, we cannot estimate region-specific types of impact functions for any other region since data for them is not available in a sufficient extent to perform a comparable econometric estimation. Therefore, we assume that the linear relationship prevails for all regions.

unknown threshold level of temperature or precipitation is crossed. Hence, already small changes in climate variables could cause large non-linear changes in crop yields (Parry 1990). Obviously, the larger the magnitude of predicted climate change is, the more probable is the passing of tolerance thresholds. However, the time horzion of the economic model is relatively short compared with the usual time horizon of climate models. The predicted climate change relevant for the short- to medium-term economic model do not produce such big changes. Thus, a simple linear relationship may be appropriate.[11] Sensitivity analyses using a wide range of possible climate impact parameters in a linear function can help to fence the results against possible non-linearities in the impact function.

Second, in equation (7) relative changes in yields are explained by relative changes in precipitation and by *absolute* changes in temperature. This specification is necessary because of missing data on relative changes in temperature.

INTEGRATING THE IMPACT FUNCTION INTO THE CGE-FRAMEWORK

Next, we decribe how impacts of climate changes are modeled within a CGE-framework by integrating a functional relationship between climate and economic impacts into the CGE model. Basically, this relationship has to satisfy two preconditions. It should be possible to incorporate the data from the impact studies into this relationship and its specification should be consistent with the rest of the model. In the following, we discuss both aspects.

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[11] But even if significant changes in climate variables are predicted, nonlinearity may be approximated by step-wise defined linear functions.

Different starting points for the functional relationship of economic impacts are possible. When considering the production function of agriculture (8), climate change may affect total factor productivity $A_Y(T,P)$, the productivity of individual factors $A_i(T,P)$ or even the supply of inputs (Kurtze and Springer 1999).

$$(8) \quad \frac{Y}{A_Y(T,P)} = f\left(A_1(T,P)*x_1,\ldots A_i(T,P)*x_i\ldots,A_n(T,P)*x_n\right) \quad \text{with}$$

Y	output of agricultural production
x_i	input in agricultural production
$A_Y(T,P),A_i(T,P)$	climate-dependent productivity indices

As we model agricultural production with a homogenous production function integrating the impacts through changes in total factor productivity $A_Y(T,P)$ is appropriate. Therefore, the yield changes found in the literature are transformed into changes of productivity of land[12].

Land can be regarded as land in physical units B, i.e. measured in hectares, which is assumed to be constant over time. For production, land in efficiency units V, which is the physical amount of land multiplied by its climate-dependent efficiency, is the relevant measure as an input factor. Land in efficiency units is thus given as:

$$(9) \quad V_t(T_t,P_t) = A_t(T_t,P_t)*\overline{B}$$

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[12] Remember that land is used only in the agricultural sector. Hence, changes in land endowments, or land productivity respectively, are sector-specific.

with $A_t\left(T_t, P_t\right)$ denoting the productivity of land, which depends on temperature, T, and precipitation, P. In this formulation, changes in land productivity can be represented by changes in the endowment with land in efficiency units. In the initial period, when land productivity is unchanged, both variables for land are identical. Hence V_0 equals B.

For determining efficiency land $V_t(T, P)$ as a function of the climate impacts, we differentiate (9) with respect to climate variables, temperature, dT, and precipitation, dP:

$$(10)\quad V_t(T,P) - V_{t-1}(T,P) = dV = \frac{\partial V}{\partial T} * dT + \frac{\partial V}{\partial P} * dP$$

The partial derivatives $\frac{\partial V}{\partial T}, \frac{\partial V}{\partial P}$ in equation (10) are determined by using the results of the impact studies and the production function of the agricultural sector from the model. Since data from the impact studies refer to output changes, i.e. changes in crop yields, impacts on the output side have to be translated into impacts on the land input by using the production function for the agricultural sector.

A scaling and aggregation problem exists when impacts are translated into input changes. Basically, very different commodities like crops, livestock products or processed goods result from agricultural production. In the existing sectoral aggregation of the CGE-model, all these commodities are aggregated to only one single agricultural good. In contrast, the data of the impact studies describe the effect of climate change on tillage production only. Therefore, data on crop yield changes cannot be equated with output changes of the entire agricultural sector in the transformation. To overcome these difficulties, we assume that that the agricultural output in the economic model is a composite of several heterogenous goods, e.g. crops and goods produced on cattle-farms or in dairies and make some simplifying technological assumptions on the production of these sub-commodities (see Appendix for details). Finally, the transformation results in equation (10’), which is implemented into the CGE model:

$$(10') \; dV = l * \left(a_1 * dT + a_2 * \frac{dP}{P} \right)$$

The term in brackets in equation (10’) is identical with the function on the right hand sight of (7), the relative yields changes. Furthermore, l is a shifter which incorporates the share of crop yields on total agricultural output and other technological conditions in the agricultural sector. Thus, the absolute climate-induced change in land in efficiency units, dV, is a multiple of the relative changes in yields per hectare.

NUMERICAL SPECIFICATION OF IMPACT PARAMETERS

After having integrated the climate-impact relationship into the CGE model, the function has to be parameterized for every region by using the results of the empirical impact studies. This parameterization must be done inspite of a number of data problems. First, the number of impact studies on crop yields for some regions is very limited. Second, the studies are usually focused on one particular crop in a single and often narrowly defined geographical area. Third, in some impact studies, the climate data are only incompletely documented. In such cases, analogue temperature and precipitation data from other sources are assumed.[13] For the assignment of parameters, we employed data derived from the following studies (cf. Table 4).

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[13] This may lead to some distortions, since the analogue data possibly deviate from the actual climate data used in the study.

Table 4 — List of Employed Impact Studies

Region	Impact Studies
North America	Adams (1989), Barry/Geng (1992), Kaiser (1991), Kokoski (1984), Mooney/ Arthur(1990), Parry (1990), Schimmelpfennig et al. (1996), Smit et al. (1989), Williams et al. (1988)
Western Europe	Bergthorsson et al. (1988), Delecolle et al. (1994), Iglesias (1995), Santer (1985)
Former Soviet Union	Fischer et al. (1996), Menzhulin et al. (1994)
Pacific Asia OECD	Baer et al. (1994), Fischer et al. (1996), IPCC (1995), Matthews et al. (1995)
Pacific Asia	Escano et al. (1994), IPCC (1995), Matthews et al. (1995), Tongyai et al. (1994)
China	Fischer et al. (1996), IPCC (1995), Jin et al (1994), Matthews et al. (1994)
India	Gadgil et al. (1988), Kokoski 1984), Karim et al.(1994), Qureshi/Iglesias (1994)
Middle East and North Africa	Eid (1994), Onyeji/Fischer (1994), Strzepek et al. (1994)
Subsaharan Africa	Akong'a et al. (1988), Muchena (1994).
Latin America	de Siqueria et al. (1994), Fischer et al. (1996), Liverman (1992).

The largest number of region-specific impact studies is available for the North America region. We have considered six impact studies for this region. The region-specific climate scenarios which underlie the impact studies cover a wide range of possible climate changes. Based on data from these studies, a functional relationship between variations in yield changes on the one hand and temperature and precipitation changes on the other hand has been estimated with an ordinary-least-square method using data of 119 different observations on climate and yield changes. The estimated coefficients are then used as climate impact parameters for North Amercia. It is, however, not possible to perform econometric estimations for the other regions, since there is only limited region-specific data available. To overcome this problem, we proceed on the assumption that yield changes can be described by a continuous function of changes in climate variables and that each single data on yield and associated climate from region-specific impact studies always represent some points on this function. That means the available data describe the region-specific relationships between yield changes on the one hand and changes in temperature and precipitation on the other hand which can be reproduced in a three-dimensional space. However, when comparing all available data for a certain region with each other, some data on yield, temperature and precipitation do not fit with the spatial relationship established by the other observations. We therefore reject those data that represent deviating points taking the risk that these rejected points may represent better predictions of climate impacts than the remaining ones. To support our decision which data to reject, we consider information about the general impact of temperature and precipitation changes on yields depending on the initial regional climate condition as described in IPCC (1996) or Parry (1990).

After a spatial relationship is established for a certain region, we determine the slope of yield changes with respect to the changes in temperature and precipitation at different points of the spatial surface. Thereby, we derive a wider range of possible values for regional impact parameters. By a slight misuse of the language we call the parameter values with the strongest (negative) influence the high impact case and those with the most positive influence the low impact case. The impact parameters for the two extremes are given in Table 5.[14]

Columns 2 and 3 show the percentage change in crop yields if temperature rises by one degree and the amount of rainfall is regarded as constant. The "high impact" parameters (cf. col. 2) capture the situation when crops show the highest vulnerability to temperature change, while the "low impact" parameter (cf. col. 3)

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[14] For the North America region, the range for the temperature coefficient results from adding +/- 4 percent to the parameter value derived form the estimation (cf. Parry 1990). For the precipitation coefficient, the lower value is the one derived from the estimation. The upper value of is taken from data in Kokoski (1984). For the Rest of the World, parameter values are the average values ot the parameters of all the other regions.

describe changes in crop yield under the most favorable conditions, e.g. due to an increasing CO_2-concentrations in the atmosphere biomass production of plants relatively increases and hence negative impacts on plant growth caused by drought, heat stress, etc. may be partly offset or even overcompensated.

Table 5 — Climate Impact Parameters

Region		Yield Changes in Percent relative to +1°C Temperature Change (♋$_1$)		Yield Changes in Percent relative to +1 % Precipitation Change (♋$_2$)	
		high impact	low impact	high impact	low impact
North America	(NAM)	-9.0	-1.0	0.4	1.5
Western Europe	(WEU)	-6.5	5.4	0.0	1.5
Former Soviet Union	(FSU)	-12.5	0.0	0.0	3.0
Pacific Asia OECD	(PAO)	-9.0	5.3	-0.3	2.8
Pacific Asia	(PAS)	-13.8	10.0	-0.7	0.0
China	(CPA)	-19.0	0.0	-3.5	3.8
India	(IDI)	-16.4	14.0	-2.0	3.2
Mid East & North Africa	(MEA)	-10.7	-4.0	0.0	0.1
Sub Saharan Africa	(AFR)	-6.8	3.6	-3.0	1.5
Latin America	(LAM)	-15.5	0.2	-1.3	1.1
Rest of the World	(ROW)	-11.1	2.8	-1.4	1.2

It is remarkable that the temperature parameters for India and Pacific Asia show a range between lower and upper limit parameter for these regions which is significantly wider than for the other regions. This is because the available impact studies for India and Pacific Asia show substantial but very diverging yield changes. Therefore, the expected temperature impact in these regions cannot be narrowed like it can be done with the other regions.

Columns 4 and 5 describe the percentage change in crop yields when the amount of precipitation increases by one percent provided that annual mean temperature stays at its current level. Note that the parameters values derived from the impact studies for regions with subtropical and tropical climate conditions show a negative sign (cf. col. 4). Hence, if precipitation increases in these regions (cf. section 3), crop yields are expected to decrease. This may be attributed to more frequent incidences of floods and rain storms because it is expected that an average increase in precipitation will be, at same time, connected with an increasing variability in precipitation. Vice versa, a positive sign of the precipitation parameter as can be derived for the other regions implies a higher level of crop yields. In this case, negative effects on crop yields due to inundation may be overcompensated by positive effects due to a less pronounced occurance of droughts.[15]

Finally, the impact parameters, together with the data on annual changes in temperature and precipitation stemming from the climate model and the shift parameter λ, whose value depends on share of crops in agriculture and on the technology used in the agricultural sector of each region, are inserted into the climate-impact-relationship (equation 10’) to calculate annual changes in land endowment dV.

Within the economic model, these changes in land endowment consequently lead to changes in relative factor prices as well as in relative commodity prices and therefore affect the allocation of other factors and commodities across sectors and regions. Thus, by incorporating climate-impacts through the functional relationships just described we can assess the welfare effects of the impacts of climate change on agriculture on a regional scale.

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[15] For the Middle East and North African Region, the impacts studies suggest that crop yields show only little sensitivity to changes in rainfalls which may be explained by the fact that irrigation practices are prevailing in this region and therefore an immediate dependence on rainfalls is less pronounced (Oram 1985). However, the availability of irrigation water may be influenced. This causal chain is not modeled here.

6.3 The Impact of Sea-Level Rise

THE PHYSICAL IMPACT OF SEA-LEVEL RISE

Another consequence of climate change is the likely increase in sea-level. The increase in global mean temperatures causes the thermal expansion of ocean water and the melting of land-based ice sheets and mountain glaciers which in turn can lead to an increase in sea-level (Cline 1992: 107; Den Elzen and Rotmans 1992).[16]

The increase in sea-level has a direct physical impact on coastal zones and islands. The impact consists of three components: First, the retreat of the shoreline causes the inundation of land (wetland and dryland) and physical assets. Second, a higher sea-level enhances the vulnerability of coastal zones to flooding, and third, their vulnerability to the intrusion of salt water (Titus et al. 1991).

If people anticipate the physical impact of sea-level rise, they are likely to adapt by taking protection measures such as building or raising dikes and nourishing and elevating beaches.

THE QUANTIFICATION OF THE PHYSICAL IMPACT OF SEA-LEVEL RISE

There is a variety of regional studies which analyze the physical impact of sea-level rise and potential adaptation measures. The most comprehensive studies have been conducted for the United States (e.g. Titus et al. 1991; Yohe et al. 1996) and the Netherlands (e.g. Den Elzen and Rotmans 1992). Further studies

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[16] The melting of sea-ice has no influence on the sea level since the volume of its submerged portion is equal to its total water equivalence (Cline 1992: 107).

refer to small island states, which are particularly threatened by sea-level rise (cf. e.g. Cline 1992: 111; IPCC 1996: Chapter 9).

On the one hand, the studies evaluate the physical impact by quantifying the damages that would result under different projections of sea-level rise. On the other hand they evaluate adaptation options by comparing the costs of different protection measures for a given projection of sea-level rise.

Some damages can be easily quantified, at least in terms of physical units if not in terms of monetary values: the acreage of lost dryland and wetland, the loss of physical assets and the people displaced or otherwise affected. Other damages are more difficult to quantify. The increasing vulnerability of coastal zones to flooding and salt water intrusion, for instance, is difficult to capture in numerical values. Also the monetary evaluation of land losses can be difficult: some coastal areas are not directly used for economic purposes but provide ecosystem services which are hard to quantify. Because the damages from sea-level rise are difficult to evaluate they are often quantified in terms of physical units, such as acres of lost land or number of species extinct, rather than in terms of monetary values.

Protection measures are evaluated in two ways. Some studies derive the optimal level of protection by comparing the monetary values of damages to the costs of the protection measures that would be necessary to avoid these damages (e.g. Den Elzen and Rotmans 1992; Fankhauser 1994). Other studies calculate the costs of different protection scenarios where, for instance, only developed areas, only densely populated areas, or all threatened areas are protected (e.g. Titus et al. 1991).

INTRODUCING THE IMPACT OF SEA-LEVEL RISE INTO THE ECONOMIC MODEL

Using a CGE framework theoretically gives us the opportunity to incorporate both, the direct physical impact of sea-level rise and the option of protection, into the model. For that purpose the model has to be extended in two ways. First, for each region the direct physical impact has to be converted into parametric changes of production functions, final demand functions, the investment function or primary factor endowments (Kurtze and Springer 1999). Second, for each region the option of protection has to be modeled as an economic activity which uses certain inputs and which has to be paid for by some agents. The extension of the model allows the endogenous determination of the optimal level of protection for each region.

Such an extension requires the introduction of additional information into the model, which is hard to obtain: The regional studies that deal with the physical impact of sea-level rise and with potential adaptation measures differ widely with respect to the assumptions made and the methodologies used. Furthermore the damage categories which are analyzed do not always coincide, either in coverage or in unit of measurement. These differences make it impossible to compare the results of the studies and therefore we cannot use them as a data basis for the extension of the model. Therefore we are not able to derive the optimal level of protection endogenously in the model.

Instead we assume that all coastal zones threatened by sea-level rise will actually be protected. This implies that protection costs are much lower than expected damages and that it is, therefore, efficient to protect all land. Even though this conclusion can, in fact, only be made on the basis of an optimization analysis, the assumption seems to be a plausible approximation of what is to be expected: Fankhauser (1994), for instance, conducts an optimization analysis for the OECD countries and concludes that “... the optimal degree of protection will vary between about 50% to 80% for open coasts and beaches, depending on the underlying SLR scenario." and that "Cities and harbors are almost invariably protected to the full." (Fankhauser 1994: 31).

As a measure of the first order economic impact of protection from sea-level rise we use annual protection costs which are determined exogenously. Dikes, elevated beaches etc. are not used as inputs for the production of goods, but protect people, capital and land that exist currently and in the future. Therefore, we interpret annual protection expenditures as investment in non-productive capital which reduces the savings available for investment that increases the productive capital stock. Protection expenditures are introduced into the model by modifying equation (2) (cf. Chapter 2) that describes capital stock accumulation in each region:

$$(2') \quad Kst_{r,t+1} = Kst_{r,t} * (1 - d_t) + Iq_{r,t} - Pc_{r,t} \qquad t \geq 1$$

where $Pc_{r,t}$ protection costs in region r in year t, in US$.

For each region protection costs in year t, $Pc_{r,t}$, are obtained from the following protection cost function:

$$(11) \quad Pc_{r,t} = GDP_{r,t} * \frac{pcs_r}{100}, \quad \text{where}$$

$GDP_{r,t}$	the gross domestic product in year t in region r, in US$.
pcs_r	constant share of GDP that has to be spent on protection each year in region r, in percent.

Protection costs are related to GDP in order to account for the effect of growth which occurs in the recursive-dynamic model. We make the assumption that the relation between GDP and protection costs remains constant over time. To operate with constant monetary values instead of GDP shares would result in an ever diminishing cost share for protection from sea-level rise in a growing economy, which does not seem very plausible.

The constant share of GDP that each region has to spend on protection annually is obtained as

$$(12)\quad pcs_r = pcsm_r * m_r, \qquad \text{where}$$

$pcsm_r$	constant share of GDP that has to be spent on protection each year in region r in case of a 1-meter rise between 1990 and 2100, in percent.
m_r	sea-level rise between 1990 and 2100 as calculated in the climate model for different CO_2-emission scenarios, in meters.

The constant share of GDP that each region has to spend on protection, pcs_r, depends on a region-specific reference value and on the CO_2-emission scenario. As a reference value we choose the share of GDP the region would have to spend in case of a 1-meter rise between 1990 and 2100, $pcsm_r$. We obtain the figures for these shares on the basis of protection cost studies (see below). The actual increase in sea-level which takes place between 1990 and 2100 in each region, m_r, depends on the CO_2-emission scenario and is calculated in the climate model. We assume that the share of GDP that has to be spent on protection is a linear function of sea-level rise.

Our approach to introduce the impact of sea-level rise into the economic model by reducing investment into productive capital by protection costs has the advantage to be manageable from the point of view of data availability. Furthermore, it still allows us to use the capacity of a multi-regional framework to derive differences in the ability of the regional economies to cope with the burden of protection costs.

CHOOSING THE DATA

Protection cost studies differ widely with respect to the scenarios of sea-level rise and the methodologies used. Not all studies show their results in terms of monetary values. We use a survey of 23 country case studies provided by the Intergovernmental Panel on Climate Change (IPCC 1996) as the basic source of information. The IPCC interprets the results of these studies according to the 'IPCC Common Methodology' (IPCC 1996: 305ff.). The methodology rests on the assumption that the sea-level rises between the present and the year 2100 in a slow, gradual process. Most of the studies use the scenario of a 1-m rise over this horizon, and for its survey the IPCC interprets the results of all studies with respect to this scenario.

"Adaptation/protection costs" are defined as costs associated with "... defensive measures by which one seeks to maintain shorelines at their present position by either building or strengthening protective structures or by artificially nourishing or maintaining beaches and dunes." (IPCC 1996: 311f.). The IPCC assumes that total protection costs accrue uniformly over 100 years (IPCC 1996: 309).

Since the protection cost estimates of the different studies are comparable, they form a suitable basis for the derivation of our region-specific protection cost functions as described in equation (11). The estimates that we use represent the total costs that accrue to a country over a time horizon of 110 years in the case of a gradual increase of the sea-level by one meter between 1990 and 2100.[17] These total costs are reproduced in Table 6.

Table 6 — Estimates of Total Protection Costs from the Studies in the IPCC-Survey

Region	Country	Total Protection Costs (billion 1990 US$)
North America	United States	156.0
Western Europe	The Netherlands	12.3
Pacific Asia OECD	Japan	156.0
Middle East & N'africa	Egypt	13.1
Subsaharan Africa	Benin	0.4
Subsaharan Africa	Nigeria	1.4
Subsaharan Africa	Senegal	1.0
Latin America	Argentina	1.8
Latin America	Guyana	0.2
Latin America	Uruguay	1.0
Latin America	Venezuela	1.6

Source: IPCC II (1996): 308, Table 9-3.

Total protection costs differ between countries because of differences in the lengths of the coast lines to be protected, the kind of protection measures chosen, and the costs of protection measures. The United States, for instance, have a much longer coastline than the Netherlands and have therefore to spend more on protection. Furthermore people in the Netherlands have a long experience with protection from the sea. Therefore the additional protection they will need if the sea-level rises will be less expensive. In developing countries, such as the African countries, labor and capital used as inputs for the building of dikes or the

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[17] The IPCC makes no explicit reference to the starting point of the time horizon over which the rise by 1 meter is to be expected. We assume the starting point to be 1990 because the protection costs of the country case studies are given in terms of 1990 US$. Consequently, we refer to a time horizon of 110 years.

elevation of beaches are much cheaper than in developed countries such as Japan.

PROCESSING THE DATA

In order to derive $pcsm_r$ in equation (12), i.e. the share of GDP each region has to spend on protection each year in case of a 1-m rise between 1990 and 2100 we proceed in three steps:

First, we derive the total protection costs that accrue to each region from 1990 to 2100 in case of a 1-m rise over this horizon. The economic model consists of eleven regions which are aggregated with respect to economic considerations. Each region consists of countries with different vulnerabilities to sea-level rise. Unfortunately, but not surprisingly, we do neither have a study for each country nor a representative study for each of the eleven regions. In order to obtain protection costs for each region we adjusted the estimates of the studies in the IPCC-survey. For that purpose we used different approaches: In case of the OECD regions Western Europe, North America and Pacific Asia OECD we were able to use the estimates from the studies of the The Netherlands, the U.S. and Japan applying the shares of these countries in overall regional costs computed by Fankhauser (1994).[18] For the other regions we had no comparable study to refer to. Therefore the adjustment was done according to coast-line characteristics in the cases of the Middle East and North African Region, Latin America and Sub-Saharan Africa. Where no studies where available at all, such as in the cases of China and Hong Kong, Pacific Asia and India, we used analogies to other regions, taking into consideration coast-line characteristics and

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[18] We could not use the protection costs derived by Fankhauser (1994) directly, because they include not only the costs for protection measures but also the costs of land loss which occurs if protection measures are taken.

economic performance.[19] The results, i.e. total regional protection costs, are shown in column 1 of Table 7.

Second, in order to obtain *annual* costs, we devide total costs that accrue from 1990 to 2100 by 110.[20] This gives us constant absolute protection costs for each year from 1990 to 2100.

Third, in order to take economic growth into account, we relate absolute annual protection costs to GDP. We assume that the relation between absolute protection costs and GDP that exists in the starting period of the model remains constant over time.[21] Using GDP values from the benchmark run of the model we calculate the share of absolute annual costs in GDP in 1990 for each region. The results represent the shares of GDP that have to be spent each year in case of a 1-m rise of the sea-level which occurs gradually between 1990 and 2100, $pcsm_r$. The shares are shown in column 3 of Table 7.

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[19] The Rest of the World region, which includes, inter alia, the highly vulnerable small island states is not considered in the analysis. Rest of the World includes countries the vulnerability of which is extremely diverse, such as Liechtenstein, which has no coast at all and Kiribati, a small island state. Considering the highly aggregated scope of our simulation, the economic importance of the highly vulnerable subregions in this Rest of the World region is, however, very limited.
Also protection costs for the Former Soviet Union are set to zero, because most of its threatened coastline is not used for economic purposes. Therefore it seems likely that protection costs are much higher than damages and that no protection measures will be taken. Protection costs for the Baltic States will probably represent a neglectable share of the GDP of that region.

[20] An economically consistent method to convert total costs into annual flows would be to interpret total costs as a present value and to derive an annuity using a discount rate. The IPCC, however, does not seem to have applied this method, in any case no discount rates are given. For that reason we divide total costs by the number of periods of the time horizon as the IPCC presumably did.

[21] The time horizon of the economic model ends in 2030 while the time horizon that we use to derive protection costs extends to 2100.

Table 7 — Regional Protection Costs in the Case of a 1-m Rise between 1990 and 2100

Region	Total Protection Costs (billion 1990 US$)	GDP in 1990 (billion 1990 US$)	Annual Protection Costs as a Share of GDP (in percent)
North America	159	5970	0.02
Western Europe	176	6887	0.02
Pacific Asia OECD	208	3568	0.05
Pacific Asia	156	739	0.19
China	78	353	0.20
India	56.5	208	0.25
Middle East & N'africa	48.5	573	0.08
Subsaharan Africa	19	282	0.06
Latin America	13.3	1115	0.01

Source: Own calculations.

The fraction of GDP a region has to spend on protection depends on the level of absolute protection costs and on the level of GDP. Absolute protection costs in India and the Middle East and North African region, for instance, are in the same order of magnitude (col. 1). The GDP of the Middle East and North African region is, however, more than twice as high than the one of India and therefore the share of GDP that has to be spent on protection is lower in Middle East and North Africa than in India.

For each region the share of GDP that has to be spent on protection each year in case of a 1-m rise, $pcsm_r$, is introduced into equation (12). Together with the projected increase in sea-level from the climate model, m_r, equation (12) gives the share of GDP each region has to spend annually on protection, pcs_r. The share depends on the underlying CO_2-emission scenario, which determines climate change and the resulting increase in sea-level for each region. Absolute protection expenditures for each year between 1993 and 2030 that correspond to the constant share of GDP are calculated by equation (11). This first order economic impact of sea-level rise is modeled by equation (2') which describes capital accumulation: protection expenditures reduce investment in productive capital.

7 THE ECONOMIC IMPACT OF CLIMATE CHANGE: SIMULATION RESULTS

So far, it has been described how the DART-model is extended by introducing impact functions which incorporate the effects of climate change on the economy. Now, the model is applied for different scenarios of climate change in order to assess the magnitude and the regional differences of the economic impact of climate change.

7.1 The Economic Impact On Agriculture

We study how sectoral production and welfare evolve across regions if the climate-sensitive agricultural sector is affected by climate change. Because of the uncertainty and the large variability of the likely effects we consider four different scenarios which result from the combination of two different sets of impact parameters (cf. Table 5) and two different projections of economic development with respect to energy use, Scenario B and the Back-to-Coal-Scenario. Before discussing the results of each scenario, we briefly describe the likely economic effects which can be expected within and outside the agricultural sector as a result of climate change.

Suppose that changes in climate conditions cause a decline in the productivity of land. Ceteris paribus, this leads to an immediate reduction in agricultural output and a drop in land prices. A decreasing supply on agricultural markets causes a price rise for agricultural commodities. Increasing prices of agricultural goods also lead to changes in relative commodity prices which in turn affects the allocation of factors between sectors. Due to increasing relative prices for agricultural commodities, the demand for primary factors like capital or labor and intermediate inputs in the agricultural sector increases. Hence, the fall in land productivity is partly compensated by increasing the input of the other factors of production.

In each region the size of the agricultural sector, the climate impacts, the technology and the input mix vary. Consequently, the agricultural sector in the regions will be affected to different degrees by climate change. However, since agricultural goods are traded internationally, the isolated effects in one region will also affect other regions through trade. Essentially, different climate impacts will change the regional structure of comparative advantage of the agricultural sector.

In summary, climate change impacts will first of all change the productivity of land. This direct effect will lead to a reallocation of resources within the agricultural sector and a change in the price of agricultural commodities. These adjustments on the input and output structure and the accompanying price changes will – as a secondary effect – change the sectoral allocation. Finally, in an open economy trade will balance the price effects in different world regions by changing the comparative advantage and thus the trade structure.

The welfare effects of climate change will directly depend on the just described effect on the productivity of land, i.e. the resource endowments of the economics are effectively reduced. However, the reallocation of resources may reduce, or enhance, these effects. The sign and the size of these indirect effects are impossible to predict in an analytical model; this can only be done by numerical simulation.

SIMULATION OF CLIMATE CHANGE IMPACTS

The chain of reaction from climate change to impacts on agricultural productivity, the adjustment of the agricultural sector, the overall economy, and finally to the reaction of world markets can only be performed with the help of a numerical simulation model. We, therefore, compute with the DART-model the economic effects of climate change on the world economy up to the year 2030 by incorporating the productivity effects shown in chapter 4.2 into the model.

The assessment of the effects of climate change on the 11 world regions is done in three consecutive steps:

1. The direct effects of climate impacts on agricultural production is computed under the assumption that no adaptation in the agricultural sector takes place, i.e. the output effect of the productivity change of land is determined. The results for the year 2030 are presented in the subsequent section.
2. The impact of climate change on the agricultural sector is computed by taking into account the reallocation of resources due to the productivity change of land and the subsequent changes in commodity prices, nationally as well as internationally. This adaptation will surely reduce the negative impacts of climate change somewhat. The questions, however, are to what degree are the effects ameliorated and are there different degrees of vulnerability in the regions.
3. The economy-wide reallocation of factors of production, the changes in the demand structure, and the adjustment in trade flows together will establish a new equilibrium. The regional welfare of this equilibrium can then be compared with the regional welfare in an equilibrium without climate change.

Before presenting the effects of climate change on agricultural production, two technical issues need to be addressed . The first one is the aggregation problem mentioned in section 4.1. The values of impact parameters presented above are derived for the production of different crops. In the aggregation of the DART-model the agricultural sector does not distinguish between crop production and other agricultural production activities. Table 8 shows that especially in the industrialized countries the share of crop production is rather low.

Table 8 — Share of Crops on Agricultural Production.

Region	Crop Share (%)
North America	17.97
Western Europe	19.82
Former Soviet Union	21.63
Pacific Asia OECD	20.25
Pacific Asia	32.00
China	51.66
India	59.73
Mid. East & N. Africa	27.25
Sub-Saharan Africa	44.83
Latin America	29.72
Rest of the World	33.37

Source: GTAP3.

Since we do not have any information on the impact of climate change on the non-crop activities we assume that the impact materializes only in the crop proportion and that the shares of crop production remains constant in each region (see also Appendix).

Second, since the climate impacts on agricultural productivity according to the studies examined vary widely we present the effects of the high as well as the low impact variants of productivity changes.

THE DIRECT IMPACT OF CLIMATE CHANGE WITHOUT ADAPTATION

When taking into account the region-specific change in temperature and precipitation (cf. Chapter 3) and the regionally varying sensitivity of plants to global warming, i.e. regionally differentiated values of the impact parameters[22], it is likely that developing regions suffer from a relatively severe immediate reduction in agricultural output due to the decline in land productivity while industrialized regions only experience comparatively low immediate losses.

For computing the direct output changes in the agricultural sector due to climate impacts, we take data from the DART-model and compute the relative output change in the agricultural sector in the year 2030 when land productivity decreases or increases due to climate change but no adaptation measure are taken, i.e. all inputs are employed in the same quantities as if no climate impacts had occurred. Therefore, we first consider data on climate change and impact and technological parameter which enter into the DART-model to compute decrease in land productivity. Next, we take these data on changes in land productivity and data on input quantities for 2030 from the benchmark run of the DART-model without impacts to compute percentual reductions in the agricultural output.

The results of the calculation are shown in the table below.

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[22] The decline of land productivity depends on the scale of climate change and the sensitivity of crop plants on increasing temperature and precipitation, i.e. the values of high impact parameter. For the regions with tropic and subtropic climate, i.e. IDI, CPA, LAM, MEA, AFR and ROW, crop plants on average show a stronger negative sensitivity to climate change than crop plants in the regions NAM, WEU and PAO with relatively temperate climate (cf. high impact parameter in Table 5). Therefore, more severe decreases in land productivity in the former regions are expected.

Table 9 — Relative Changes in Agricultural Output without Adaptation (Output Change in Percent, Emission Scenario B)

Region	High Impact	Low Impact
North America	-1.15	+0.09
Western Europe	-0.78	+0.48
Former Soviet Union	-1.95	+0.97
Pacific Asia OECD	-1.07	+1.65
Pacific Asia	-2.33	+1.45
China	-9.36	+2.71
India	-11.50	+11.73
Mid. East & N. Africa	-2.22	-0.27
Sub-Saharan Africa	-3.50	+1.44
Latin America	-2.91	+0.44
Rest of the World	-4.02	+2.11

The numbers in Table 9 basically confirm the presumption that the direct impact in developing regions is higher than in industrialized regions. In the pessimistic high impact scenario one can see remarkable immediate reductions for India and China which result from a combination of a high vulnerability of plants and a high proportion on crops in agricultural production.

Under the most favorable conditions, i.e. the low impact scenario, agricultural output might grow somewhat in the industrialized countries and somewhat more in the Asian economies. Only the Middle East and North Africa will suffer from climate change.

ECONOMIC IMPACTS ON AGRICULTURAL AND NON-AGRICULTURAL PRODUCTION AND ON TRADE

Since in the high impact scenario all regions experience output losses, the increasing scarcity of agricultural commodities leads to an increase in prices world wide. In the developing regions, we would expect to observe a drop in income which suggests a decrease in domestic demand for agricultural and non-agricultural goods, and therefore, a slight counter effect to the increase in commodity prices.[23]

Since the expected changes in the domestic prices of agricultural commodities will vary across regions a change in the trade flows of agricultural and – to a lesser degree – of other commodities can be expected. The productivity effects of climate changes and the relative price changes which are caused by the climate impact are simulated and can then be compared to the international allocation of goods and factors in a world without climate change.

In Table 10 the general equilibrium effects of climate change are summarized for the high impact scenario, i.e. the most unfavourable climate impacts. The percentage changes refer to the deviations of prices, quantities, and welfare relative to the benchmark scenario without climate change.

Not surprisingly, the economic impact on climate-sensitive agricultural sector is stronger than the one on the other sectors. The first column shows the change in the ratio of import to export prices. The slight increase in this ratio for the OECD and the Former Soviet Union indicate that the international competitiveness of their agricultural sector increases.[24] In contrast, regions like India and China which are most strongly affected by climate change will increase the imports of agricultural commodities because prices on world markets are now comparatively lower relative to their domestic prices. Consequently, agricultural production expands somewhat in the OECD despite the negative climate impact and it contracts especially in the most affected regions India and China. For the

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[23] Total factor income is decreasing in developing regions between 0.2 percent for Sub-Saharan Africa and 1 percent for India.

[24] Note that in the DART-model agricultural products are modeled with the Armington assumption, i.e. imports and exports are not identical commodities.

OECD countries, the economy-wide reallocation and the reaction of the world market for agricultural commodities is strong enough to reverse the originally negative productivity effect on the output (compare Table 9, col. 1, and Table 10, col. 2). This means that additional factors of production will move in the agricultural sector of OECD countries which compensate for the productivity slowdown in such a way that output overall increases.

Table 10 — General Equilibrium Effects of Climate Change in 2030 (High Impact Scenario, Emission Scenario B)*

Region	Ratio of Import to Export Price in Agriculture	Output Change in Agriculture	Output Change in Other Sectors	Welfare Change
North America	+0.24	+0.46	-0.04	-0.15
Western Europe	+0.31	+0.47	-0.07	-0.14
Former Soviet Union	+0.16	-0.67	-0.14	-0.34
Pacific Asia OECD	+0.17	+0.17	-0.10	-0.23
Pacific Asia	-0.03	-1.58	-0.19	-0.70
China	-1.79	-7.48	-1.71	-3.85
India	-2.27	-8.36	-1.55	-5.32
Mid. East & N. Africa	+0.17	-1.12	-0.25	-0.67
Sub-Saharan Africa	-0.23	-2.27	-0.49	-1.00
Latin America	-0.34	-2.09	-0.20	-0.82
Rest of the World	-0.53	-3.14	-0.32	-1.04

*Percentage Change

In all the regions, the immediate climate impact is mitigated through adaptation. The output changes in the other sectors (cf. Table 10, col. 3) show that the compensating factor movements into the agricultural sector will, however, come at a cost: The output in the remaining sectors in the economy will shrink. These effects are very small in the industrialized countries mainly because the agricultural sector is comparatively small such that the factor movements out of industry and services into agriculture have little impact on the rest of the economy.

Furthermore, since relative commodity price on world markets changes in favor of agricultural goods relative to non-agricultural goods, the terms of trade for net-exporting regions of agricultural goods improve. Therefore, net-exporting regions experience a relative gain in welfare. These are primarily developing regions like IDI, CPA, LAM and AFR but also the industrialized region NAM. Vice versa, the terms of trade for net-importing regions of agricultural goods, i.e. WEU, FSU, PAO, PAS, ROW and MEA are deteriorating and are thus contributing to a relative loss in welfare.

SENSITIVITY ANALYSIS OF DIFFERENT SCENARIOS OF LAND PRODUCTIVITY

The uncertainty of the predictions of the climate change models combined with that of the impact parameters for the productivity of agricultural land has already become evident in the variability of the direct climate impacts shown in Table 9. A fall as well as an increase in agricultural production is possible, mainly because the impact of a combined change in temperature and precipitation is very difficult to predict.

Table 11 summarizes the general equilibrium results of the optimistic low impact scenario. Except for the Middle East and North Africa Region, which clearly will suffer from a lack of water, agricultural productivity would increase. However, since the climate impact effect interacts with the world market price effect for agricultural products the welfare effects of the low impact scenario are not the same as the productivity effects. This optimistic scenario increases land productivity on average, hence world production of agricultural commodities increases and prices consequently fall. The resulting shift in world trade flows will have a remarkable effect on the Middle East and North Africa where the decline in land productivity is more than compensated by the fall in import prices for agricultural commodities thus resulting in a welfare gain. An opposite effect happens to the net-exporting regions – welfare relatively decreases in these regions since their terms-of-trade declines. Neverthless, the welfare effect of increased land productivity dominates the terms-of-trade effect so that the net-exporting regions gain in this low impact scenario.

Table 11 — General Equilibrium Effects of Climate Change in 2030 (Low Impact Scenario, Emission Scenario B)*

Region	Ratio of Import to Export Price in Agriculture	Output Change in Agriculture	Output Change in Other Sectors	Welfare Change
North America	-0.17	-0.52	+0.02	+0.03
Western Europe	-0.12	-0.07	+0.04	+0.08
Former Soviet Union	-0.03	+0.40	+0.06	+0.18
Pacific Asia OECD	+0.19	+0.99	+0.06	+0.25
Pacific Asia	+0.13	+1.16	+0.10	+0.36
China	+0.57	+2.44	+0.41	+1.19
India	+3.13	+11.57	+1.85	+6.88
Mid. East & N. Africa	-0.50	-0.97	+0.13	+0.19
Sub-Saharan Africa	+0.16	+1.21	+0.21	+0.52
Latin America	+0.01	+0.16	+0.07	+0.13
Rest of the World	+0.30	+1.80	+0.13	+0.56
*Percentage Change				

In order to illustrate the variability of climate impacts which stem from the uncertain effects of changes in temperature and precipitation on land productivity, Figures 11 and 12 show the low- as well as the high impact scenario. Figure 11 shows the productivity effect without adjustments in the economies whereas Figure 12 presents the overall welfare effect after all adjustments have taken place. It is evident that the welfare effects in the period up to the year 2030 remain small. This may mainly be due to the fact that strong climate impacts are predicted by climate models for the second half of the 21st century.

Figure 11 — Sensitivity of Output Effect in Agriculture to Different Impact, Scenarios in 2030 (Emission Scenario B)

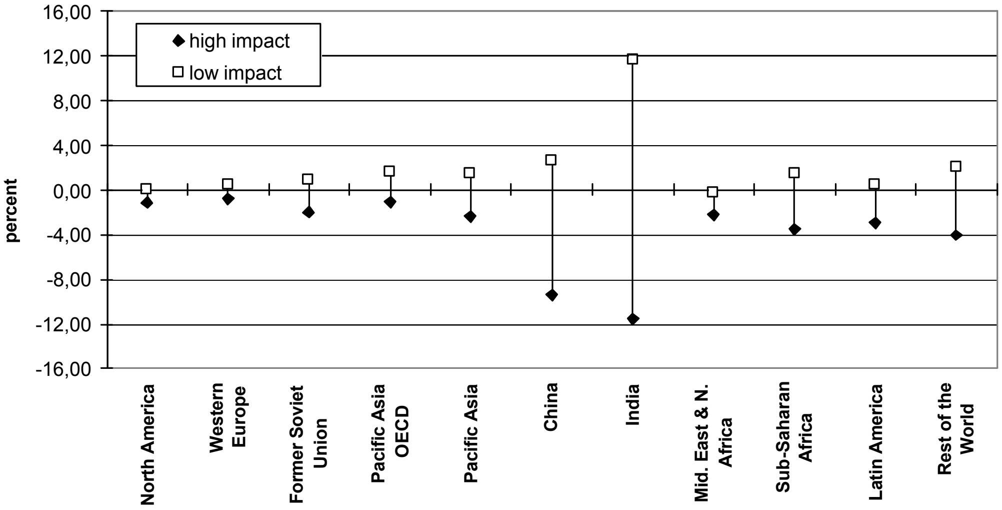
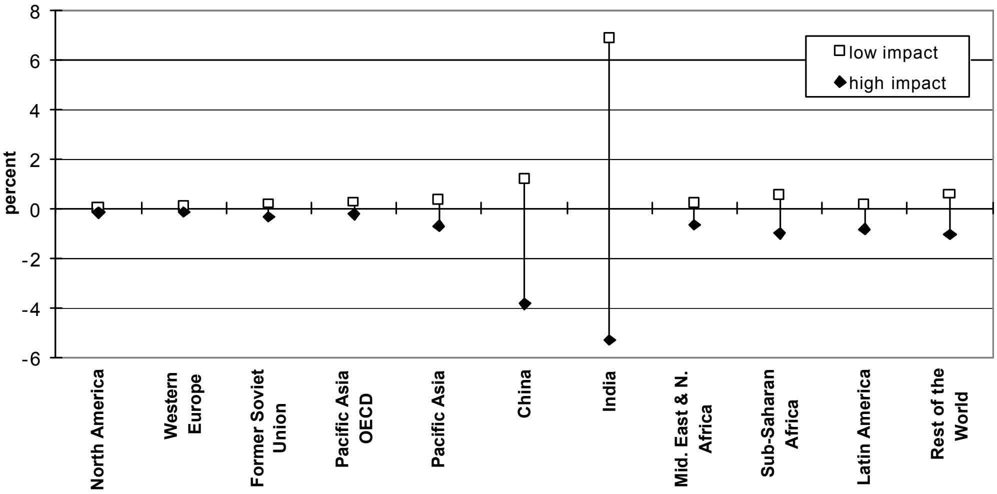


Figure 12 — Sensitivity of Welfare Effect to Different Impact Scenarios in 2030 (Emission Scenario B)



SENSITIVITY ANALYSIS OF DIFFERENT EMISSION SCENARIOS

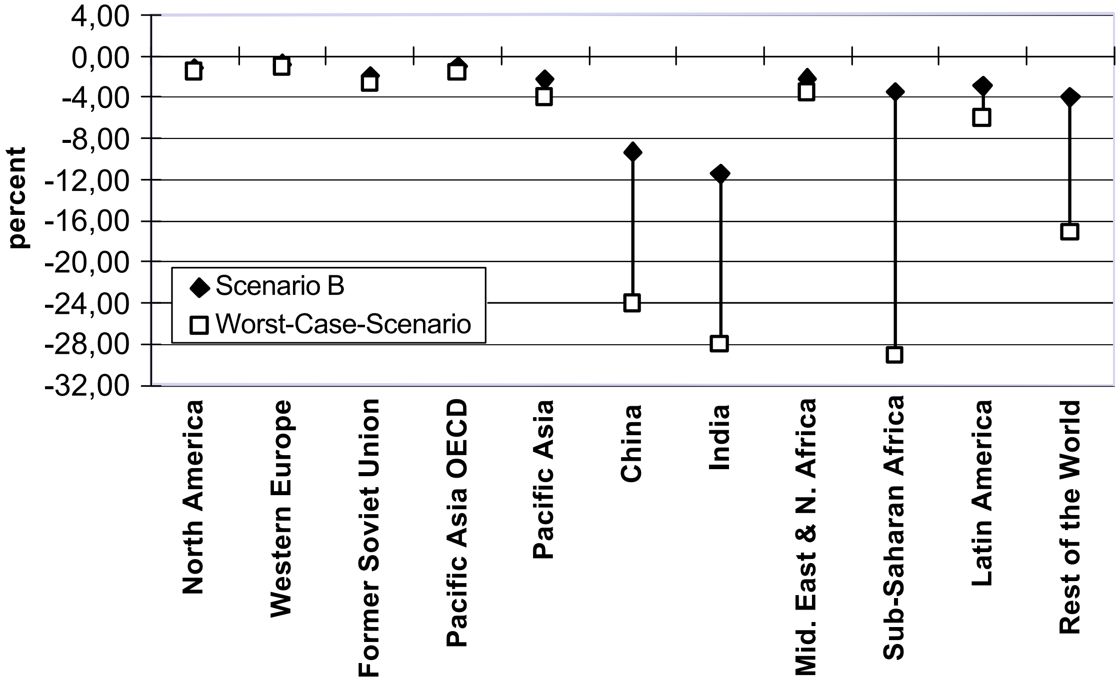
The simulations of the economic effects of climate change have revealed a large variability which is mostly due to the uncertainties about the impact of such change on the productivity of agricultural soils. However, this is not the only uncertainty which long-term modelling has to be concerned with. The basic cause of climate change, the emissions of greenhouse gases, especially of CO_2, in the next decades depends on a large number of factors which are almost impossible to predict. These encompass the speed of improvements in energy efficiency, the supply elasticities of fossile fuels, energy policies, and many other developments.

Among the many possible scenarios we therefore present two different emission scenarios in order to assess the impact of alternative emission paths on the economic effects of climate impacts, the Scenario B and a kind of Worst-Case-Scenario. The Back-to-Coal-Scenario essentially leads to emissions in 2030 of about 12 Gt.

Again these higher emissions are fed into the climate model and are translated into changes in temperature and precipitation. In order to really get close to the worst case, we have added to the regional mean values of the climate model output two times the regional spread (see Chapter 3.7). For the comparison of impacts of alternative emission paths only the pessimistic, i.e. high impact, estimates of changes in the agricultural productivity are considered. We compute the output change in agriculture, both with and without the adaptation through the general equilibrium effects.

Figure 13 shows the range of the output change in the agricultural sector without adaptation for Scenario B, the most likely emission scenario, and for the worst scenario, the Back-to-Coal-Scenario. It is evident that the variation of output changes increases with the size of the negative impact.

Figure 13 — Sensitivity of Output Change in Agriculture without Adaptation to



Different Emission Scenarios in 2030

The magnitude of the impact increase is highest in India, China and Sub-Saharan Africa. In relative terms, the increase in world-wide emissions by about one quarter leads to an increase in output losses which is more than proportional for all regions but of different extent when comparing the regions with each other. For example, Sub-Saharan Africa and Rest of the World show severe relative increases in output losses by more than 300 percent while North America, Western Europe and Former Soviet Union only experience a comparatively low increase in output reduction by about 40 percent. These differences are presumably due to different regional changes in temperature and precipitation since otherwise the same impact parameters have been used.

The consequences of different emission scenarios on the welfare effects of climate change are shown in Figure 14. Again, we compare the Worst-Case-Scenario to the Scenario B for the pessimistic high impact case only. Since the general equilibrium effects of an adjustment of the factor and commodity allocation in general reduce the negative impacts of climate change, it is not surprising that the variability of the welfare effects is comparatively lower than the variability of the output effects (cf. Figure 13). In the OECD regions (NAM, WEU, PAO), there is hardly a difference, mainly because the reference level of Scenario B is already very low. Only China and India and partly Subsaharan Africa and Rest of the World show a significant increase in welfare effects for the Worst-Case-Scenario, hence these regions seem to be more vulnerable to increased emissions.

Figure 14 — Sensitivity of Welfare Effect to Different Emission Scenarios in 2030

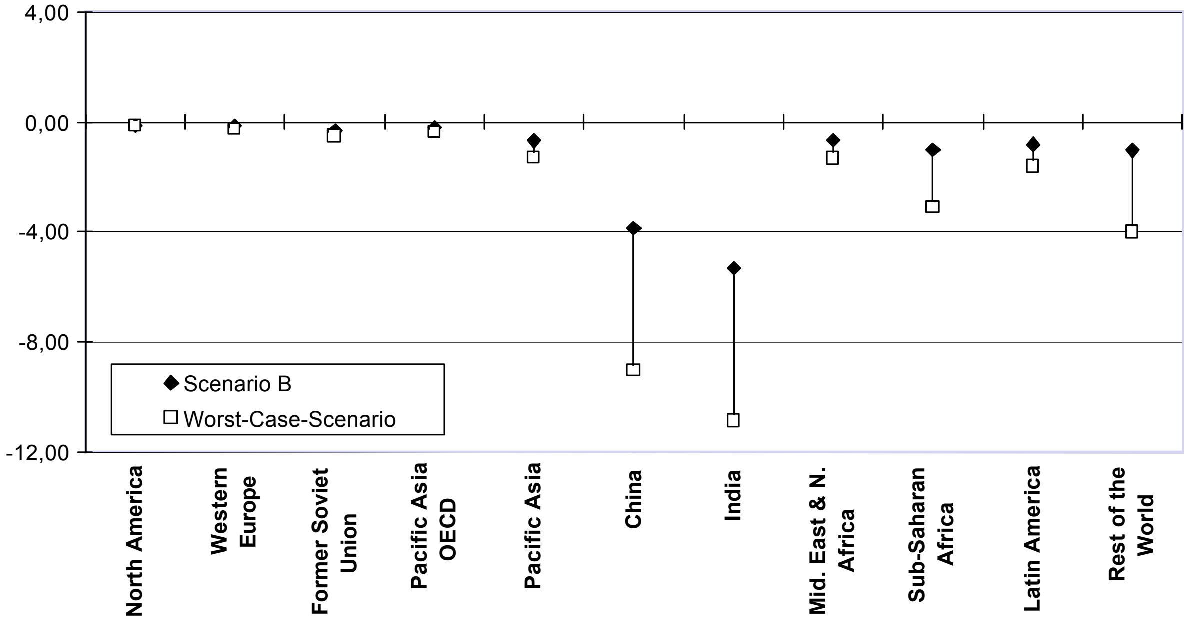
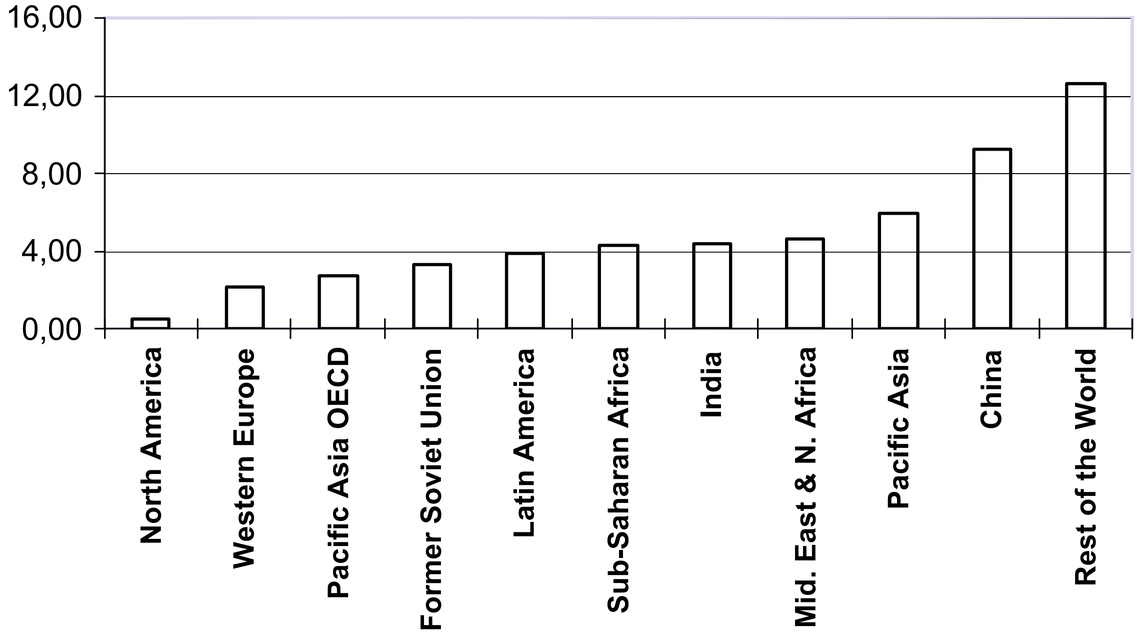


Figure 15 — Elasticity of Welfare Effects with Respect to Increased Emissions



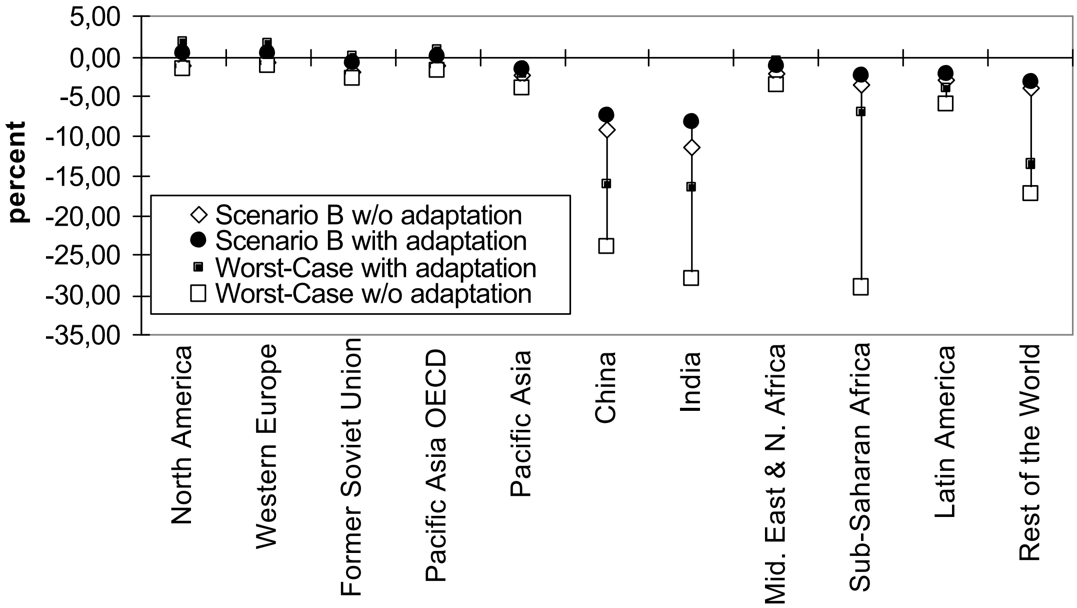
In order to better illustrate the response of impacts and the subsequent welfare losses to increasing emissions the elasticity of regional welfare with respect to CO_2-emissions is presented in Figure 15. This elasticity measures the percentage change in welfare which results from the higher CO_2-emissions. The percentage increase of CO_2-emissions in the Worst-Case-Scenario relative to Scenario B amounts to 23% in the year 2030.

Figure 15 shows that there are substantial differences in regional elasticities. The elasticity values can be interpreted in the following way: For example, a 10% increase in emissions leads in North America to a 5% higher loss in welfare. In contrast, in China a 10% emission increase will accelerate welfare losses by more than 90%. The overall picture confirms the expectation that less developed countries with a comparatively large agricultural sector are more vulnerable to a growth path with higher emissions than are industrialized countries. However, the size of the differences in the elasticities is surprising.

Another measure which can illustrate the ability of economies to adapt to climate change can be obtained by comparing the direct climate impact on agricultural output with the output change once all adjustments within the agricultural sector, between sectors in the economy, and among regions have taken place.

The ability of economies to adapt to climate impacts in agriculture is illustrated in Figure 16 for the pessimistic high impact scenario. Figure 16 displays the output effect in agriculture of climate change for Scenario B and the Back-to-Coal-Scenario. For each scenario the output effect with and without adaptation can be compared.

Figure 16 — Change in Agricultural Output (2030) in Percent for Different Emission Scenarios



One can see two types of patterns. The Annex I-countries and the Middle East with North Africa end up at a higher output level after adaptation when the high

Worst-Case-Scenario is simulated than in Scenario B. This is mainly due to increases in competitiveness of the agricultural sector in these regions since their land productivity is relatively less affected than that of the other regions. Hence, these regions can gain in terms of agricultural output from higher emissions.

The other regions adapt to the direct impact of climate change to a large extent, as one can see by the distance between the output with and without adaptation in the figure. Nevertheless, the output after adaptation remains below the output level in the former emission scenario, since the direct output impact has increased with the size of emissions. The comparison of the adaptive responses among regions shows that the economic forces tend to favor adaptation in regions that are less affected by increased climate impacts since the food shortage on world markets will improve the competitiveness of those regions.

The simulations of climate impacts on the agricultural sector suffer from a very weak data base concerning the combined influence of changes in temperature and precipitation on the productivity of agricultural land. For the time horizon up to 2030 almost anything from strongly negative to positive output and welfare effects can happen. In a most pessimistic scenario only India, China and Subsaharan Africa would suffer severely. The vulnerability of regions to higher emission paths differs strongly between industrialized and less developed countries. In other words, Annex I-countries are less vulnerable than Non-Annex I-countries.

7.2 The Economic Impact of Sea-Level Rise

Since reliable estimates of the economic impacts of damages incurred through sea-level rise are not available and since studies comparing damages to prevention come out strongly in favor of prevention, we model the consequences of sea-level rise by assuming that potential damages are prevented through appropriate investments. The necessary protection expenditures reduce the fraction of savings available for investment in productive capital. Annually each region has to spend a certain share of GDP on protection. The share is determined by multiplying the above derived share that applies in case of a 1-meter rise with the rise that is projected in the climate model on the basis of a CO_2-emission scenario. As before the effects are simulated for two CO_2-emission scenarios: Scenario B and the Back-to-Coal-Scenario (with worst case climate effects (Section 3.7).

NUMERICAL RESULTS

Table 12 summarizes the basic data for the simulation of Scenario B. Column 1 shows the sea-level rise that is projected for each region. Column 2 shows the share of GDP each region has to spend on protection each year.

Table 12 — The Impact of Sea-Level Rise in Emission Scenario B

Region	Projected Sea-Level Rise between 1990 and 2100 (Meters)	Protection Costs as Share of GDP (%)	GDP in 1990 (Billion 1990 US$)
North America	0.13	0.003	5970
Western Europe	0.13	0.003	6887
Pacific Asia OECD	0.14	0.007	3568
Pacific Asia	0.13	0.025	739
China	0.14	0.028	353
India	0.14	0.035	208
Middle East & N'africa	0.13	0.010	573
Subsaharan Africa	0.13	0.008	282
Latin America	0.13	0.001	1115

Source: Own calculations.

Protection costs are only a tiny share of GDP for several reasons: First, the climate model projects sea-level to rise by only 13 to 14 centimeters over a period of more than one hundred years. This projections lie in the lower region of the range between 0.09 and 0.88 m that was presented in the latest IPCC report (IPCC 2001). It has to be kept in mind, however, that the climate model computes only the thermal expansion of ocean water whereas the impact of the melting of land-based ice sheets and mountain glaciers is neglected. Since the effect of changes in the land-based ice is still subject to debate, the sea-level projections used for our simulations should be regarded as preliminary (cf. section 3). Second, it is assumed that the sea-level rises gradually. Consequently, protection measures are taken gradually and costs are spread evenly over the entire period of 110 years of which the economic model considers but the first 37 years. The assumption neglects the possibility of abrupt changes that could occur in the future development of climate and sea-level and which would require protection measures to be taken earlier and to a greater extent than assumed here. Finally, protection costs themselves are subject to uncertainty as we derived them on the basis of relatively few country case studies the results of which had to be scaled up to obtain values for the regions of the model.

The projected increase in sea-level is roughly equal for all regions whereas the direct economic impact varies over the regions: Relatively poor regions have to spend a higher share of their GDP on protection than richer regions. The regions Pacific Asia and Pacific Asia OECD, for instance, have to face absolute protection costs that are in the same order of magnitude (cf. Table 7, col. 1). Since the GDP of the region Pacific Asia OECD is, however, about five times as high as the GDP of the Pacific Asia region (cf. Table 12, col. 3), the shares of GDP the regions have to spend on protection differ substantially.

The first order economic impact to be expected from the introduction of protection expenditures into the model is the slow-down of capital accumulation. The slow-down occurs because protection expenditures reduce the fraction of savings that is available for capital accumulation. Lower savings can be expected to induce two kinds of second order effects in the economies.

The first effect can be thought of as the capital accumulation effect. Capital accumulation, as described in equation (2’) (cf. section 4), is one of the driving forces of economic growth. The slow-down of capital accumulation will therefore weaken economic growth.

The second effect can be thought of as the capital endowment effect. The slow-down of capital accumulation leads to different rates of capital accumulation in the regions. This in turn results in different relative scarcities of capital as a factor of production. The change in relative factor endowment induces changes in the composition and the total level of production.

Compared to the case without sea-level rise and hence without protection expenditures, the capital accumulation effect depends on the level of expenditures relative to total savings in the region. The endowment effect also depends on the composition of capital stocks across regions. Table 13 summarizes the results of a simulation run of the model when the protection costs given in Table 12 are spent on measures against sea-level rise. The numbers in Table 13 are measured relative to the benchmark without protection expenditures and they refer to the year 2030 only.

Columns 1 and 2 show the relative changes of the capital stock and of the rate of return. As expected, capital accumulation is slowed down and because of the increasing scarcity of capital its rate of return increases.

It is already evident that the economic effects of investments in protection from sea-level rise are extremely small for all economies overall. This is firstly due to relatively small expenditures (see col. 4 in Table 13). Secondly, the aggregation of the world economy in 11 regions makes coastal ranges small compared to the economies of the regions. And finally, dramatic local consequences such as the threat to the small island states for which protection might be impossible are ignored.

Table 13 — The Economic Impact of Protection Against Sea-Level Rise (Emission Scenario B, Relative to Benchmark without Protection, 2030)

Region	Change in Capital Stock (%)	Change in Rate of Return on Capital (%)	Change in Welfare (%)	Protection Costs as Share of GDP (%)
North America	-0.029	0.018	-0.027 **(5)**	0.003 **(7)**
Western Europe	-0.020	0.017	-0.006 **(9)**	0.003 **(7)**
Former Soviet Union	-0.015	0.002	-0.009 **(8)**	—
Pacific Asia OECD	-0.041	0.034	-0.020 **(7)**	0.007 **(6)**
Pacific Asia	-0.614	0.388	-0.309 **(1)**	0.025 **(3)**
China	-0.150	0.158	-0.040 **(4)**	0.028 **(2)**
India	-1.316	1.044	-0.309 **(1)**	0.035 **(1)**
Middle East & N'africa	-0.112	0.058	-0.087 **(2)**	0.010 **(4)**
Subsaharan Africa	-0.087	0.057	-0.053 **(3)**	0.008 **(5)**
Latin America	-0.029	0.013	-0.024 **(6)**	0.001 **(8)**
Rest of the World	-0.013	0.015	-0.009 **(8)**	—

The small impact on capital accumulation results in even lower welfare costs of the protection measures since the economies can adapt to the increasing scarcity of capital. The adaptive capacity differs across regions as is evident from columns 3 and 4 where the regions are ranked (numbers in brackets) according to protection costs on the one hand and welfare effects on the other. These differences between the ranking in protection costs and welfare effects – although tiny – represent the combined effect of regional as well as international allocation effects of a slightly lower path of investment.

The Impact of Sea-level Rise under an Alternative Emission Scenario

The simulation results presented so far have been derived from Scenario B with a rise in sea-levels of roughly 13-14 cm between 1990 and 2100. The most pessimistic Worst-Case-Scenario produces higher emissions, thus a stronger greenhouse effect and therefore a sea-level rise of about 17-18 cm.

Table 14 — Sea-Level Rise, Protection Expenditures and the Economic Impact of Protection Expenditures (Back-to-Coal-Scenario, Relative to Benchmark without Protection, 2030)

Region	Projected Sea-Level Rise 1990 - 2100 (in meters)	Change in Capital Stock (in %)	Change in Rate of Return on Capital (in %)	Change in Welfare (%)	Protection Costs as Share of GDP (%)
North America	0.17	-0.037	0.021	-0.035 **(6)**	0.003 **(7)**
Western Europe	0.17	-0.026	0.019	-0.011 **(10)**	0.003 **(7)**
Former Soviet Union	—	-0.017	0.000	-0.010 **(11)**	—
Pacific Asia OECD	0.18	-0.053	0.041	0.029 **(8)**	0.009 **(6)**
Pacific Asia	0.17	-0.806	0.494	-0.414 **(2)**	0.032 **(3)**
China	0.18	-0.204	0.182	-0.065 **(5)**	0.036 **(2)**
India	0.18	-1.759	1.256	-0.779 **(1)**	0.045 **(1)**
Middle East & N'africa	0.17	-0.142	0.067	-0.114 **(3)**	0.014 **(4)**
Subsaharan Africa	0.17	-0.112	0.062	-0.071 **(4)**	0.010 **(5)**
Latin America	0.17	-0.036	0.012	-0.031 **(7)**	0.002 **(8)**
Rest of the World	—	-0.016	0.013	-0.012 **(9)**	—

In Table 14 the economic effects of the increased protection expenditures for adapting to higher sea-levels are summarized. Sea-level increases in the Worst-Case-Scenario are about 30 percent higher and the protection costs as a share of GDP rise by roughly the same amount. The impacts on the capital stock and the rate of return are also similar (see col. 2 and 3 in Table 14 compared to col. 1 and 2 in Table 13). However, the welfare effects in the different regions deviate more strongly. The welfare loss in India more than doubles, but still remains below 1 percent. Overall the welfare losses tend to increase more than proportionally with sea-level rise and protection costs. Nevertheless, they are still quite small and thus indicate that the protection from damages of sea-level rise caused by thermal expansion does not impose major economic costs on the aggregated level which was used in this model.

8 IMPLICATONS

The coupling of the regionally disaggregated NICCS-model with the DART-model of the world economy by using reduced form impact functions is intended to shed some light on the size of the economic costs of climate change, on the regional distribution of these costs, and – most importantly – on the repercussions of the regional economic effects on the international division of labour, hence on interregional economic feedbacks. Despite the many problems encountered in this endeavour, some important insights can be gained.

This regionally and sectorally disaggregated coupled climate-economy-model is located between the highly aggregated macro-models using damage-functions which usually compute climate damages with the help of a quadratic or higher order function which derives damages in percent of GDP from temperature and/or precipitation changes. At the other extreme are the detailed models of particular media or regions which can describe the impact of climate change but they need to ignore the feedback effects of the economic system overall. Our model is designed to identify these feedback effects and to assess the approximate importance of such effects.

Well aware of all the uncertainties involved there seems to be a significant variation in regional climate impacts and their direct effects of agriculture. More importantly so, the costs of these direct impacts will be significantly lowered through adjustments in the factor allocation within each region. In addition, the world trading system also functions as a buffer which can resolve scarcities, e.g. in foodstuffs, through increased international trade. The international adjustments in trade flows to regional disturbances turn out to be an important factor in the assessment of the costs of climate change.

The ability of the international economy to adjust to regional disturbances lowers the costs of climate change. It still remains true that the developing world is more vulnerable to the negative impacts on agriculture than the industrialized countries. This remains true despite the huge uncertainties about the likely impacts of climate change on the agricultural sectors in the different regions of the world.

One of the most serious problems in the coupling of climate models with economic models relates to the time horizons over which these models need to be defined. Whereas climate models necessarily need to be concerned with time frames of centuries, economic growth models can at best present possible scenarios and these only for a few decades. This makes them inherently inappropriate for the assessment of long-term climate change. Yet, there is no alternative! As a consequence, the assessment of the economic costs of climate change up to 2030 will be based on rather small climate effects. This, however, is only the beginning of a rising trend of climate change which will continue in the future but of which the costs can not be assessed at the moment. The analysis of the sensitivity of economic effects to climate changes has shown that especially those most vulnerable to climate change are likely to suffer most from further climate change.

There are many opportunities for improving the results and all disciplines can contribute to that endeavour:

- The regional disaggregation was limited by the ability of climate models to produce reliable regional climate change results. Because of this high scaled regional resolution of the DART-model, less attention is paid to subregions which may be more severely affected than their neighbour regions since data from the climate model and data from impact studies are averaged out across regions. We could be able to point at those vulnerable regions of smaller scale with a more detailed regional resolution. However, this would cause an increasing need for information about regional climate impacts which cannot be covered by the current impact studies.
- The sectoral disaggregation could be more refined – especially in the agricultural sector – without difficulties. Such finer resolution, however, is only helpful if appropriate impact functions for these more detailed activities were available. So far, this is not the case.
- The time horizon for a meaningful climate impact analysis is limited by the ability or develop reasonable scenarios for long-term economic growth. Research on growth processes is well under way and may lead to better insights. On the other hand, social systems do not follow predescribed rules and shocks external to the economic allocation mechanisms such as political crises, natural disasters, technological breakthroughs, etc. will never be accounted although they can have a major influence on growth paths.[25]
- A major improvement would be the expansion of impacts on agriculture and from sea-level rise to other equally likely important impacts such as health effects, impacts of more extreme weather events, and many more.

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[25] Just witness the development in the former Sovjet Union, the Impact of the Asian crisis, or the breakdown of institutions in Africa.

Nevertheless, despite the large variance in possible results and our lack of knowledge about the likely distribution of uncertain effects, it is possible that even within a few decades the world might experience significant economic costs of climate change. The precautionary principle would suggest to enact an active climate policy without a definite cost-benefit-analysis (which is impossible at the moment).

9 Appendix

Derivation of the Impact Function

Within the CGE framework, repercussions of climate change on production possibilities in the agricultural sector shall be modeled as variations in land endowments. More specifically, an impact function has to be developed which relates changes in land endowment to changes in climate variables. For that purpose, we use information on the production technology underlying the sectoral production within the CGE framework in order to derive a relationship between land input and yield as well as empirical data from the impact studies on the agricultural yield and climate change.

Climate Impact on Land in Efficiency Units

In the real world, climate change is supposed to affect agricultural yield through variations of soil productivity and changes in the land area available for tillage and livestock production. For the derivation of the impact function, we assume that land in physical units (B) remains constant, i.e. we consider climate-induced changes in land productivity only. These changes in productivity are described as changes in “effective land” (V). “Effective land” is the physical amount of land multiplied by its efficiency (A). Efficiency (A) in turn is determined by temperature (T) and precipitation (P). Economic agents in the agricultural sector then optimize their choice as if one of the available inputs were land in efficiency units (V) (cf. Barro and Sala-i-Martin 1995, p. 35).

$$\text{(A.1)} \qquad V_t = A_t\left(T_t, P_t\right) * B \; V_t = A_t\left(T_t, P_t\right) * B \quad \text{with}$$

$$A_0 = 1, V_0 = \overline{B} \; A_0 = 1, V_0 = \overline{B}\text{, where}$$

V: “effective land”; i.e. land area in efficiency units,

A: efficiency parameter,

T: temperature,

P: precipitation,

B: land area in physical units.

Variations in land (dV) are explained by variations in climate variables (T, P)

$$\text{(A.1')} \qquad dV = dA * B + A * dB = \left(\frac{\partial A}{\partial T} * dT + \frac{\partial A}{\partial P} * dP \right) * B + A * dB \, .$$

Equation (A.1’) is the equation that will finally be introduced in the model. At first, however, we have to specify the partial derivatives of the efficiency parameter (A) with respect to the climate variables. For that purpose, we use information from empirical impact studies on the effect of climate change on yield per hectare (q)[26].

Empirical Data on Climate Impact: Relative Changes in Yields per Hectare.

Since the empirical data stem from studies which only deal with crop yields - not with agricultural production in a broader sense - it is appropriate to define yield per hectare as the quotient of crop yields (y_{crp}) per physical land area (B)

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[26] Empirical impact studies on crops usually provide data in terms of relative changes in yields per hectare depending on absolute changes in temperature and relative changes in precipitation.

$$\text{(A.2)} \qquad q(T,P) = \frac{y_{crp}(T,P)}{B}, \text{ where}$$

q: yield per hectare,

y_{crp}: crop yields.

Relative changes of yields per hectare (*q*) can be expressed as the difference between relative output changes in the crop production (y_{crp}) and relative changes of physical land (*B*)

$$\text{(A.3)} \qquad \frac{dq}{q} = \frac{dy_{crp}}{y_{crp}} - \frac{dB}{B}.$$

To calculate relative changes of crop yields (y_{crp}), i.e. the first term on the right hand side of equation (A.3), some information is needed about the technology and factor input of crop production. In the CGE model, only the technology in the production of the aggregated agricultural output is specified. Thus, we have to make some additional technological assumptions on the agricultural production process: Sectoral agricultural output is a composite of several heterogeneous commodities including crops, livestock, processed commodities, etc. Each of these agricultural goods serves both as commodities for final demand and as intermediates for the production of other agricultural goods. Hence, an expected climate-induced loss in land productivity, expressed by negative relative changes of crop yields per hectare, will not only cause a reallocation of factors within crop production but also spill-over effects to the production of the other agricultural goods which employ crops as an intermediate input[27].

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[27] The data from the GTAP3-database, which are used for the empirical implementation of the CGE-model, show that land is employed in the production of crops and lifestock production.

Assumptions on Intermediates

For this relationship of intermediate production, we make some strong assumptions: Crops serve as intermediates in the production of every other agricultural commodities and a limitational Leontief-technology is applied in each of these production processes. The crop production itself depends only on primary inputs and not on any agricultural intermediate. Thus, relative yield changes in crops as an input cause identical relative output changes of the produced agricultural commodity. Total sectoral production is the sum of all agricultural commodities. Hence, the relative changes in sectoral production can be expressed as the weighted sum of relative output changes of each of the agricultural commodity which is equal to relative changes in crop production.

The relative change in sectoral production can be derived from the nested function which describes for the sectoral production in the CGE model (cf. Chapter 2., also Springer 1998)

$$\text{(A.4)} \qquad Y(T,P) = f\left(A(T,P) * B, ..\right),$$

$$\text{(A.5)} \qquad \frac{df}{f} = \frac{dy_{crp}}{y_{crp}}, \text{ where}$$

Y(T,P): total output in agricultural sector.

However, since there is a lack of studies on climate-induced changes in lifestock production, we neglect land use in this subsector and assume that the factor land is completely used in crop production.

Using equation (A.5), we can replace changes in crop yields in equation (A.3) which describes relative changes in yields per hectare

$$\text{(A.3')} \qquad \frac{dq}{q} = \frac{dy_{crp}}{y_{crp}} = \frac{df}{f} = \frac{\frac{\partial f}{\partial A} * dA}{f} = \frac{\frac{\partial f}{\partial A} * \left(\frac{\partial A}{\partial T} * dT + \frac{\partial A}{\partial P} * dP \right)}{f},$$

with $dB = 0$.

Under the assumption that the impact parameters remain constant, equation (A.3') can be rearranged as

$$\text{(A.6)} \qquad \frac{dq}{q} = \alpha_1 * dT + \alpha_2 * \frac{dP}{P}, \text{ with}$$

$$\alpha_1 = \frac{1}{f} * \frac{\partial f}{\partial A} * \frac{\partial A}{\partial T}, \alpha_2 = \frac{P}{f} * \frac{\partial f}{\partial A} * \frac{\partial A}{\partial P},$$

α_1, α_2 impact parameter.

The objective is to specify the partial derivates $\left(\frac{\P A}{\P T}, \frac{\P A}{\P P} \right)$ in equation (A.1') in order to relate changes in the endowment of land in efficiency units to changes in temperature and precipitation. These partial derivatives are obtained by rearranging the terms of the impact parameter

$$\text{(A.6a)} \qquad \frac{\P A}{\P T} = a_1 * \frac{f}{\frac{\P f}{\P A}} \qquad \text{(A.6b)} \qquad \frac{\P A}{\P P} = \frac{a_2}{P} * \frac{f}{\frac{\P f}{\P A}}.$$

The expressions for the partial derivatives are inserted into equation (A.1’)

$$\text{(A.1'')} \qquad dV = B * \left[\left(\alpha_1 * \frac{f}{\frac{\partial f}{\partial A}} \right) * dT + \left(\frac{\alpha_2}{P} * \frac{f}{\frac{\partial f}{\partial A}} \right) * dP \right]$$

$$= \lambda * \left(\alpha_1 * dT + \alpha_2 * \frac{dP}{P} \right) \quad \text{with } \lambda = \left(B * \frac{f}{\frac{\partial f}{\partial A}} \right).$$

Comparing equation (A.1’’) with equation (A.6) shows that the absolute climate-induced change in effective land is a multiple of the relative change in yield per hectare. After all, equation (A.1’’) expresses relative changes of yield per hectare as a function of variations in temperature and precipitation. These climate-induced changes in crop yield per hectare depend on land as input in crop production and the impact of climate on the endowment of land in efficiency units ($A*B$). The impact parameters (α_1, α_2) which have been derived from the empirical studies (cf. Chapter 3) can be regarded as multipliers which contain these partial effects.

10 Specification of l

Next, the shifting parameter (l) has to be specified by using information about the production technology in the agricultural sector. Production technology is described by a nested production function (cf. Chapter 2., also Springer 1998). In the top nest, the sectoral output results from a limitational production technology

(A.7) $$Y = f(T,P) = \min\left[\frac{I}{\eta_{Y,I}}, \frac{C\left(A(T,P) * B,..\right)}{\eta_{Y,C}}\right],$$

with $\eta_{Y,I} = \frac{I}{Y}; \eta_{Y,C} = \frac{C}{Y}$, where

I: intermediate input,

C: composite input composed of energy (*E*) and a value-added-composite (H) (see eq. A.8),

$\eta_{Y,i}$: input-coefficients.

In the production of the composite input (*C*), a CES-technology is applied. The elasticity of substitution ($s_{E,H}$) is 0.5 and remains constant over time

(A.8) $$C(T,P) = \left[\theta * E^{-\pi} + (1-\theta) * H\left(A(T,P) * B,..\right)^{-\pi}\right]^{-\frac{1}{\pi}},$$

with $\sigma_{E,H} = \frac{1}{1+\pi} = 0,5; \pi = 1$, where

E: energy input,

H: value-added input produced out of primary inputs using Cobb-Douglas-technology (see eq. A.9),

θ: share parameter of energy (E),

π: production parameter depending on the elasticity of substitution σ between (E) and (H).

Finally, the valued-added input (H) results from a Cobb-Douglas production technology. The elasticities of production vary by region and remain constant over time

(A.9) $$H(T,P) = K^{\beta} * \left(A(T,P) * B\right)^{\gamma} * L^{\omega} = K^{\beta} * \left(A(T,P)\right)^{\gamma} * B^{\gamma} * L^{\omega},$$

with $\beta + \gamma + \omega = 1$, where

K: capital,

L: labor,

β,γ,ω: elasticities of production.

Using equations (A.8) and (A.9), the derivative needed for the specification of (λ) in equation (A.1’’) can be written as follows.

(A.10) $$\frac{f}{\frac{\partial f}{\partial A}} = \frac{f}{\frac{df}{dC} * \frac{dC}{dH} * \frac{dH}{dA}} = \frac{\frac{C}{\eta_{Y,C}}}{\frac{1}{\eta_{Y,C}} * \left[(1-\theta) * \left(\frac{C}{H}\right)^{1+1}\right] * \left[\gamma * \frac{H}{A}\right]}$$

$$= \frac{C}{(1-\theta) * \frac{C}{H} * C * \gamma * A^{-1}} = \frac{A}{(1-\theta) * \frac{C}{H} * \gamma}$$

Conclusion

Using equation (A.10), the shifting factor λ in (A.1’’), can be described in terms of the underlying production technology.

(A.11) $$\lambda = B * \frac{\frac{V}{B}}{(1-\theta) * \frac{C}{H} * \gamma} = V * \frac{1}{\varepsilon_{C,H} * \gamma},$$

with $$\varepsilon_{C,H} = \frac{dC}{dH} * \frac{H}{C} = (1-\theta) * \frac{C}{H},$$

$\varepsilon_{C,H}$: elasticity of input (C) with respect to value-added input (H),
γ: elasticity of input (H) with respect to land in efficiency units (V).

When inserting the specification of λ in equation (A.1''), we obtain the impact function for changes in the endowment of efficiency land (V) depending on changes in climate variables, impact parameters and $\frac{1}{e_{C,H} * g}$ parameters of the agricultural production.

$$\text{(A.1''')} \qquad dV = V * \frac{1}{\varepsilon_{C,H} * \gamma} * \left(\alpha_1 * dT + \alpha_2 * \frac{dP}{P} \right)$$

Scaling

Remember that this specification of an impact function relies on the strong assumption that relative output changes in the sectoral output are identical to relative changes in crop production (cf. equation (A.3). In the real world, the reduction in sectoral output will probably be lower than the reduction in the crops subsector since rather a substitutional than a limitational relationship between inputs in the non-crops production prevails. If other factors can be substituted for crops then the output reductions for non-crops commodities are smaller than the climate-induced reduction in the availability of the crops input. Consequently, the reduction in the sectoral output as the weighted sum of relative output changes for each commodity is smaller than the reduction in crop production. Thus, the loss in land in efficiency units might be overestimated by the impact function specified in equation (A.1''').

Since the gap between the decline in crops production and the decline of the sectoral output is the greater, the smaller the share of crops on overall agricultural production is, we just scale the effect of relative changes in yields per hectare on the sectoral output by a factor f, that is the share of crops on total sectoral output in the initial period, i.e. the period for which data from GTAP3 database exist (cf. Table 8 in Section 4 above).

$$\text{(A.4')} \qquad \phi * \frac{dy_{crp}}{y_{crp}} = \frac{df}{f} \qquad \text{with } \phi = \frac{y_{crp}(t_0)}{Y(t_0)}.$$

Having repeated the calculation above with the modified relation in equation (A.4’), the functional relationship for the relative changes of land endowment (V) in equation (A.1’’’) is augmented by the crop share as an additional factor on the right hand side of the equation

$$\text{(A.1*)} \qquad dV = \phi * \lambda * \left(\alpha_1 * dT + \alpha_2 * \frac{dP}{P} \right) dV = \phi * \lambda * \left(\alpha_1 * dT + \alpha_2 * \frac{dP}{P} \right)$$

Equation (A.1*) then represents the functional relationship which is introduced into the CGE model.

B. Figures

Figure 5 — Spatial Pattern of Change in Near-Surface Temperature (mean=1).

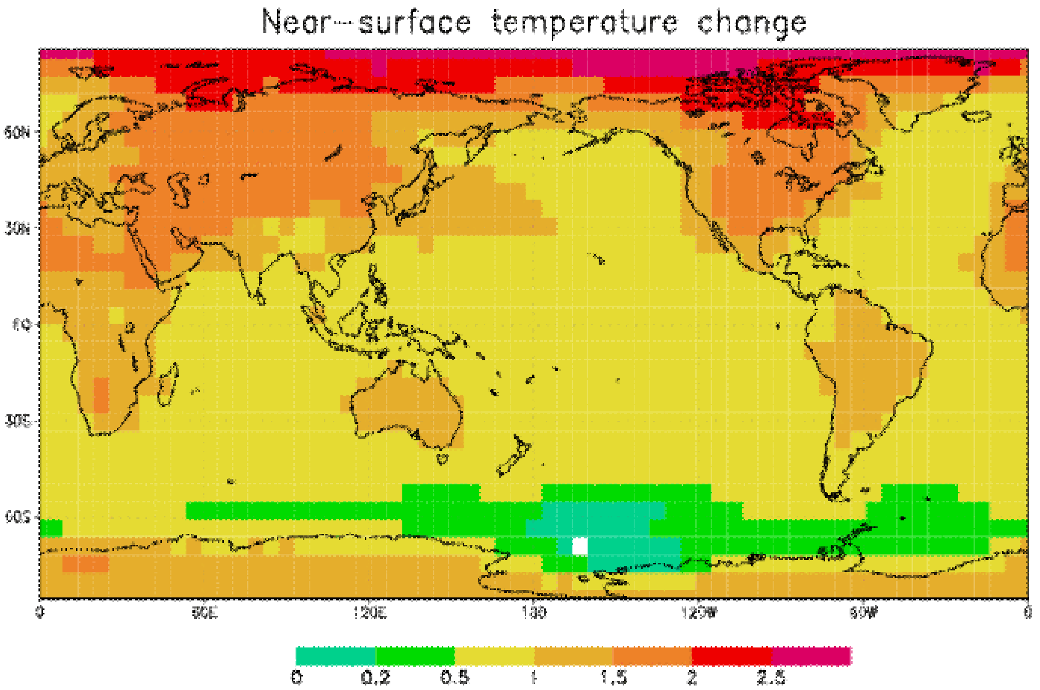


Figure 6 — Spatial Pattern of Change in Precipitation (mean=1).

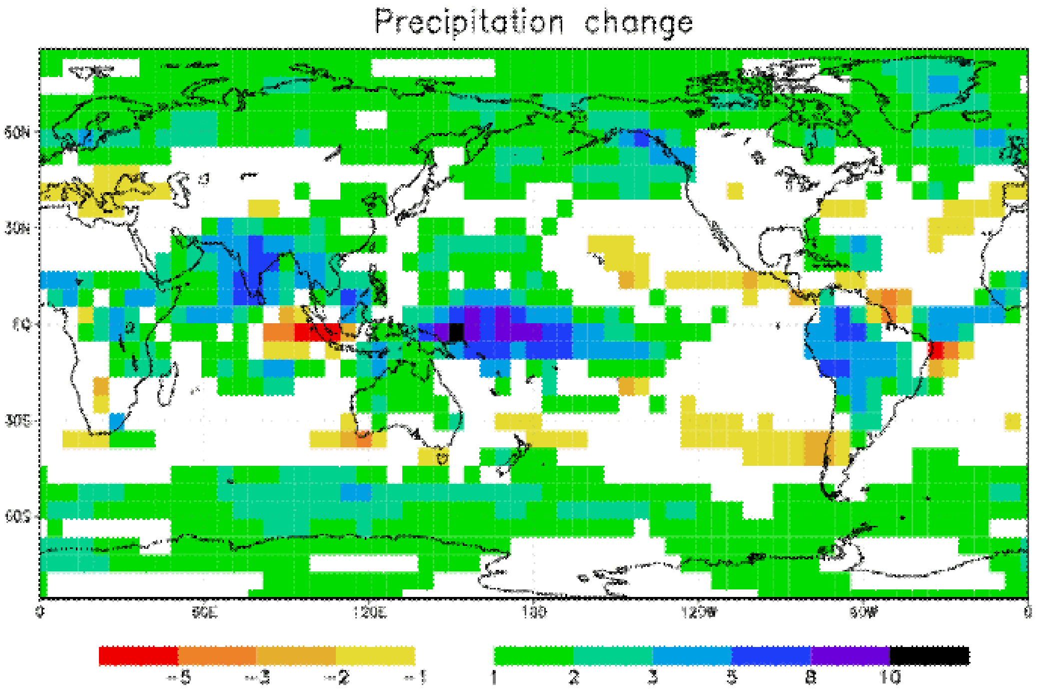


Figure 7 — Spatial Pattern of Change of Sea-Level Rise (mean=1).

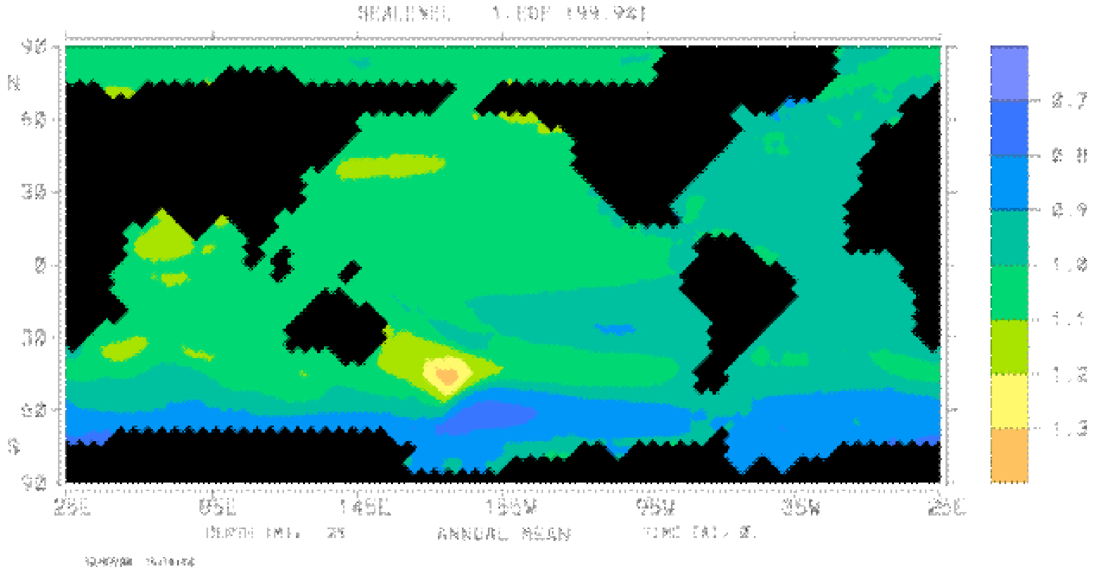
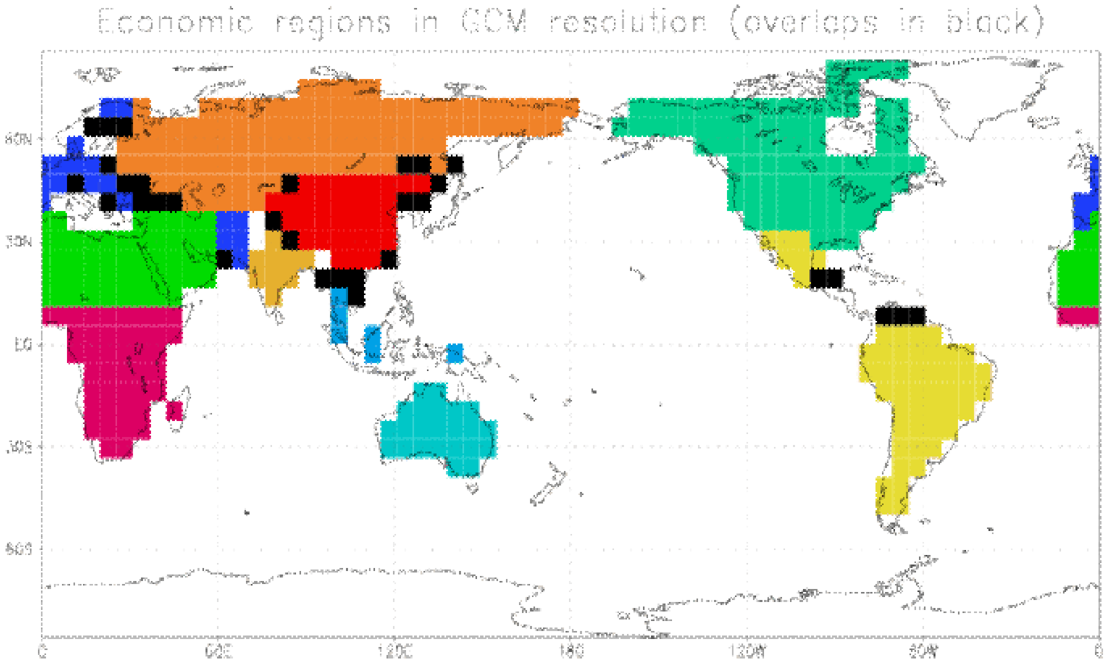


Figure 8 — Economic Regions in Spatial Resolution of the Climate Model



(Overlap cells are drawn in black. Due to a software problem, some overlap cells also appear in white).

C. Tables

Table A1 — Regional Averages and Regional Spreads of the Spatial Pattern of Near-Surface Temperature Change

Region	$\langle f_T \rangle_r$	$q(T,P)=\frac{y_{ap}(T,P)}{B}$
North America	1.6559	0.2954
Western Europe	1.3428	0.1566
Former Soviet Union	1.6437	0.1857
Pacific Asia OECD	1.1883	0.1189
Pacific Asia	1.0343	0.1826
China	1.4489	0.2791
India	1.1300	0.2327
Middle East & N'africa	1.5734	0.2352
Subsaharan Africa	1.1981	0.1507
Latin America	1.1506	0.1859
Rest of the World	1.2995	0.2775
GLOBE	1.0000	0.4022

Table A2 — Regional Mean of Absolute Precipitation Pctr (in mm/Day) from the ECHAM3-LSG Control Run, Regional Mean of the Precipitation Changes Pattern (Dimension Unity), Regional Mean and Spread of Pattern of Relative Changes (Both in % (mm/Day)$^{-1}$).

Region	$\langle P_{ctr} \rangle_r$	$\langle f_P \rangle_r$	$\left\langle \frac{f_P}{P_{ctr}} \right\rangle_r$	$\boldsymbol{s}_{f,\frac{P}{P_{ctr}},r}$
North America	1.8505	0.6891	30.5351	55.6320
Western Europe	1.9750	0.2147	-16.3887	81.3676
Former Soviet Union	1.5228	1.0025	56.0314	77.5903
Pacific Asia OECD	2.0944	1.1222	71.8907	58.9384
Pacific Asia	4.5663	2.2612	59.6154	51.4962
China	1.9491	0.9136	53.2525	61.2937
India	2.4125	4.0510	170.2440	96.4515
Middle East & N'africa	0.2733	0.7580	643.5140	849.3860
Subsaharan Africa	3.0815	1.2187	39.7174	62.7685
Latin America	3.9450	2.0992	46.8359	67.4052
Rest of the World	2.3231	1.0224	152.5130	354.2590
GLOBE	2.7343	1.0000	61.1596	226.4780

Table A3 — Regional Averages and Spreads of the Sea-Level Pattern

Region	$\langle f_S \rangle_r$	$s_{f,S,r}$
North America	0.99	0.05
Western Europe	0.98	0.05
Former Soviet Union	1.06	0.05
Pacific Asia OECD	1.08	0.05
Pacific Asia	1.08	0.05
China	1.07	0.05
India	1.12	0.05
Mid East & N'africa	0.98	0.05
Subsaharan Africa	1.01	0.05
Latin America	0.95	0.05
Rest of the World	1.00	0.05
GLOBE	1.00	0.05

Note that the spatial patterns are constant in time. The numbers in these tables are to be used as regional weighting factors to the time-dependent global mean change.

Table A4 — Absolute Global-Mean Changes in Precipitation (in mm/Day) in the Year 2030

Scenario	Sc B	BTC	CoE
$\langle \Delta P \rangle_{GLOBE}$	0.0528	0.0484	0.0426

REFERENCES

Adams, R.M. (1989): Global Climate Change and Agriculture: An Economic Perspective. *American Journal of Agricultural Economics* 71: 1272-1279.

Akong'a, J., T.E. Downing, N.T. Konijn, D.N. Mungai, H.R. Muturi, and H.L. Potter (1988): The Effects of Climatic Variations on Agriculture in Central and Eastern Kenya. In: M.L. Parry, T.R. Carter; and N.T. Konijn (Eds.): The Impact of Climatic Variations on Agriculture, Vol. 2, Assessment in Semi-Arid Regions.

Armington, P. (1969): A Theory of Demand for Products Distinguished by Place of Production. IMF Staff Papers, 16:159-178.

Baer, B.D., W.S. Meyer, and D. Erskine (1994): Possible Effects of Global Climate Change on Wheat and Rice Production in Australia. In: C. Rosenzweig, and A. Iglesias (Eds.): Implications of Climate Change for International Agriculture: Crop Modeling Study.

Barro, R.J., and X. Sala-i-Martin (1995): Economic Growth. New York.

Barry, T.A., and S. Geng (1992): The Impact of Wheather and Climate Change on Wheat Yield in the United States. World Resource Review 4 (4): 419-450.

Bergthorsson, P., H. Björnsson, O. Dyrmundsson, B. Gudmundsson, A. Helgadottir, and J.V.Jonmunndsson (1988): The Effects of Climatic Variations on Agriculture in Iceland. In: M.L. Parry, T.R. Carter, and N.T. Konijn (Eds.): The Impact of Climatic Variations on Agriculture, Volume 1 – Assessment in Cool Temperate and Cold Regions.

Bos, E., M.T. Vu, E. Massiah, and R.A. Bulatao (1994): World Population Projections: Estimates and Projections with Related Demographic Statistics. World Bank, Baltimore. The Johns Hopkins University Press.

Bruckner, T, G. Hooss, H.-M. Füssel, and K. Hasselmann (2001): The ICLIPS Climate Model. Climate Change, submitted to special ICLIPS issue.

T. Bruckner, G. Petschel-Held, F. L. Toth, H.-M. Füssel, C. Helm, M. Leimbach, and H.-J. Schellnhuber (1999): Climate Change Decision-Support and the Tolerable Windows Approach. Environmental Modeling and Assessment 4:217-234.

Cline, W.R. (1992): The Economics of Global Warming. Institute for International Economics, Washington, DC.

Denz Elzen, M.G.J., and J. Rotmans (1992): The Socio-Economic Impact of Sea-level Rise on The Netherlands: A Study of Possible Scenarios. Climatic Change 20: 169-195

De Siqueria, O.J.F., J.R. Boucas Farias, and L.M. Aguiar Sans (1994) : Potential Effects of Global Climate Change for Brazilian Agriculture: Applied Simulation Studies for Wheat, Maize, and Soybeans. In: C. Rosenzweig, and A. Iglesias (Eds.): Implications of Climate Change for International Agriculture: Crop Modeling Study.

Delecolle, R., D. Ripoche, F. Ruget, and G. Gosse (1994): Possible Effects of Increasing CO_2-Concentration on Wheat and Maize Crops in North and Southeast France. In: C.Rosenzweig, and A. Iglesias (Eds.): Implications of Climate Change for International Agriculture: Crop Modeling Study.

Eid, H.M. (1994): Impact of Climate Change on Simulated Wheat and Maize Yields in Egypt. In: C. Rosenzweig, and A. Iglesias (Eds.): Implications of Climate Change for International Agriculture: Crop Modeling Study.

Escano, C.R., and L.V. Buendia (1994): Climate Impact Assessment for Agriculture in the Philippines: Simulation of Rice Yield under Climate Change Scenarios. In: C. Rosenzweig, and A. Iglesias (Eds.): Implications of Climate Change for International Agriculture: Crop Modeling Study.

Feenstra, J.F., I. Burton, J.B. Smith, and R.S.J. Tol (1998): Handbook on Methods for Climate Change Impact Assessment and Adaption Strategies. Amsterdam.

Fankhauser, S. (1994): Protection vs. Retreat: Estimating the Costs of Sea-level Rise. CSERGE Working Paper GEC 94-02, Norwich.

Fischer, G., K. Frohberg, M.L. Parry, and C. Rosenzweig (1996): The Potential Effects of Climate Change on World Food Production and Security. In: F. Bazzaz, and W. Sombroek (Eds.): Global Climate Change and Agricultural Production.

Füssel, H.-M., and J. G. van Minnen(2000): Deriving Climate Protection Targets From Guard-rails for the Preservation of Terrestrial Ecosystems. Integrated Assessment, accepted.

Hasselmann, K., S. Hasselmann, R. Giering, V. Ocana, and H. v.Storch (1997): Sensitivity Study of Optimal CO_2-Émission Paths Using a Simplified Structural Integrated Assessment Model (SIAM). Climatic Change 37:345-386.

Gadgil, S., A.K.S. Huda, N.S. Jodha, R.P. Singh, and S.M. Virmani (1988): The Effects of Climatic Variations on Agriculture in Dry Tropical Regions of India. In M.L. Parry, T.R.Carter, and N.T. Konijn (Eds.): The Impact of Climatic Variations on Agriculture, Volume 2 - Assessment in Semi-Arid Regions.

Hall, R.E., and C.I. Jones (1999): Why Do Some Countries Produce So Much More Output per Worker than Others? *The Quarterly Journal of Economics*, 114(1): 83-116.

Hooss, G., R. Voss, K. Hasselmann, E. Maier-Reimer, and F. Joos (2000): A Nonlinear Impulse Response Model of the Coupled Carbon Cycle-Ocean-Atmosphere Climate System (NICCS). Climatic Dynamics, in pint.

Iglesias, A. (1995): Effects on Wheat and Maize in Spain. In: P.A. Harrison, R.E. Butterfield, and T.E. Downing (Eds.): Climate Change and Agriculture in Europe – Assessment of Impacts and Adapations.

Intergovernmental Panel on Climate Change (IPCC) (1996): Climate Change 1995. Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Cambridge University Press, Cambridge, New York, Melbourne.

Intergovernmental Panel on Climate Change (IPCC) (2001): Summary for Policymakers. A Report of Working Group I of the Intergovernmental Panel on Climate Change.

Intergovernmental Panel on Climate Change (IPCC) (2001): Summary for Policymakers. Climate Change 2001: Impacts, Adaptation, and Vulnerability. Draft. IPCC Working Group II. Geneva.

Jin, Z., Ge D., H. Chen, and J. Fang (1994): Effects of Climate Change on Rice Production and Strategies for Adaptation in Southern China. In: C. Rosenzweig, and A. Iglesias (Eds.): Implications of Climate Change for International Agriculture: Crop Modeling Study.

Joos, F., M. Bruno, R. Fink, U. Siegenthaler, T. Stocker, C. LeQuere, and J. Sarmiento (1996): An Efficient and Accurate Representation of Complex Oceanic and Biospheric Models of Anthropogenic Carbon Uptake. Tellus, 48B:397-417.

Joos,F., G.-K. Plattner, T. Stocker, O. Marchal, and A. Schmittner (1999): Global Warming and Marine Carbon Cycle Feedbacks on Future Atmospheric CO_2. Science 284:464-467.

Joos, F., C. Prentice, S. Sitch, R. Meyer, G. Hooss, G.-K. Plattner, and K. Hasselmann (2001): Global Wwarming Feedbacks on Terrestrial Carbon Uptake under the IPCC Emission Scenarios. Global Biogeochemical Cycles, submitted.

Kaiser, H.M. (1991): Climate Change and Agriculture. *Northeastern Journal of Agricultural and Resource Economics,* 20: 151-163.

Klepper, G., and K. Springer (2000): Benchmarking the Future: A Dynamic, Multi-Regional, Multi-Sectoral Trade Model for the Analysis of Climate Policies. Kiel Working Paper, No.976, The Institute of World Economics, Kiel.

Kokoski, M.F. (1984): A General Equilibrium Analysis of the Measurement of Economic Impacts of Climatic Changes. University of North Carolina at Chapel Hill.

Kurtze, C., and K. Springer (1999): Modelling the Economic Impact of Global Warming in a General Equlibrium Framework. Kiel Working Paper, No. 922, The Institute of World Economics, Kiel.

Liverman, D.M. (1992): Global Warming and Mexican Agriculture: Some Preliminary Results. In: J.M. Reilly, and M. Anderson (Eds.): Economic Issues in Global Climate Change: Agriculture, Forestry and Natural Resources.

Maier-Reimer, E., and K. Hasselmann (1987): Transport and Storage of CO2 in the Ocean – An Inorganic Ocean-Circulation Carbon Cycle Model. Clim.Dyn. 2:63-90.

Manne, A.S., and R.G. Richels (1992): Buying Greenhouse Insurance: The Economic Cost of CO_2-Emission Limits. Cambridge, MIT Press.

Matthews, R.B., M.J. Kropff, and D. Bachelet (1994): Climate Change and Rice Production in Asia. Entwicklung und ländlicher Raum 1: 16-19.

Menzhulin, G.V., L.A. Koval, and A.L. Badenko (1994): Potential Effects of Global Warming and Carbon Dioxide on Wheat Production in the Former Soviet Union. In: C. Rosenzweig, and A. Iglesias (Eds.): Implications of Climate Change for International Agriculture: Crop Modeling Study.

Mooney, S., and L.M. Arthur (1990): The Impacts of Climate Change on Agriculture in Manitoba. *Canadian Journal of Agricultural Economics,* 38: 685-694.

Muchena, P. (1994): Implications of Climate Change for Maize Yields in Zimbabwe. In: C.Rosenzweig, and A. Iglesias (Eds.): Implications of Climate Change for International Agriculture: Crop Modeling Study.

Onyeji, S.C., and G. Fischer (1994): An Economic Analysis of Potential Impacts of Climate Change in Egypt. Global Environmental Change 4 (4): 281-299.

Oram, R.C. (1985): Sensitivity of Agricultural Production to Climate Change. In: Climatic Change 7:129-152.

Parry, M. (1990): Climate Change and World Agriculture. London.

Petschel-Held, G., H.-J. Schellnhuber, T. Bruckner, F. L. Toth, and K. Hasselmann (1999): The Tolerable Windows Approach: Theoretical and methodological Foundations. Climatic Change, 41:303-331.

Qureshi, A., and A. Iglesias (1994): Implications of Global Climate Change for Agriculture in Pakistan: Impacts on Simulated Wheat Production. In: C. Rosenzweig, and A. Iglesias (Eds.): Implications of Climate Change for International Agriculture: Crop Modeling Study.

Rosenzweig, C., Parry, M.L., Fischer, G., and K. Fromberg (1993): Climate Change and World Food Supply. Research Report, No. 3. Environmental Change Unit, University of Oxford.

Santer, B. (1985): The Use of General Circulation Models in Climate Impact Analysis – A Preliminary Study of Impacts of a CO2-Induced Climatic Change on Western European Agriculture. Climatic Change 7: 71-93.

Schimmelpfennig, D., J. Lewandrowski, J. Reilly, M. Tsigas, and I. Parry (1996): Agricultural Adaption to Climate Change: Issues of Longrun Sustainability. Vortrag gehalten auf der Konferenz Agricultural Economic Report, No. 740, Natural Resources and Environment Division, Economic Research Service, U.S. Department of Agriculture.

Schmidt-Hebel, K., and L. Serén (1997): Saving Across the World: Puzzles and Policies. World Bank, Discussion Paper, No. 354, Washington, D.C.

Smit, B., M. Brklacich, R.B. Stewart, R. McBride, M. Brown, and D. Bond (1989): Sensitivity of Crop Yields and Land Resource Potential to Climatic Change in Ontario, Canada. Climatic Change 14: 153-174.

Springer, K. (1998): The DART General Equilibrium Model: A Technical Description. Kiel Working Paper, No. 883, The Institute of World Economics, Kiel.

Strzepek, K.M., S.C. Onyeji, M. Saleh, and D.N. Yates (1994): An Assessment of Integrated Climate Change Impacts on Egypt. Working Paper 94-48. International Institute for Applied Systems Analysis,

Titus, J.G., Park, R.A., Leatherman, S.P., Weggel, J.R., Greene, M.S., Mausel, P.W., Brown, S., Gaunt, G., Trehan, M., and G. Yohe (1991): Greenhouse Effect and Sea-level Rise. The Cost of Holding Back the Sea. Coastal Management 19:171-204.

Tol, R.S.J. (1999): The Marginal Costs of Greenhouse Gas Emissions. *The Energy Journal*, 20(1):61-81.

Tol, R.S.J. et al. (2001): How Much Damage will Climate Change Do? *Recent Estimates. World Economics*, 1(4):179-206.

Tongyai, C. (1994): Impact of Climate Change on Simulated Rice Production in Thailand . In: C. Rosenzweig, and A. Iglesias (Eds.): Implications of Climate Change for International Agriculture: Crop Modeling Study.

Voss, R., and U. Mikolajewicz (2000): Long-Term Climate Changes Due to Increased CO_2-Concentration in the Coupled Atmosphere-Ocean General Circulation Model ECHAM3/ LSG.Climate Dynamics, in print.

Voss, R., Sausen R., and U. Cubasch (1998): Periodically Synchronously Coupled Integrations with the Atmosphere-Ocean General Circulation Model ECHAM3/LSG. Climate Dynamics 14:249-266.

Williams, G.D.V., R.A. Fautley, K.H. Jones, R.B. Stewart, and E.E. Wheaton (1988): The Effects of Climatic Variations on Agriculture in Saskatchewan, Canada. In: M.L. Parry, T.R. Carter, and N.T. Konijn (Eds.): The Impact of Climatic Variations on Agriculture, Vol. 1 - Assessment in Cool Temperate and Cold Regions.

Yohe, G., Neumann, J., Marshall, P., and H. Ameden (1996): The Economic Cost of Greenhouse-Induced Sea-Level Rise for Developed Property in The United States. Climatic Change 32: 387-410.