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An Integrated Assessment Model of Economy-Energy-Climate – The Model Wiagem

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ABSTRACT

This paper presents an integrated economy-energy-climate model WIAGEM (**W**orld **I**ntegrated **A**ssessment **G**eneral **E**quilibrium **M**odel) incorporating economic, energy and climatic modules in an integrated assessment approach. To evaluate market and non-market costs and benefits of climate change, WIAGEM combines an economic approach with a special focus on the international energy market, and integrates climate interrelations with temperature changes and sea level variations. WIAGEM is based on 25 world regions aggregated to 11 trading regions, each with 14 sectors. The representation of the economic relations is based on an intertemporal general equilibrium approach and contains the international markets for oil, coal and gas. The model incorporates all greenhouse gases (GHG) influencing potential global temperature, sea level variation and the assessed probable impacts in terms of climate change costs and benefits. Market and non-market damages are evaluated according to the impact assessment approaches of Tol [1]. Additionally, this model includes net changes in GHG-source emissions as well as removals by sinks resulting from land use change and de-foresting activities. This paper describes the model structure in detail and outlines general results with emphasis on the impacts of climate change. As a result, climate change impacts are significant within the next 50 years; developing regions face high economic losses in terms of welfare and GDP losses resulting from sinks and other GHG changes.

Keywords: integrated assessment modeling, Kyoto mechanisms.

1. INTRODUCTION

Nearly all scientific reports, including the youngest IPCC report, confirm once more that humankind's impact on the natural environment has never been greater and is causing substantial long-term and irreversible climatic changes. One important source of climate change are anthropogenic greenhouse gas emissions. Increasing atmospheric concentrations of greenhouse gases have a substantial impact on the global temperature and sea level which generate extensive economic, ecological and climatic impacts. Potential climate change impacts encompass a general reduction in crop yields in most tropical and sub-tropical regions, decreased water availability in water-scarce regions, an increased number of people exposed to vector and water-borne diseases and heat stress, intensification in the risk of flooding from heavy precipitation events and rising sea levels, and augmented energy demand for space cooling due to higher summer temperatures. Beneficial impacts include an increased potential crop yield in some higher latitude regions, a potential increase in global timber supply from appropriately managed forests, increased water availability, reduced winter mortality and reduced energy demand for space heating due to higher winter temperatures [2]. Additionally, working group I of the IPCC reports that the global average surface temperature has risen by 0.6 ± 0.2 °C over the 20th century, stressing the fact that the temperature increases in the Northern Hemisphere have been the largest of any century during the past 1,000 years. 1990 was the warmest decade and 1998 the warmest year, and the atmospheric concentration of the greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have increased drastically since 1750.

A comprehensive analysis of all previously described effects caused by climate change must be based on a broad and integrated evaluation tool combining economic, energy and climate relations into one modeling instrument, thus allowing an integrated assessment of the costs and benefits of emissions reduction policies. Models based only on economic, ecological or climate considerations allow an assessment of only one aspect of climate change and are therefore not comprehensive. Current models trying to integrate climate interrelations into an economic framework typically use stylized and reduced interrelations of all domains.

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This paper presents a novel integrated assessment modeling approach based on a detailed account of economic relations. Its core is an intertemporal general equilibrium model WIAGEM which includes all world regions and main economic sectors. The general equilibrium model also includes a representation of the international energy markets for oil, coal and gas. The economic model is paired with a model of the ocean carbon cycle and climate.

WIAGEM comprises a model of 25 world regions aggregated into 11 trading regions, each with 14 sectors. The model incorporates the greenhouse gases (GHG) CO_2, CH_4 and N_2O, affecting global temperature and sea level; both determine the impacts of climate change. Market and non-market impacts are evaluated according to the damage cost approaches of [3]. Additionally, this model includes net changes in GHG emissions from sources and removals by sinks resulting from land use change and de-forestation activities.

The first part of this paper gives a brief overview of existing economic, climate and ecosystem models and integrated assessment approaches. The main focus of this paper is describing the integrated assessment model WIAGEM. The model's economic, energy and climate modules are thoroughly explained. The paper concludes with a short illustration of selected key model results.

2. INTEGRATED ASSESSMENT MODELS

2.1. Basic Remarks

Economic assessment of climate change is based either on pure economic models focusing on economic relations and interlinkages, economic models enlarged by stylized climatic interrelations, or submodels, usually known as integrated assessment (IAM) models. Ecological effects such as the impact of climate change on biodiversity are mainly modeled by ecosystem models concentrating on ecological interrelations (see [4–10]). Climatic impacts can be assessed chiefly by sophisticated climate models [11–18].

Pure economic models based primarily on an intertemporal optimization approach covering aggregated world regions do not normally incorporate a sectoral disaggregation. In order to assess the impact of climate and ecosystem changes, an integrated assessment model must cover both climatic and ecosystem as well as economic interrelations. Economic models including sectoral disaggregation of world regions by a general equilibrium model mainly do not embrace ecological or climatic interrelations. In economic modeling approaches, there is a trade off between either a representation and replication of a long term, dynamic but highly aggregated economic system, or a detailed reproduction of regional economic systems comprising regional world trade effects. Economic modeling approaches covering detailed regional and sectoral trade options are based primarily on a general equilibrium approach. Economic modeling approaches covering long-term dynamic effects with an intertemporal optimization framework neglect these interregional and intersectoral trade options. We have chosen this economic general equilibrium approach because we would like to focus on international trade options and assess regional and sectoral effects of different emissions reduction policies. This is due to the fact that most cost benefit climate change analyses are based on a highly aggregated economic approach that does not cover sectoral and trade effects.[1] Because we are applying a detailed representation of the economy by a CGE approach, we are able on the one hand to reproduce detailed regional and sectoral impacts and on the other hand only cover (from the climatic perspective) a relatively short time horizon of 50 years.

Costs and benefits of climate change are predominantly assessed by integrated assessment models (IAM) incorporating physical relations of climate change and economic effects of damage functions. Integrated assessment models are characterized by combining multidisciplinary approaches to thoroughly evaluate climate change impacts. However, as previously described, the economic system is based on a highly aggregated intertemporal optimization framework that neither covers detailed regional and sectoral interrelations, nor involves international trade effects. Examples for such IAM approaches are MERGE [19], RICE or DICE [20], CETA [21] or FUND [22]. Edmonds [23] gives an overview of the latest modeling approaches; previous overviews can be found in Dowlatabadi [24–26].

2.2. The Role of Uncertainty

Uncertainty about the future climate is the dominant cause of uncertainty about the character and significance of impacts. Integrated assessment models cover different uncertainties resulting from data inconsistencies and gaps, unknown functional relationships or errors in the structure of a model, and unknown or incorrect assumptions about important parameter values. Uncertainty about the correct determination of the model, data and key parameter distorts the understanding of the social, economic and ecologic impacts of climate change. Uncertainties could justify the postponement of significant mitigation efforts. However, uncertainty also includes the risk of significant climate changes inducing considerable impacts. Because the climate change issue is a long-term, global, non-linear and therefore very complex issue, climatic, ecological and economic uncertainties [27] become evident. Economic impacts assessment of climate change is based on uncertainties resulting from the above described ecological and climatic uncertainties. Uncertainties about irreversibilities of climate change, intergenerational effects, market and agents behavior and expectations make a prediction and impact assessment highly speculative.

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[1] Examples of economic impact assessment studies based on a pure CGE modeling framework are [28–32].

Furthermore, uncertainty costs, investment decisions under uncertainties and forecast uncertainties are only a few examples of economic uncertainties that make a concrete cost and benefit evaluation of climate change extremely tentative. Furthermore, socioeconomic behavior is extremely tainted with societal randomness and variability that is difficult to predict.

Most importantly, there is a need to link physical climate and biogeochemical system models more effectively, and in turn improve coupling with descriptions of human activities. Currently, human influences are generally treated only through emission scenarios providing climate system external forcings. More comprehensive human activities models must begin to interact with the dynamics of physical, chemical, and biological sub-systems through a diverse set of contributing activities, feedbacks, and responses.

The model WIAGEM is a first attempt to reduce the above described uncertainties by combining a simplified climatic and ecologic model with a detailed economic feedback system. The model includes all greenhouse gases and potential net emissions changes due to sink potential from land use change and de-forestation. The climatic model is based on general interrelations between energy and non-energy related emissions, temperature changes and sea level variations, all inducing substantial market and non-market damage cost economic impacts. The uncertainty about data quality is reduced because the model is based on a detailed economic database representing a well known and scientifically accepted economic database. Model and parameter uncertainties are covered by choosing an innovative modeling approach and including parameter sensitivity analysis. Of course, not all uncertainties can be covered. However, there is a need to develop more sophisticated economic models that cover ecological and climatic interlinkages. WIAGEM is a first attempt to fill this gap.

3. THE MODEL WIAGEM

WIAGEM is an integrated assessment model integrating an economy model based on a dynamic intertemporal general equilibrium approach combined with an energy market model and climatic submodel covering a time horizon of 50 years. This model is incremented into five-year time steps.[2] The basic idea behind this modeling approach is the evaluation of market and non-market impacts induced by climate change.

WIAGEM is benchmarked to the base year 1992. Benchmark data determine the parameter and coefficients of the CES production, demand and utility functions. To calibrate the model, we determine the reference level of emissions growth, radiative forcing, energy production and energy and non-energy related trade. Prices and quantities of all non-energy data are based on the 1995 GTAP version 4, with adjustments to GTAP version 5. This database provides trade and production statistics for more than 50 regions and 50 commodities. The model covers 26 regions which are aggregated to the 11 trading regions.[3]

The model is based on the concept of a general equilibrium approach. Therefore the model determines market clearing prices by equalizing economic demand and supply. It is assumed that all factor markets have perfect competitive behavior, and that demand and supply is cleared by market prices (market clearance condition). The output of domestically produced goods of sector j is an input to the Armington production sector. Armington goods are produced by the Armington sector and are used for energy, consumption, investment and public production. Furthermore, profit maximization implies that no activity earns a positive profit (zero profit condition). Consumption maximization implies that excess demand is always zero, i.e., means income must be balanced with expenditures (income balance condition).

The sectoral disaggregation contains five energy sectors: coal, natural gas, crude oil, petroleum and coal products and electricity. The dynamic international competitive energy market for oil, coal and gas is modeled by global and regional supply and demand, while the oil market is characterized by imperfect competition with the intention that OPEC regions can use their market power to influence market prices. Energy related greenhouse emissions occur as a result of economic and energy consumption and production activities. Currently, a number of gases have been identified as having a positive effect on radiative forcing [35] and are included in the Kyoto protocol as “basket” greenhouse gases. The model includes three of these gases: carbon dioxide (CO_2), methane (CH_4) and nitrous dioxide (N_2O) which are considered the most influential greenhouse gases within the short term modeling period of 50 years. Excluding the other gases is not believed to have substantial impacts on the analysis’ insights.

Because of the short term application of the climate submodel, we consider only the first atmospheric lifetime of greenhouse gases, assuming that the remaining emissions have an infinite life time. The atmospheric concentrations induced by energy related and non-energy related emissions of CO_2, CH_4 and N_2O have impacts on radiative forcing, influencing potential and actual surface temperature and sea level. Market and non-market damages determine regional and overall welfare development.

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[2] The model core code is based on an original version developed by Tom Rutherford in 1999. A similar model version of the economic model has been published by [33]. The model has been modified to include greenhouse gases, sinks, climate change impacts and induced technological change.

[3] The model is written in the computer language GAMS (MPSGE) and solved by the algorithm MILES, see [34]. The model uses the so-called “Mixed Complementary Format” (MCP). The MCP formulation covers the transformed non-linear optimization problem into the first order optimization conditions. The solver works in a way that the equilibrium condition of the equations explained later is fulfilled.

3.1. Economy

The economy is represented by an intertemporal computable general equilibrium and multi-regional trade model covering 25 world regions aggregated to 11 trading regions linked through bilateral sectoral trade flows. The model is based on GTAP 4.0 data[4] from 1995. The world regions are aggregated to the following 11 trading regions (see Tables 1 and 2).

The economic structure of each region consists of five energy sectors: (1) coal, (2) natural gas, (3) crude oil, (4) petroleum and coal products and (5) electricity and industrial sectors, agriculture and services. Because of the intertemporal optimization framework, a savings good sector is included. The aggregated factors for production include land, labor and capital.

All products are demanded by intermediate production, exports, investment and a representative consumer; market actors behave within a full competition context. Consumption and investment decisions are based on rational point expectations of future prices. The representative agent for each region maximizes lifetime utility from consumption which implicitly determines the savings level. Firms choose investment maximizing the present value of their companies.

Table 1. World regions.

	Regions
ASIA	India and other Asian Countries (Republic of Korea, Indonesia, Malaysia, Philippines, Singapore, Thailand, China, Hong Kong, Taiwan)
CHN	China
CAN	Canada, New Zealand and Australia
EU15	European Union
JPN	Japan
LSA	Latin America (Mexico, Argentina, Brazil, Chile, Rest of Latin America)
MIDE	Middle East and North Africa
REC	Russia, Eastern and Central European Countries
ROW	Other Countries (Rest of the World)
SSA	Sub Saharan Africa
USA	United States of America

Table 2. Sectoral classification.

	Sectors
COL	Coal
CRU	Crude Oil
GAS	Natural Gas
EGW	Electricity
OIL	Petroleum and Coal Products
ORE	Iron and Steel
CRP	Chemical Rubber and Plastics
NFM	Non Ferrous Metals
NMM	Non Metal mineral Products
AGR	Agriculture
PPP	Pulp and Paper
TRN	Transport Industries
Y	Other Manufactures and Services
CSG	Savings Good

In each region, production of the non-energy macro good is captured by an aggregate production function, i.e., each production process is described by a production function transforming output by applying a specific technology. The factor inputs could be substituted against each other depending on the ''nesting structure'' of the CES production function. CES production functions use different ''nesting levels'' of input combinations (see Fig. 1). At different levels, input composites could be substituted against other input factors. Goods are produced for the domestic and export market. Production of the energy aggregate is described by a CES function reflecting substitution possibilities for different fossil fuels (i.e., coal, gas, and oil), capital, and labor representing trade off effects with a constant substitution elasticity. Fossil fuels are produced from fuel-specific resources and the non-energy macro good subject to a CES technology. Energy efficiency is improved endogenously by increased expenditures in R&D. That means, in the CES production function, energy productivity is endogenously influenced by changes in R&D expenditures.

The CES production structure follows the concept of ETA-MACRO[5] combining nested capital and labor at lower levels. Energy is treated as a substitute of a capital labor composite determining (together with material inputs) overall output (see Fig. 1). Energy productivity is increased endogenously by increased R&D expenditures.

To fulfill the zero profit condition, producers minimize production costs to get a certain value of output. In other words, at any point the profit function gives the maximum profit Π while costs are minimized. Markets are perfectly competitive, output and factor prices are fully elastic. The representative producer of sector j ascertains the CES *profit function*[6]

$$
\begin{aligned}
\prod_{i}^{Y}(p) = {} & [a_j^{dx}(p_j^{1-\sigma_{dx}} + (1-a_j^{dx})pfx^{1-\sigma_{dx}}]^{\frac{1}{1-\sigma_{dx}}} - \\
& - \Bigg[a^m pm_j^{1-\sigma_{klem}} + (1-a^m)\Big[EP_j^e p_j^{e1-\sigma_{kle}} + \\
& + (1-EP_j^e)[a_j^k(p_j^{rk})^{1-\sigma_{kl}} + \\
& + (1-a_j^k)(p_j^l)^{1-\sigma_{kl}}]^{\frac{1-\sigma_{kle}}{1-\sigma_{kl}}}\Big]^{\frac{1-\sigma_{klem}}{1-\sigma_{kle}}}\Bigg]^{\frac{1}{1-\sigma_{klem}}} \qquad (1.1)
\end{aligned}
$$

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[4] See [36].

[5] CES production functions can be based on different combinations of input factors. For example, at the very first level a capital energy composite could be substituted against a labor input, whereas at the second level capital can be substituted against energy (which is mostly a composite of non-electric and electric energy). [37] shows an overview of different CES production functions and their nesting options.

[6] In the mathematical description, we refer to the dual approach, i.e., we show the cost minimization where the independent variable is the price and not the quantity as in the primal case. For further explanations about the theoretical framework to determine the general equilibrium, see [38].

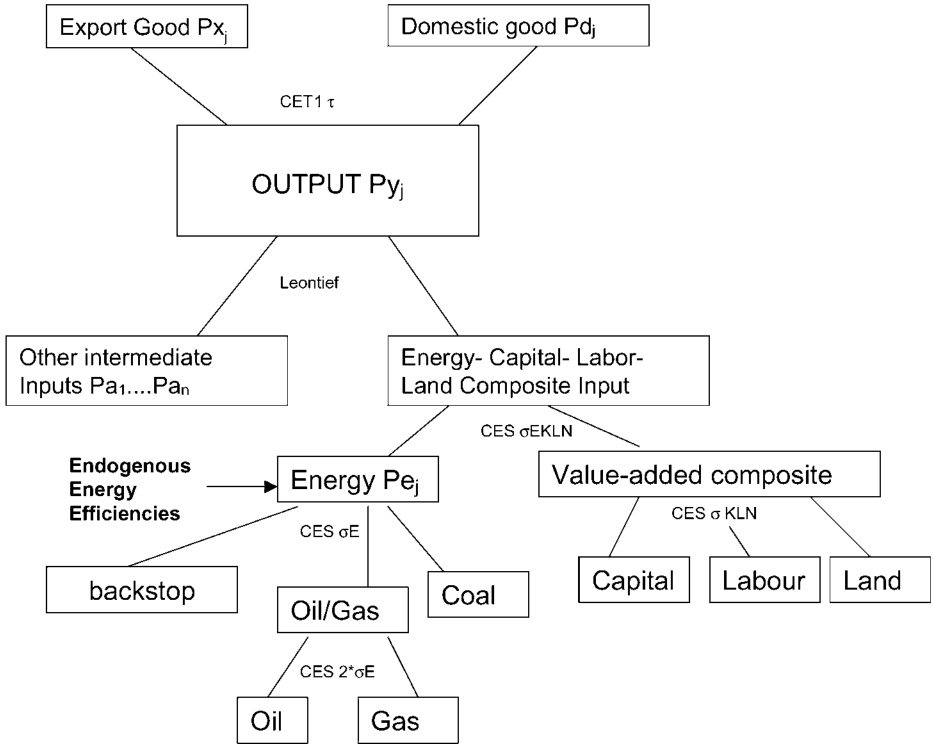

Fig. 1. Production structure of sector j in region r.

with:

Π_j^Y:	Profit function of sector j[7]
Y_j:	Activity level of production sector j
a_j^{dx}:	Domestic production share of total production by sector i
a_j^k:	Value share of capital within capital-energy composite
a_j^l:	Value share of labor within capital-energy-labor aggregate
a_j^m:	Value share of material within capital-energy-labor material aggregate
p_j:	Price of domestic good j
pfx:	Price of foreign exchange (exchange rate)
prk:	Price of capital
p_j^e:	Price of energy
p_j^m:	Price of material/land
p^l:	Price of labor
σ_{dx}:	Elasticity of transformation between production for the domestic and production for the export market
σ_{ke}:	Substitution elasticity between capital and energy
σ_{kle}:	Substitution elasticity between labor, capital, and energy composite
σ_{klem}:	Substitution elasticity between material and labor, capital, and energy composite
CET:	Constant elasticity of transformation τ
CES:	Constant elasticity of substitution σ
$EP_{j,t}^E$:	Endogenous energy productivity

With $EP_{j,t}^E = \delta_{j,t}^E \cdot KR \,\&\, D_{j,t}^{\theta}$ as increase of energy productivity. R&D expenditures (*KR&D*) improve innovations in more energy efficient technologies.[8] δ parameterizes the efficiency of research and development.

A representative agent for each region maximizes its region's discounted utility over the model's time horizon (50 years). This is done under budget constraints equating the present value of consumption demand to the present value of wage income, initial capital stock, present value of rents on fossil energy production, and tax revenue. In each period, households face the choice between current and future consumption which can be purchased via savings. The trade-off between current consumption and savings is given by a constant intertemporal substitution elasticity. Producers invest as long as the marginal return on investment equals the marginal cost of capital formation. The rates of return are determined by uniform and endogenous world interest rates such that the marginal productivity of a unit of investment and a unit of consumption is equalized within and across countries. The primary factors capital, labor, and energy are combined to produce output in period t. In addition, some energy is delivered directly to the final consumer. Output is separated into consumption and investment, and investment enhances the (depreciated) capital stock of the next period.

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[7] The notation Π with the subscript Y is used to consider the activity subset which is represented by production Y. Because of the zero profit condition, this equation must be equalized to zero.

[8] We follow theoretic and applied approaches of [39], [40] or [41].

Capital, labor, and the energy resources earn income which is spent on consumption or saved. Savings equals investment through the usual identity. Increased protection costs of climate change and R&D expenditures lower other economic investments (crowding out).

Sectoral capital stocks depreciate at a constant rate δ and are enlarged by investments which cover both investment to protect against climate change and R&D investment. Capital evolution is assumed to be determined by a specific time lag which is represented by a capital survival share λ. Capital is used for production with a capital price p_t^K and a capital utility price of p_t^{RK}, and is depreciated by rate δ.[9]

$$\begin{aligned}&\prod_t^K(p) = \lambda \cdot p_{p+1}^k + p_t^{rk}\\ &\quad \forall\lambda = (1-\delta)^\tau, \quad \tau = \nu + \vartheta\\ &\quad p_t^{rk} = \nu \cdot p_{\tau-\nu}^{rk} + \vartheta p_{\tau-\vartheta}^{rk} - ptc_t^\gamma - p_t^{R\&D}\\ &\forall\nu + \vartheta = \tau\end{aligned} \tag{1.2}$$

with:

$\prod_t^K$: Profit function of activity K in time period t

K_t: Activity level of capital in period t

p_t^k: Price of capital in period t

p_t^{rk}: Price of capital services in period t

λ: Capital survival share

δ: Depreciation rate

τ: Time solution parameter

υ, ϑ: Time lag parameter

ptc_t^r: Price of regional protection costs

$p_t^{R\&D}$: Price of regional R&D investments

Investments are produced by Leontief technology:

$$\prod_{t+1}^I(p) = p_{t+1}^k - \sum_j a_j^i p_{j,t}^a \tag{1.3}$$

$\prod_t^I$: Profit function for investment activity I in time period t

a_j^i: Value share investment of good j

$p_{j,t}^a$: Price of Armington good j in time period t

I_t: Activity level of investments in period t

R&D investments follow the same determination:

$$\begin{aligned}&\prod_{t+1}^{R\&DI}(p) = p_{t+1}^K - \sum_j a_j^{R\&DI} p_{j,t}^{R\&DA}\\ &ITOT = \sum_j I_t + R\&D_t\end{aligned} \tag{1.4}$$

The model solves for a finite time horizon. Because of that, we need to include a steady state condition to determine capital in the terminal period. We introduce terminal capital as an additional variable for each capital stock. We assume a growth rate constraint of sectoral investment in the terminal period:

$$g_{KT+1} = \frac{I_{j,T}}{I_{j,T-1}} = \frac{C_{j,T}}{C_{j,T-1}} \tag{1.5}$$

Labor is supplied by households and demanded by firms; all households are confronted with a specific time quota to be spent for labor or leisure. This labor–leisure decision is determined by net wages ensuring a price elastic labor supply. One representative agent by each region demands a composite consumption good produced by combining the Armington good and household energy aggregate good according to a CES configuration. σ_{end} describes the elasticity of substitution between the composite macro good and energy aggregate. Aggregate end-use energy comprises oil, gas, and coal with an interfuel elasticity of substitution equal to one. Backstop fuel is a perfect substitute for the energy aggregate. Purchase of the good is financed from the value of the household's endowments of labor, capital, energy-specific resources, and revenue from any carbon tax or permit prices, respectively (see Fig. 2).

Mathematically, this dependence can be written:

$$\prod^{CG}(p) = p^{cg} - \left[a_E^{cg}(p_E^{hh})^{1-\sigma_C} + \sum_i a_i^{cg}(p_i^a)^{1-\sigma_C}\right]^{\frac{1}{1-\sigma_C}} \tag{1.6}$$

with:

$\prod^{CG}$: Profit function for consumption activity CG

p^{cg}: Price of consumption good

p_i^a: Price of Armington good i

a_E^{cg}: Value share of energy aggregate in final demand

σ_c: Substitution elasticity between energy and the non-energy Armington composite in the consumption sector

a_i^{cg}: Value share of non-energy good in final demand

CG: Activity level of real consumption good production

Domestic and imported varieties of non-energy goods for all domestic market buyers are treated as incomplete substitutes. This is represented by a CES Armington[10] aggregation function providing a constant substitution elasticity. With respect to energy trade, fossil fuels are treated as perfect substitutes, and net trade cannot be cross-transferred. International capital flows reflect borrowing and lending at the world interest rate, and are endogenous subject to an intertemporal balance of payments constraint assuming no changes in net indebtedness over the entire model horizon.

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[9] As with the previous notation, we use the zero profit hypothesis for capital activity K.

[10] In contrast to the assumption of homogenous goods that can be fully substituted internationally by a Heckscher-Ohlin framework, we assume that international traded goods cannot be perfectly substituted, i.e., these goods are treated as imperfect substitutes. This is represented by an Armington trade approach.

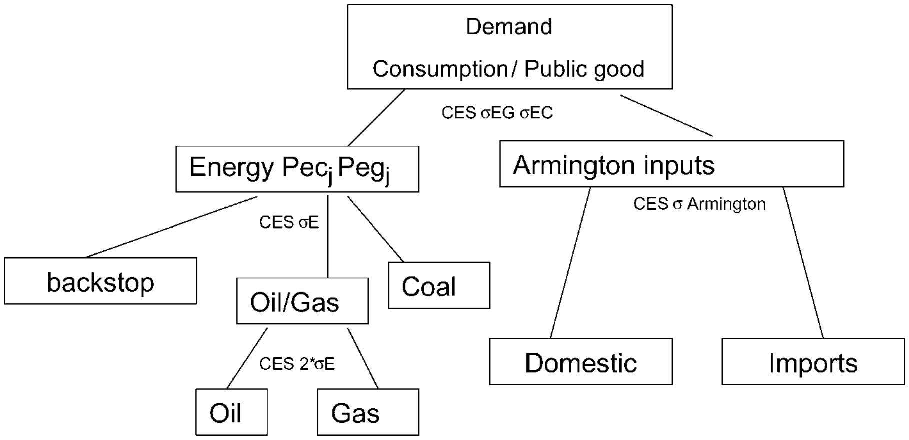

Fig. 2. Final demand structure.

The profit function of *Armington production* is specified by:

$$\prod_j^A (p) = p_j^a - [a_j^a p_j^{1-\sigma_{DM}} + (1-a_j^a)(pfx)^{1-\sigma_{DM}}]^{\frac{1}{1-\sigma_{DM}}} \qquad (1.7)$$

with:

$\prod_j^A$: Profit function for the production of the Armington good j
p_j^a: Price of Armington good j
a_j^a: Domestically produced good j value share of domestic and import good aggregate
pfx: Price of foreign exchange (exchange rate)
σ_{DM}: Substitution elasticity between domestic and imported good
A_j: Armington activity level

Key model parameters cover Armington elasticities, backstop costs and oil supply elasticities. Within the default or BAU scenario, all key parameters are adopted as demonstrated in Table 3.

Table 3. Overview of key parameters.

Type of Elasticity	Value
Fossil Fuel Supply	
Coal	.5
Gas	1.2
Oil	.3
Armington	
Elasticity of Substitution Domestic vs. Imported Goods	4
Elasticity of Transformation Exports vs. Domestic Sales	8
Production Elasticities	
Interfuel Elasticity of Substitution	
Final demand	.5
Industry:	
Oil/Gas	2
Coal/Oil/Gas	1
Elasticity of Substitution Energy Aggregate vs. Primary Factors KLM	.5

The intertemporal balance of payment condition determines the equivalence of the sum of exports and balance of payments and the sum of imports. This means that potential trade deficits or surpluses must be equalized over the entire time period. This condition represents the model's basic closure.

3.2. Energy

WIAGEM includes four energy production sectors, one non-energy sector and three fossil fuel sectors traded internationally for oil, gas and coal. Coal production in the OECD and gas production in Russia grow with energy demand at constant prices. The elasticity of substitution between the resource input and non-energy inputs is calibrated to meet a given price elasticity of supply. Exhaustion leads to rising fossil fuel prices at constant demand quantities. The carbon-free backstop technology establishes an upper boundary on the world oil price; this backstop fuel is a perfect substitute for the three fossil fuels and is available in infinite supply at one price calculated to be a multiple of the world oil price in the benchmark year. Demand elasticities depend on backstop technologies when low backstop cost demand elasticities are high and vice versa.

A composite energy good is produced by either conventional fossil fuels – oil, gas, and coal – represented by a nested CES technology (with an elasticity of interfuel substitution σ_{fuel}) or from a backstop source with Leontief technology structures. Oil and gas can be substituted by an elasticity of substitution twice as large as the elasticity between their aggregate and coal. The energy good production is determined by industry and household final demand.

$$\begin{aligned}\prod_j^E (p) = {} & p_j^e - EP_{j,t}^e[a_j^{ele} p_j^{ele 1-\sigma_{ele}} + (1-a_j^{ele}) \cdot a_j^{oil} (p_j^{oil})^{1-\sigma_{fossil}}] + \\ & + a_j^{gas} (p_j^{gas})^{1-\sigma_{fossil}} + a_j^{coa} [a_j^{hco} (p_j^{hco})^{1-\sigma_{coa}}] + \\ & + a_j^{sco} (p_j^{sco})^{1-\sigma_{coa}}]^{\frac{1-\sigma_{fossil}}{1-\sigma_{coa}}}]^{\frac{1-\sigma_{ele}}{1-\sigma_{fossil}}}]^{\frac{1}{1-\sigma_{ele}}} - \\ & - p^{ET} EMISS_j \qquad (2.1)\end{aligned}$$

With:

$\prod_j^E$: Profit function for the production of energy
a_j^{ele}: Electricity value share of energy aggregate by sector j
a_j^{oil}: Oil value share of fossil energy aggregate by sector j
a_j^{gas}: Gas value share of fossil energy aggregate by sector j
a_j^{hco}: Hard coal value share of coal aggregate by sector j
a_j^{sco}: Soft coal value share of coal aggregate by sector j
σ_{ele}: Substitution elasticity between electricity and fossil energy
σ_{fossil}: Substitution elasticity between fossil energy inputs
σ_{coa}: Substitution elasticity between hard and soft coal
ef_j^{oil,co_2}: CO_2 share of oil in sector j
ef_j^{gas,co_2}: CO_2 share of gas in sector j
ef_j^{hco,co_2}: CO_2 share of hard coal in sector j
ef_j^{sco,co_2}: CO_2 share of soft coal in sector j
p^{EP}: Price emissions permits
Ej: Activity level of energy production
$EMISS$ Sectoral GHG emissions allowances

Demanded energy by households is produced by a CES function:

$$\prod_{hh}^{E}(p) = p_{hh}^{e} - \left[\sum_{i=eg} a_{i,hh}^{e}(p_i^a + a_i^e p^e)^{1-\sigma^{eg}}\right]^{\frac{1}{1-\sigma^{eg}}} \qquad (2.2)$$

with:

$a_{i,hh}^e$: Value share of energy good i of household
p_{hh}^e: Price of energy by household demand
σ_{eg}: Substitution elasticities between energy goods
E_{hh}: Activity level of energy production by household

The intertemporal optimal dynamic allocation is characterized by a steady state growth path. This means that all sizes must rise by a common growth rate in order to reach equilibrium conditions. In the long run, conventional energy (i.e., fossil fuels) are typified by exhaustion, thus increasing resource prices. We assume that within future time periods a carbon-free backstop technology will be developed and utilized as a substitute for conventional energy. As a result, a carbon-free backstop technology can be utilized within future times at price f^{BS} \$/t CO_2. Zero profit condition is determined by:

$$\prod^{BS} = p^e - p^{CG} f^{BS} \qquad (2.3)$$

with:

p^{CG}: Price of consumption good
f^{BS}: Costs of carbon-free energy supply
BS: Activity level of backstop technology

Emission limits can be reached by domestic action or by trading Annex B emission permits initially allocated according to regional commitment targets. Those countries meeting the Kyoto emissions reduction target stabilize their mitigated emissions at the 2010 level.[11]

According to regional abatement costs, countries sell or buy emission permits. Countries facing high abatement costs above permit prices will purchase emission permits, regions with marginal abatement costs lower than the permit price will sell emission licenses. Revenues from permit sales are refunded as a lump sum back to the abating country's representative consumer. It must be stressed that problems concerning concrete implementation of the flexible mechanisms and emissions trading scheme such as compliance, early crediting and deception influencing permit prices are neglected within the modeling context.

3.3. Climate

The model comprises three of the most important anthropogenic greenhouse gases: carbon dioxide (CO_2), covering over 80 percent of total forced radiation by anthropogenic greenhouse gases, methane (CH_4) and nitrous oxide (N_2O). Primarily due to human activities, the concentration of these gases in the earth's atmosphere have been increasing since the industrial revolution.

In WIAGEM, we consider the relationship between man-made emissions and atmospheric concentrations and their resulting impact on temperature and sea level. Because of the 50-year short term analysis lasting until 2050, we neglect classes of atmospheric greenhouse gas stocks with different atmospheric lifetimes (usually modeled by the impulse response function) and reduced forms of the carbon cycle model developed by [42] and applied by [43]. Energy and non-energy related atmospheric concentrations of CO_2, CH_4 and N_2O have an impact on forced radiation relative to their base year levels. Energy related emissions are calculated according to the energy development of each period. Energy related CO_2 emissions are considered according to the emissions coefficients of the EMF group (see Table 4).

Energy related CH_4 emissions are determined by the CH_4 emissions coefficients of gas and coal production in billions of tons of CH_4 per exajoule gas and coal production; the coefficients are taken from the MERGE model 4.0 [44]. Tables 5 and 6 show the regional emission coefficients.

Table 4. CO_2 coefficients.

	Coal	Oil	Gas
CO_2 coefficients in billions of metric tons/exaj.	0.2412	0.1374	0.1994

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[11] This can be referred to as the "Kyoto Forever" scenario.

Table 5. Emissions coefficients in billions of tons of CH_4 per exajoule gas production. (source: MERGE 4.0).

	USA	EU15	JPN	CNA	FSU	CHN	MIDE	ASIA	ROW
2000	0.187	0.493	0.000	0.225	1.005	1.170	1.377	0.468	0.982
2010	0.168	0.413	0.000	0.222	0.823	0.955	1.121	1.121	0.805
2020	0.149	0.333	0.000	0.190	0.641	0.740	0.864	0.864	0.627
2030	0.131	0.253	0.000	0.158	0.458	0.524	0.607	0.607	0.449
2040	0.112	0.173	0.000	0.126	0.276	0.309	0.350	0.350	0.271
2050	0.094	0.094	0.000	0.094	0.094	0.094	0.094	0.094	0.094

Table 6. Emissions coefficients in billions of tons of CH_4 per exajoule coal production. (source: MERGE 4.0)[23].

	USA	EU15	JPN	CNA	FSU	CHN	MIDE	ASIA	ROW
2000	0.354	0.196	0.000	0.371	0.512	0.963	0.000	0.117	0.356
2010	0.354	0.196	0.000	0.371	0.512	0.963	0.000	0.117	0.356
2020	0.354	0.196	0.000	0.371	0.512	0.963	0.000	0.117	0.356
2030	0.354	0.196	0.000	0.371	0.512	0.963	0.000	0.117	0.356
2040	0.354	0.196	0.000	0.371	0.512	0.963	0.000	0.117	0.356
2050	0.354	0.196	0.000	0.371	0.512	0.963	0.000	0.117	0.356

Note. [23] One model version covers further time periods until 2100. We assume the same projections until 2100.

Table 7. Non-energy related emissions in millions of tons-1990; source: MERGE 4.0, [45] and [46].

	USA	EU15	JPN	CNA	FSU	CHN	MIDE	ASIA	ROW
CH_4	25.8	15	1	5	7	43.2	0	46	132
N_2O	1.1	0.8	0.1	0.3	0.3	0.7	0.2	0.5	1.7

Table 8. Potential sinks enhancement in 2010 in million of tons of carbon; source: MERGE 4.0[24].

	USA	EU15	JPN	CNA	FSU	CHN	MIDE	ASIA	ROW
Sinks 2010	50	17	0	50	34	25	25	13	250

Note. [24] See [49].

Non-energy related emissions cover parts of the CH_4 emissions and N_2O emissions.[12] The global carbon dioxide emissions baseline pathway is assumed to start from 6 to 11 billion tons of carbon in 2030 which is roughly consistent with the carbon emissions projections of the IPCC reference case of medium economic growth [35].

Additionally, net changes in greenhouse gas emissions are covered from sources and removal by sinks resulting from human-induced land use change and forest activities such as aforestation, reforestation and deforestation. We use potential sinks enhancements as measured by the [35] and used in MERGE 4.0:[13]

Total emissions are therefore determined by:

$$TOTEM_{r,t} = \sum_{GHG} E_{r,t} + \sum_{GHG} NonE_{r,t} - S_{r,t} \tag{3.1}$$

with TOTEM indicating the total emissions per region and time period, and $E_{r,t}$ as regional emissions per time period. Non-energy related emissions are countered for each greenhouse gas, regional and time period. Sinks ($S_{r,t}$) reduce total emissions.[14]

Atmospheric concentrations of CO_2, CH_4 and N_2O have impacts on the forced radiation relative to the base level. Carbon emissions are divided into five classes, each with different atmospheric lifetimes. The impulse response function to an instantaneous atmospheric injection is expressed as the weighted sum of the exponentials:

$$G(t) = \sum_{i=1}^{5} a_i \exp\left(\frac{-\tau}{\tau}\right)$$

where a_i represents scaling factors $\sum a_i = 1$ and τ the decay constraints.

The atmospheric stock of CH_4 and N_2O in year t+1 equals the fraction of the stock in year t remaining in the atmosphere additional to new emissions:

$$S_{G,t+1} = k_G \cdot S_{G,t} + E_{G,t}$$

With $S_{G,t}$ as the stock of gas G in year t and kG as retention factor for gas G and $E_{g,t}$ as emission in year t.[15]

The atmospheric concentration of different greenhouse gases have the following impact on radiative forcing relative to their base level [50]:

$$\Delta F_{CO_2} = 6.3\ln\left(\frac{CO_2}{CO_{2_0}}\right) \tag{3.2}$$

$$\begin{aligned}\Delta F_{CH_4} = {} & 0.036(CH_4^{0.5} - CH_{4_0}^{0.5}) - f(CH_4, N_2O) + \\ & + f(CH_{4_0}, N_2O_0)\end{aligned} \tag{3.3}$$

$$\begin{aligned}\Delta F_{N_2O} = {} & 0.14(N_2O^{0.5} - N_2O_0^{0.5}) - f(CH_{4_0}, N_2O) + \\ & + f(CH_{4_0}, N_2O_0)\end{aligned} \tag{3.4}$$

with ΔF measured in Wm^{-2} as changes in radiative forcing of each greenhouse gas corresponding to a volumetric concentration change for each greenhouse gas relative to the base level. The $CH_4 - N_2O$ interaction term is determined by:

$$\begin{aligned}f(CH_4, N_2O) = {} & 0.47\ln\lfloor 1 + 2.01 \cdot 10^{-5} \cdot (\mathrm{CH_4} \cdot \mathrm{N_2O})^{0.75} + \\ & + 5.31 \cdot 10^{-15} \cdot CH_4 \cdot (CH_4 \cdot N_2O)^{1.52} \rfloor\end{aligned} \tag{3.5}$$

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[12] See Table 7.

[13] We follow the approach of [47] that additional sinks enhancement activities are costless. An assessment of different sink options analyses are provided by [48], see Table 8.

[14] This also means that the emissions reductions targets are reduced.

[15] The Key assumptions about greenhouse gases summarizes Table 9.

Table 9. Summary key assumptions greenhouse gases[25].

Trace Gas	CO_2	CH_4	N_2O
Atmospheric concentration	280	.8	288
Pre-Industrial (ppmv)	353	1.72	310
1992 (ppmv)			
Energy related emissions			
1992 (billions of tons)	6.0	.08	.0001
Growth Rate, Post-1992			
Non-energy related emissions			
1992 (billions of tons)	.2	.454	.0139
Growth rate, Post-1992	0	.8	.2

Note. [25]Source: [51] and [52].

Total chances of radiative forcing F is obtained by adding each greenhouse gas radiative forcing effect. The potential temperature PT is influenced by radiative forcing with d as parameter (d = 0.455):

$$\Delta PT = d \cdot \Delta F \tag{3.6}$$

Actual temperature is reached by a time lag resulting from the lag of potential climate change impacts due to tempertature changes:

$$\Delta AT_{t-1} - \Delta AT = tlag \cdot (\Delta PT_t - \Delta AT_t) \tag{3.7}$$

with *tlag* as the time lag, ΔAT_t measures the actual change in temperature in year t relative to the base year.

Because of the short term 50-year analysis, sea level will change insignificantly during this time period. However, newest calculations estimate a rough linear relationship between temperature changes and sea level variations. Assuming that sea level will vary by 7 cm with every 1 °C temperature change (s = 7), we calculate minor sea level changes caused by actual temperature changes. Sea level variations are determined by the very rough estimates of a linear relationship between actual temperatures:[16]

$$\Delta SL = s \cdot \Delta AT \tag{3.8}$$

Impacts of climate change cover market and non-market damages; the former comprise all sectoral damages, production impacts, loss of welfare etc., while the latter contain ecological effects such as biodiversity losses, migration, and natural disasters. To assess impacts by climate change, we follow Tol's approach [3] to cover impacts on forestry, agriculture, water resources and ecosystem changes as an approximation of a linear relationship between temperature changes, per capita income or GDP and protection costs due to sea level increase. Tol [3] estimates climate change vulnerability covering a comprehensive evaluation of diverse climate change impacts. Along with sectoral impacts on agriculture, forestry, water resources and energy consumption, he covers impacts on ecosystems and mortality due to vector borne diseases and cardiovascular and respiratory disorders. We use the assessed protection costs and an approximation of potential impacts, i.e., additional costs to the economy lowering other investments (crowding out effect). Protection costs due to sea level rise summarizes Table 10.

Table 10. Protection costs of one meter sea level rise in $\$10^9$; source: [1].

USA	EU15	JPN	CNA	FSU	CHN	ASIA	MIDE
71.38	136	63	10.79	53	171	305	5

We follow the approach of (3) for economic impact assessment of ecosystem changes:

$$E_{t,r} = a \frac{y_{t,r}}{y_{1990,r}} P_{t,r} \frac{y_{t,r}/y_b}{1 + y_{t,r}/y_b} \tag{3.9}$$

with E as the value of the loss of ecosystems and y the per capita income and P as population size. α and y_b are parameter ($\alpha = 0.5$, $y_b = \$20.000$).

Impact assessment of vector borne diseases are determined by:

$$m_{r,t} = \alpha_r T_t^{\beta} \left(\frac{y_c - y_{t,r}}{y_c - y_{base,r}} \right)^{\gamma}$$
$$\perp y_{t,r} \geq y_c \tag{3.10}$$

with m representing mortality, and α, γ and y_c denoting parameter ($\alpha = 1$ (0.5–1.5), $\gamma = 1$ (0.5–1.5), $y_c = \$3100$ (2100–4100).

Furthermore, mortality due to changes in global warming are measured:

$$\Delta M = \alpha + \beta T_B \tag{3.11}$$

where ΔM denotes the change in mortality due to a one degree increase in global warming, T_b as current temperature and α and β are parameter.

Furthermore, we take into account Tol's approach to determine demand for space heating (SH) and space cooling energy (SC):

$$SH_{t,r} = a_r T_t^{\beta} \left(\frac{y_{t,r}}{y_{t,1990}} \right)^{\varepsilon} \left(\frac{P_{t,r}}{P_{t,1990}} \right) \prod_{s=1990}^{t} EP_{s,r} \tag{3.12}$$

$$SC_{t,r} = a_r T_t^{\beta} \left(\frac{y_{t,r}}{y_{t,1990}} \right)^{\varepsilon} \left(\frac{P_{t,r}}{P_{t,1990}} \right) \prod_{s=1990}^{t} EP_{s,r} \tag{3.13}$$

Total damages are assessed by the following relation:

$$\Delta DAM_t^r = \alpha_t^r \cdot \left(\Delta PT_t^{\beta} \cdot \frac{y_t^r}{y_0^r} \right) + PC_t^r \tag{3.14}$$

with DAM as total impacts (damages), α and β are parameters (varying from .5 to 1.5), PC represents the sectoral protection costs due to sea level rise.

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[16] These estimates are based on assumptions by the climate model NICCS, [43] and [53].

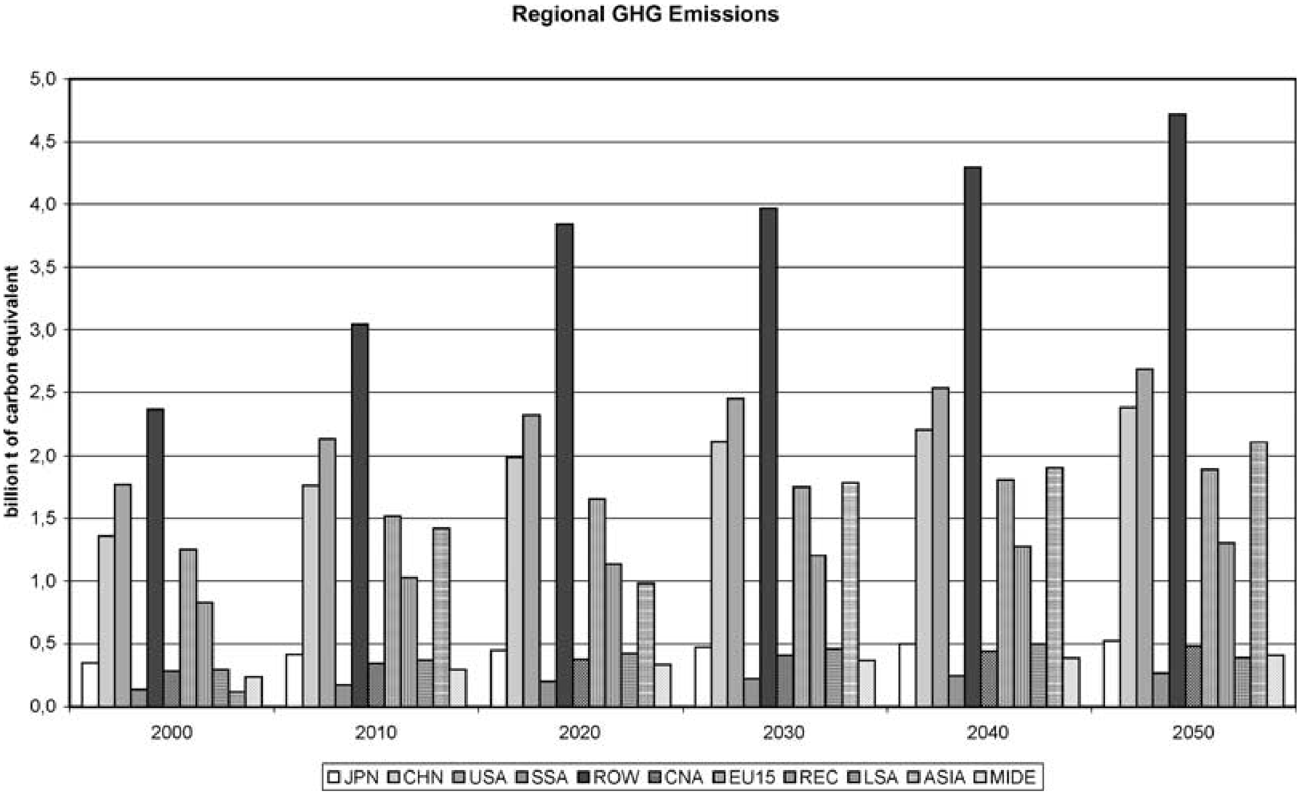

Fig. 3. Regional greenhouse gas emissions.

3.4. Climate Change and Ecological Impact Assessment

This section describes some basic model results. The model horizon encompasses 50 years, solving problems in 5-year increments. By including all greenhouse gases (as described in Section 2), total GHG emissions increase from roughly 9 billion tons to 17 billion tons of carbon equivalent emissions in 2050 (see Fig. 5 and [50]).

Regional greenhouse gas emissions differ substantially. The inclusion of the other greenhouse gases CH_4 and N_2O raises reference emissions for the European Union from 1.517 in 2010 to 1.894 billion tons of carbon. For the US, the inclusion of sinks lowers the greenhouse gas emissions from 2.133 to 2.030 in 2010 and 2.686 to 2.496 billion tons of carbon in 2050. Japan has no significant net emissions changes resulting from sinks inclusion.[17] The global CO_2 emissions baseline pathway is assumed to start from 6 to 12,7 billion tons of carbon in 2050, roughly consistent with the carbon emissions projections of the IPCC reference case of medium economic growth (see Fig. 3).[18]

The inclusion of sinks lowers total net GHG emissions to roughly 15.5 billion tons of carbon equivalent in 2050 (see Fig. 4). Because of the time deceleration of response impacts by potential and actual temperature changes ranging from 0.15 to 0.25 °C from 2030 to 2050, the inclusion of sinks causes comparatively marginal actual temperature declines after 2030.

Because of the assumed linearity between temperature changes and sea level rise, potential sea level increases by 1 cm in 2025 to roughly 1.8 cm in 2050.[19] As seen before, the incorporation of sinks by land use change and forestry tends to lower this increase marginally after 2030. These changes are low in comparison to other projected studies [2] and can be explained mainly by the short term time horizon considered and the time deceleration of response impacts (see Figs. 6 and 7).

In contrast to many other climate impact assessment studies detecting only insignificant economic climate change short-term impacts but significant impacts in the long run, we find that climate change impacts also matter within the next 50 years.[20] Model results demonstrate that primarily the developing countries must accept high welfare losses and GDP reductions in comparison to a scenario where no climate change impacts are included. Potential total damages of climate change are measured in global GDP percentage covering impacts on forestry, agriculture, water

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[17] We follow the approach of [47] that additional sinks enhancement activities are cost free. An assessment of different sink options analyses are provided by [48].

[18] See [49].

[19] These estimates are based on assumptions by the climate model NICCS [43].

[20] [53] find only marginal climate impacts until 2050.

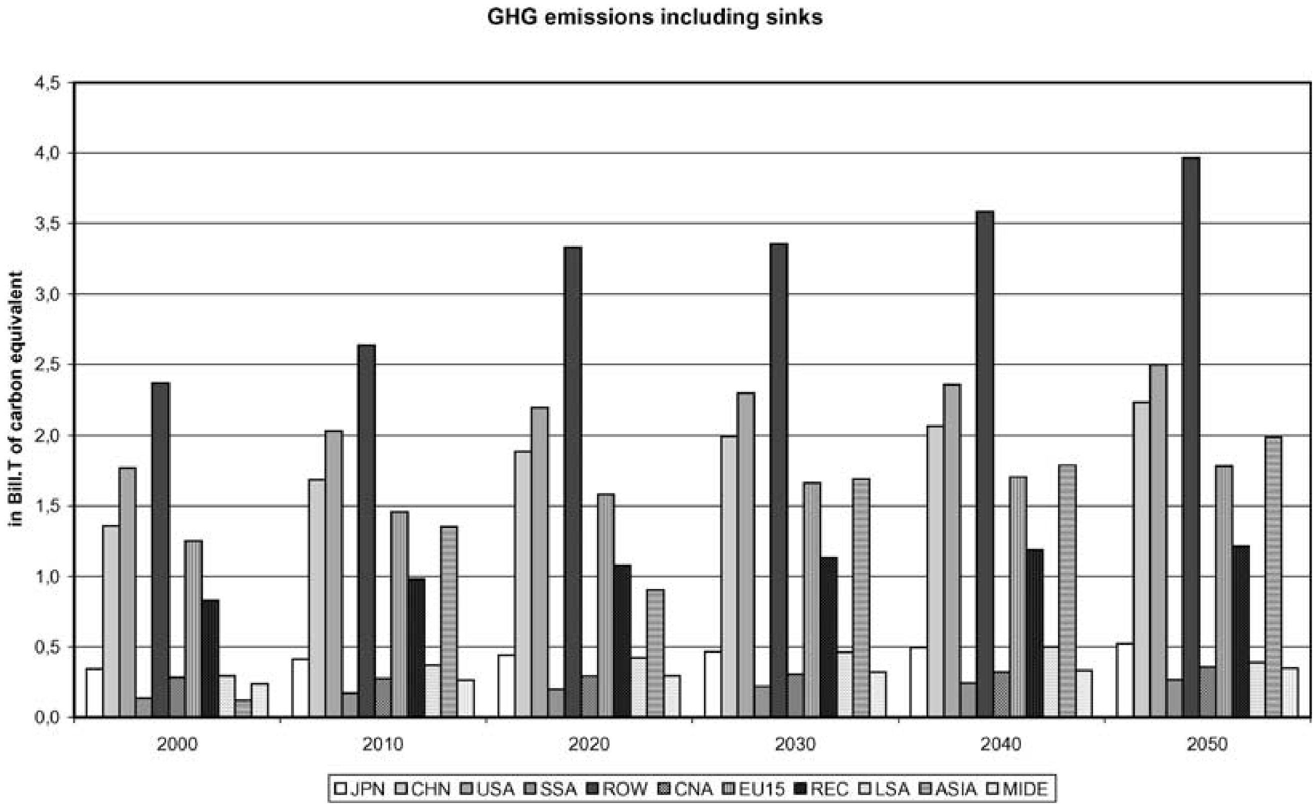

Fig. 4. Regional GHG emissions including sinks.

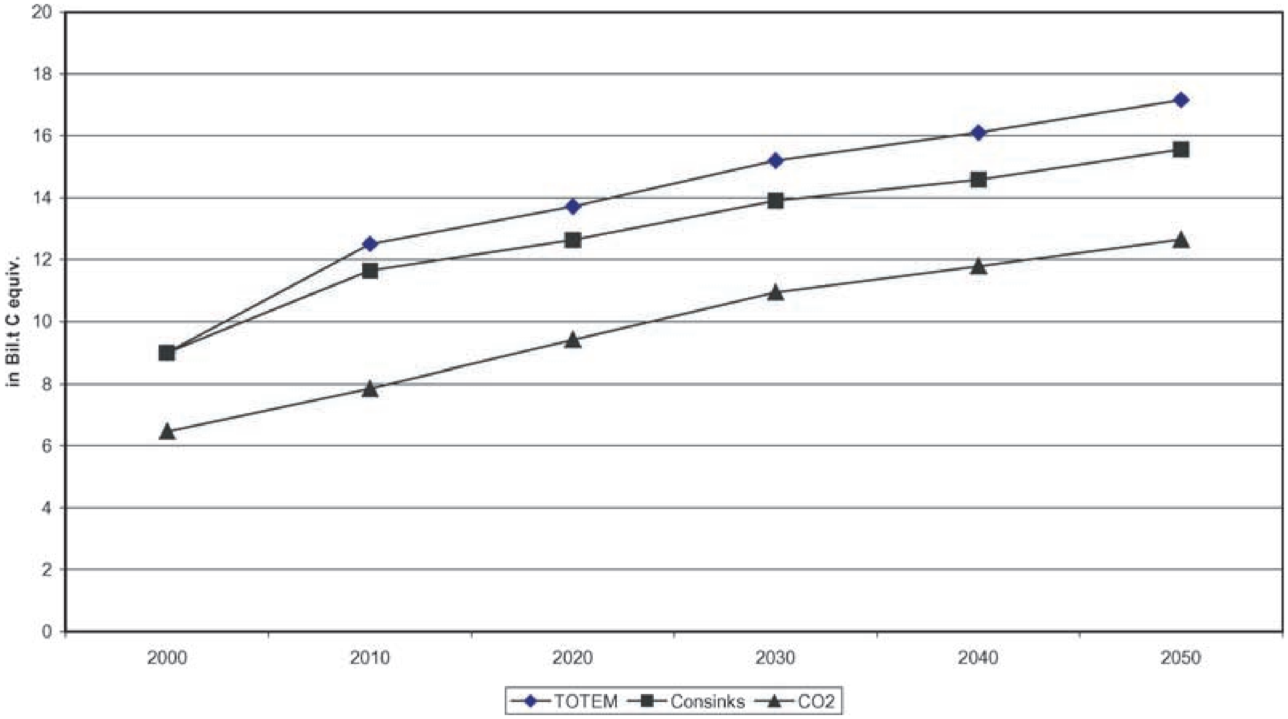

Fig. 5. Total CO_2 and GHG emissions with and without inclusion of sinks.

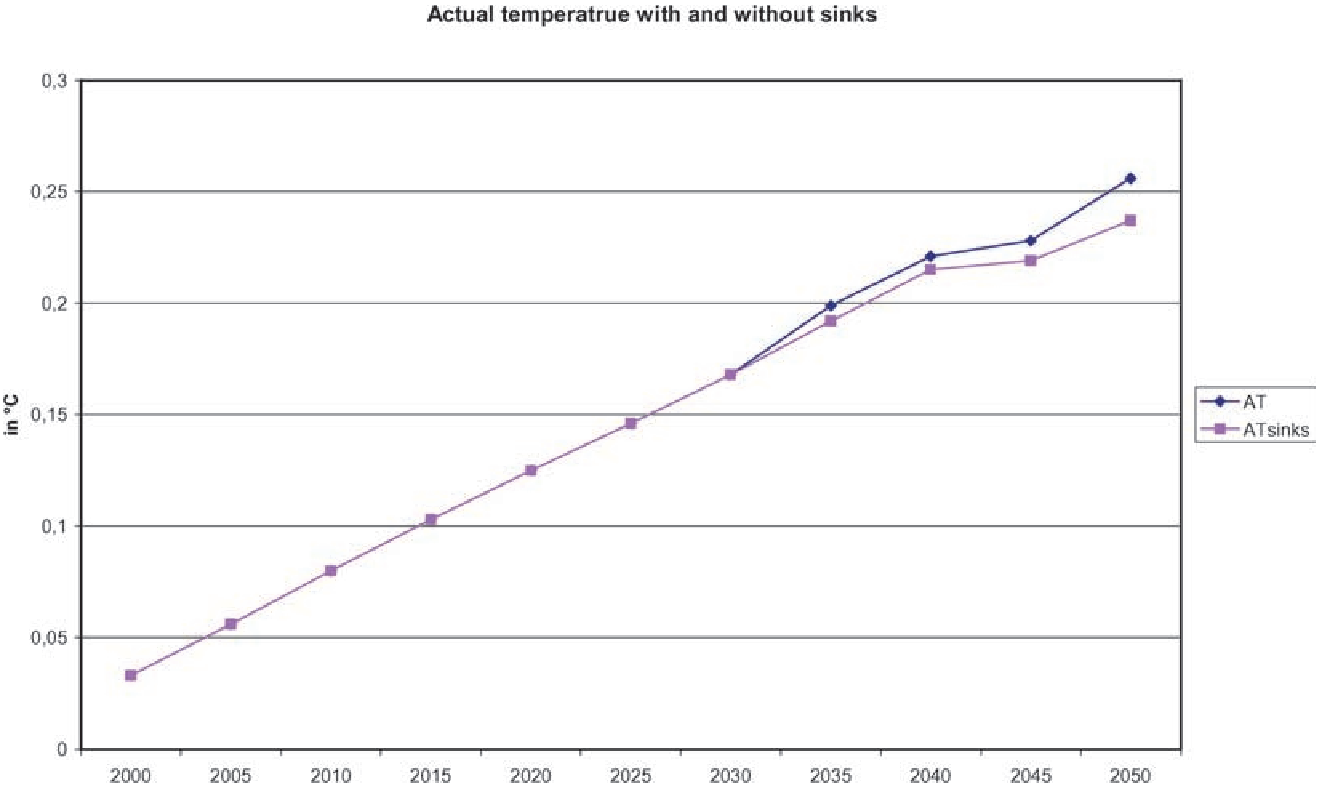

Fig. 6. Actual temperature changes with and without inclusion of sinks.

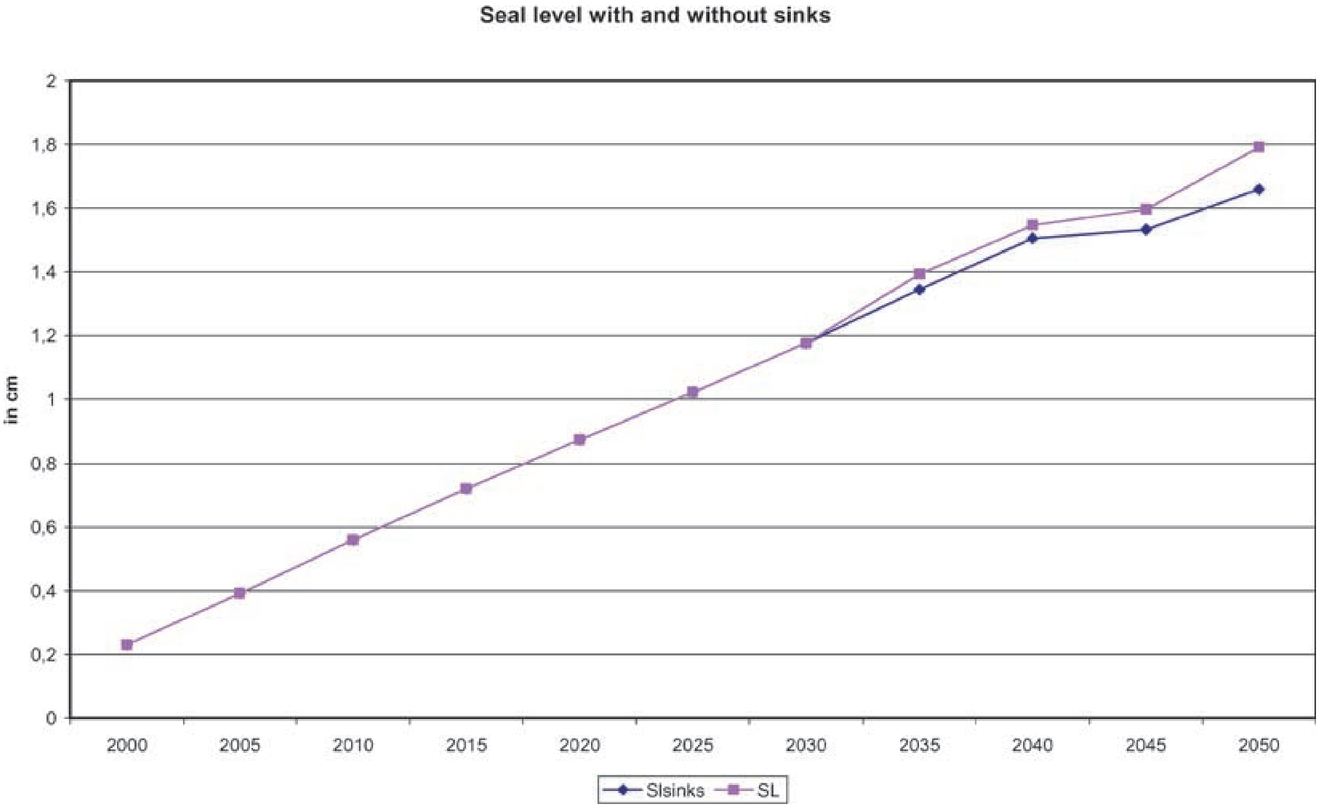

Fig. 7. Sea level changes with and without the inclusion of sinks, in cm.

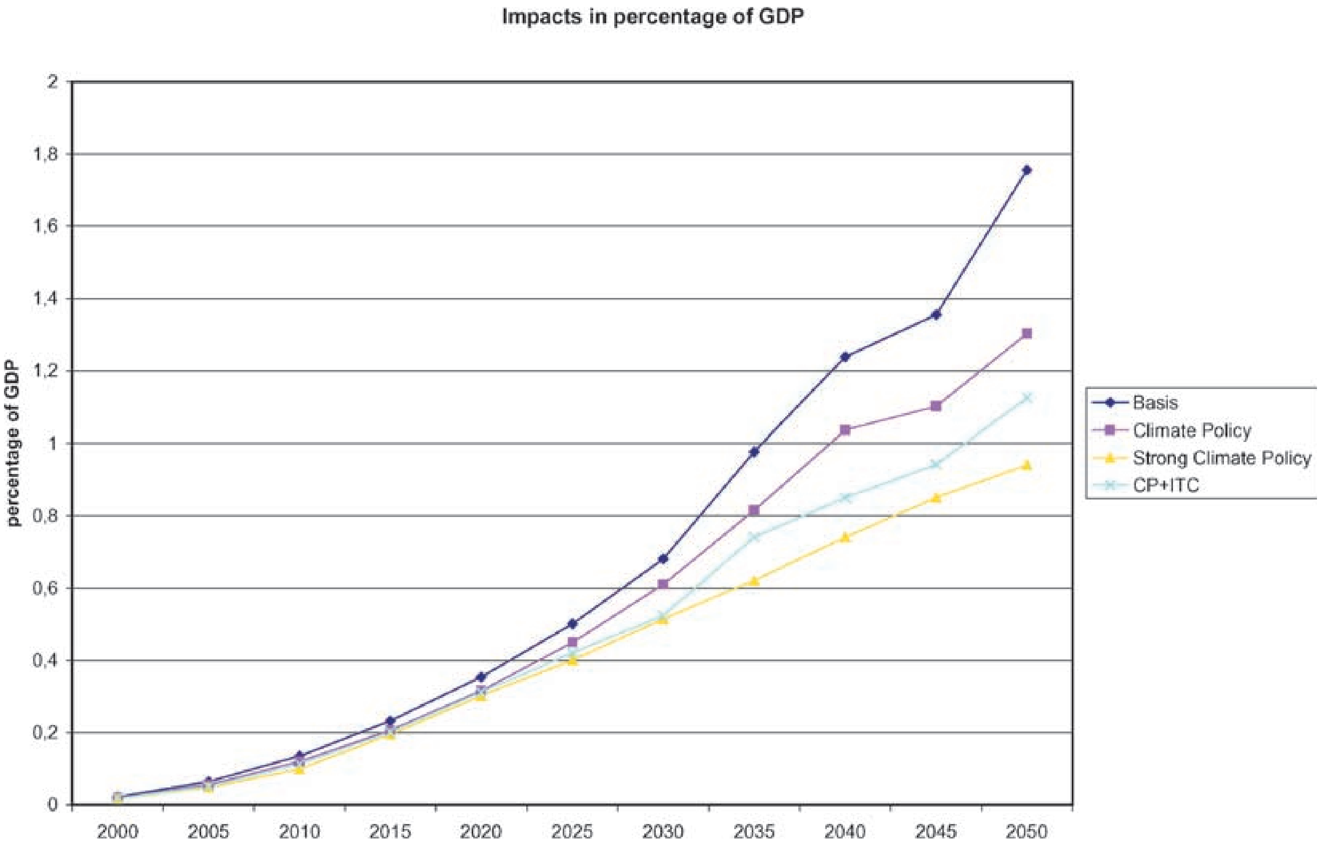

Fig. 8. Impacts of climate change in percentage of global GDP.

resources and ecosystem changes as an approximation of a linear relationship between temperature changes, per capita income or GDP and protection costs due to sea level rise, see equation (3.14). Emissions upsurge augments climate change impacts through global warming and sea level rise. Figure 8 compares the impacts of climate change through the emissions reductions induced by the Kyoto protocol.[21] The emissions reductions prescribed by the Kyoto protocol require a huge economic effort to drastically reduce GHG emissions, thus inducing lower economic impacts of climate change measured in GDP percentage. Figure 8 compares the impacts of climate change of a so-called ‘‘business as usual’’ scenario where no emissions reduction takes place and two further scenarios where both weak and very strong climate policy is implemented. As can be seen in Figure 8, climate policy implying drastic emisions reductions induces less impacts, here measured in percentage of GDP. That means that without any climate policy, economic damages and costs are much higher than related benefits; with increasing greenhouse gas emissions reduction these damages are further decreased. The option of technological changes through R&D investments could offer better emissions reduction opportunities. For that, total impacts in terms of GDP are lower than if it would not be included. Although the costs of climate change are higher than economic benefits, a strong climate policy that leads to substantial emissions reductions could reduce these costs and improve long-term benefits.

We determine impacts of climate change according to equations (3.9) to (3.14). Table 11 summarizes total impacts of climate change and its breakdown into its individual resulting effects. Developing regions suffer economic deficits if climate impacts are included due to their vulnerability and higher percentage impacts of economic values. These impacts can be explained through different effects: First, relatively poor countries must spend a higher percentage of their income on protection costs. As a consequence, higher production losses result from decreased economic investments. Second (this effect dominates the economic consequences), fast-growing regions like China and Asia increase production, resulting in negative climatic and ecological effects. Together with huge population and production growth, these negative impacts augment drastically until 2050.

Figure 9 summarizes the total impacts in terms of GDP changes in forestry, water, and air conditioning and heating. The decomposition of these effects demonstrate only negative impacts on forestry for the regions of Eastern

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[21] We assume a GHG reduction by 5.8% (as was previously intended).

Table 11. Impacts of climate change, measured in percentage of GDP (−negative, +positive impacts).

	2010	2020	2030	2040	2050
Ecological impacts					
JPN	−0.018	−0.018	−0.018	−0.018	−0.017
CHN	−1.585	−1.870	−1.945	−2.139	−2.600
USA	−0.019	−0.019	−0.020	−0.021	−0.021
SSA	−1.031	−1.039	−1.119	−1.237	−1.293
ROW	−0.022	−0.037	−0.063	−0.095	−0.134
CAN	−0.058	−0.051	−0.056	−0.062	−0.066
EU15	−0.027	−0.027	−0.027	−0.027	−0.037
REC	−0.170	−0.176	−0.231	−0.284	−0.344
LSA	−0.253	−0.381	−0.630	−1.000	−1.408
ASIA	−1.254	−1.937	−2.917	−3.860	−4.964
Vector borne diseases					
JPN	0	0	0	0	0
CHN	−0.077	−0.120	−0.185	−0.211	−0.246
USA	0.000	0.000	0.000	0.000	0.000
SSA	−0.080	−0.126	−0.193	−0.221	−0.256
ROW	0.000	0.000	0.000	0.000	0.000
CAN	0.000	0.000	0.000	0.000	0.000
EU15	0.000	0.000	0.000	0.000	0.000
REC	−0.096	−0.143	−0.188	−0.160	−0.147
LSA	−0.035	−0.055	−0.037	−0.060	−0.111
ASIA	−0.080	−0.125	−0.190	−0.217	−0.252
Forestry and water, heating and cooling					
JPN	0.017	0.021	0.026	0.028	0.029
CHN	0.002	0.003	0.004	0.004	0.004
USA	0.035	0.046	0.053	0.056	0.059
SSA	−0.006	−0.007	−0.008	−0.009	−0.010
ROW	0.009	0.011	0.014	0.014	0.016
CAN	0.008	0.010	0.012	0.013	0.014
EU15	0.009	0.011	0.014	0.014	0.017
REC	−0.049	−0.063	−0.086	−0.102	−0.114
LSA	−0.002	−0.003	−0.003	−0.004	−0.004
ASIA	0.016	0.020	0.026	0.028	0.030
Mortality	−0.564	−0.600	−0.654	−0.675	−0.703
Sum impacts					
JPN	−0.565	−0.597	−0.645	−0.665	−0.690
CHN	−2.223	−2.587	−2.779	−3.021	−3.544
USA	−0.548	−0.574	−0.620	−0.640	−0.665
SSA	−1.681	−1.771	−1.974	−2.142	−2.262
ROW	−0.577	−0.627	−0.703	−0.755	−0.821
CAN	−0.614	−0.641	−0.698	−0.725	−0.756
EU15	−0.582	−0.616	−0.667	−0.688	−0.723
REC	−0.878	−0.982	−1.160	−1.220	−1.308
LSA	−0.854	−1.039	−1.324	−1.739	−2.226
ASIA	−1.882	−2.642	−3.735	−4.724	−5.889

Europe and Russia and Latin South America. Regions like the USA and Europe boost positive economic effects of forestry changes. On the other hand, climate change induces negative impacts to all world regions except China regarding water resources. The energy demand for space heating is reduced in most of the world regions so that positive impacts in terms of GDP are induced. Contrarily, space heating for cooling increases due to increased temperature changes. This generates negative economic impacts.

Emissions reduction as assumed in the latest climate change negotiations[22] could lead to fewer negative economic impacts. However, these effects are only marginal until 2050. To deal with uncertainty as mentioned in the previous part of this article, we calculate sensitivity scenarios using parameter variation. Sensitivity calculations show that

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[22] We assume that the USA does not reduce emissions, resulting in a total GHG emissions reduction of only 1.8%.

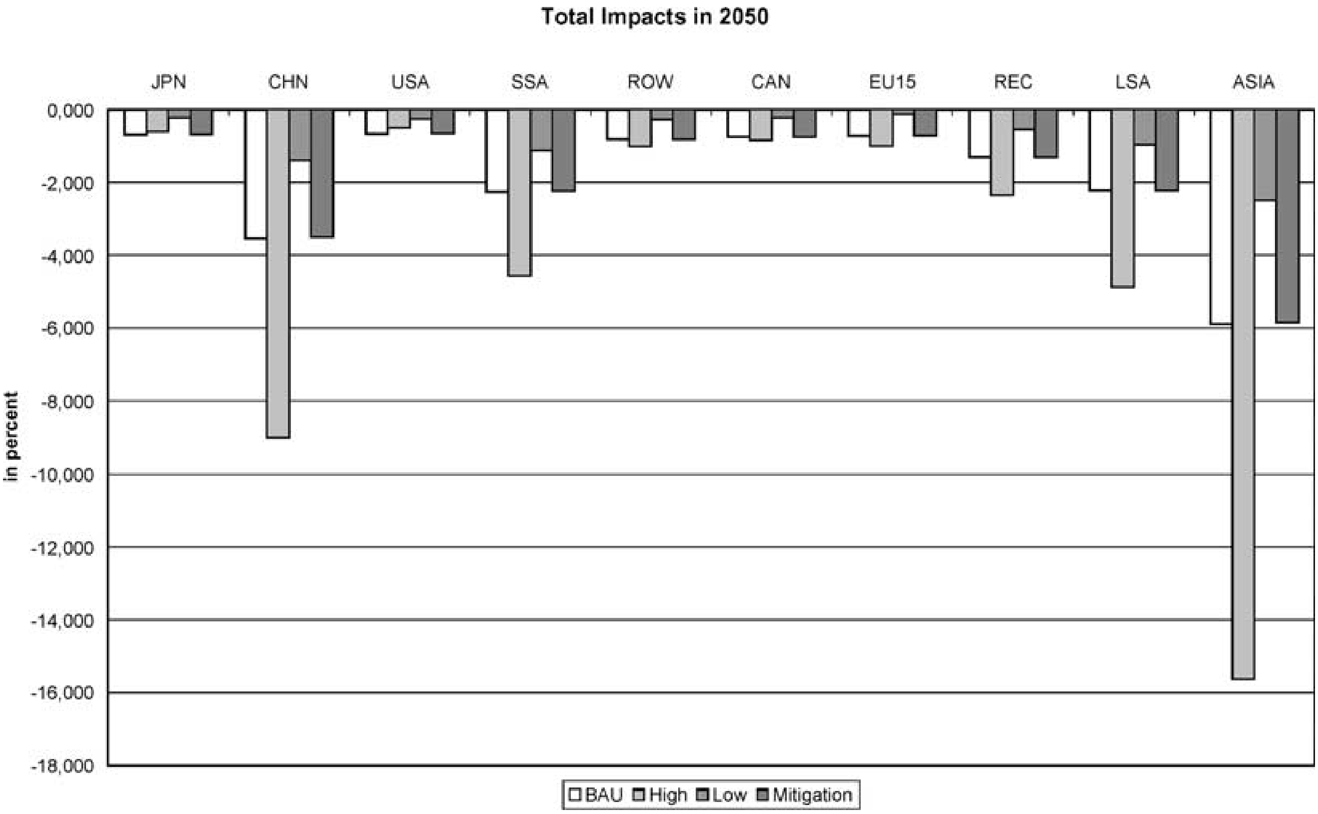

Fig. 9. Impacts of climate change measured in % of GDP in 2050, mitigation and sensitivity analysis.

results can vary significantly if high or low basic parameter are assumed. Total impacts of climate change increase in high growing regions if parameter α, β and γ of equation (3.9) to (3.14) are very high. This can be explained by the stronger impact resulting from temperature changes and income variations.

4. CONCLUSION

The model WIAGEM is an integrated assessment model building on a detailed economic intertemporal general equilibrium model covering 25 world regions and 14 sectors of each world region. It contains an energy submodel representing the international market for oil, coal and gas and allows a more realistic representation of the oil market in the sense that OPEC regions can influence the oil market price with their market power. Technological innovations improve energy efficiencies endogenously. An integrated assessment of economic, ecological and climate impacts is reached through an incorporation of climate and ecologic interlinkages attempting to evaluate economic market and non-market damages of climate change. Coverage of all GHGs improves the economic welfare impacts especially for OECD regions. Here, not only do the additional options of emissions abatement increase by the inclusion of all greenhouse gases, but the international price diminishes as well. The additional inclusion of sinks improves the welfare impacts in comparison to all other scenarios, leading to higher economic impacts. The decomposition of climatic effects shows a high share of ecosystem damages. Vulnerable nations suffer huge economic losses.

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