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GRACE model and applications

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Abstract: This report is a documentation of the GRACE model. GRACE is a computable general equilibrium model aimed at supporting studies of the global consequences of human activities that affect the drivers of climate change. The model is comprehensive, in the sense that is comprises all economic activities in the world, as expressed by national accounts data, and links greenhouse gas emissions and impacts of climate change to these economic activities. It explains human responses to changes in socioeconomic drivers, policies and impacts of climate change by means of economic theories of production and consumption, and derive the socioeconomic consequences from the impacts on prices in market equilibrium. The comprehensiveness combined with the modelling of individual behaviour makes GRACE a tool for integrating knowledge from research with different perspectives and help derive dependencies between countries, sectors and scales. The report gives examples on how important these dependencies are for evaluations of climate policies and challenges related to the future impacts of climate change.

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Contents

1 Introduction

The climate is changing because of human interactions with nature. Substantial research efforts are ongoing to understand the drivers of change and how to control them, how the climate system is affected and how this lead to changes in future weather, what impacts there will be on nature and on societies, and on possible ways to adapt. The research tends to develop by narrowing scope in order to obtain deeper insights. It thereby become challenging to see how findings from all the ongoing research from individual stands affects the general picture, by which all this research is motivated.

This underlines the need for an approach to make findings from research on the different aspects of global warming comparable, and put them in a common framework to provide information about the different challenges in terms familiar to policy makers and other users. Global computable general equilibrium (CGE) models largely satisfy these demands. First, they explain how economic decisions by commercial businesses, public companies, and consumers are affected by the socioeconomic framings, such as income and resource constraints. Economic decisions give rise to the main drivers of climate change, while most impacts affect the income and resource constraints. Second, global CGE models link together all economic activities in the world, based on descriptions of deliverances of goods and services across sectors and between countries. The results are presented by figures defined in the national accounts, which are basic for evaluations of economic development.

GRACE (Global Responses to Anthropogenic Changes in the Environment) is a global CGE model developed to show the consequences of actions taken to mitigate climate change, and the impacts of the resulting climatic changes on the economic development in selected countries or regions of the world. The first version of the model was available in 2005 (Aaheim and Rive, 2005), and highlighted measures to reduce emissions of CO2. Later versions include more greenhouse gases, and integrate impacts of climate change, which allows for assessments of the economic consequences of climate projections. The model is programmed in GAMS, and uses the GTAP database (latest version is Aguiar et al., 2016), which comprises national accounts data for 57 sectors in 140 world regions, most of them countries. GRACE is seldom run with more than 15 sectors and 15 regions, but aggregation of sectors and regions is flexible and easy to change. Thereby, the model can be used flexibly to focus on specific sectors or regions, depending on the research question.

This report is a documentation of the basic model, and shows examples of applications, where different research questions have been addressed by separate model versions with extensions. The motivation for developing GRACE was to establish a point of reference for integrating insights about climate change from different perspectives. The remainder of this introduction gives a general presentation of the main properties of the model for non-experts, and a discussion of strengths, weaknesses and possibilities for improvements. Thereafter follows a detailed description of the core model, and a documentation of the modelling of the energy sector and of impacts of climate change, which are frequently used when running GRACE. Finally, we provide examples of applications that show different uses of the model.

1.1 Global computable general equilibrium models

Global CGE models describe all economic decisions in the world by standard economic theory, and show how world markets respond to changes in income and availability of the primary economic production factors, labour, real capital and natural resources. Climate policies aim, in most cases, at changing economic decisions made by people and firms, and the impacts of climate change of most concern are those affecting income, labour, real capital and the productivity of natural resources. CGE models thereby help trace impacts of climate policies and climate change on world economies by a consistent theory of economic behaviour. A main reason why climate change has emerged is that the benefits of any action taken to mitigate climate change are shared by everybody on the earth. This means that nobody has a sufficient incentive to act according to their own interests, which gives rise to the phenomenon called “the tragedy of the commons”. As CGE models take the economic motives of individuals as a point of departure to explain decisions, the model can be used to analyse privately motivated initiatives and policies aimed at mitigating climate change. The need to quantify economic contributions from primary resources, products, and services in the model moreover represents a door opener for putting insights from research on different issues related to climate change into a global context to analyse the basic challenges behind global warming.

The model combine theories of economic behaviour and market equilibrium with statistical information from the national accounts, and coordinate the descriptions of all world economies to show how the economies will develop under a chosen set of underlying assumptions, such as population growth, technological change, and policies. The square on the left hand side in Figure 1.1 illustrates the main flows described for one region in the model, called a social accounting matrix.

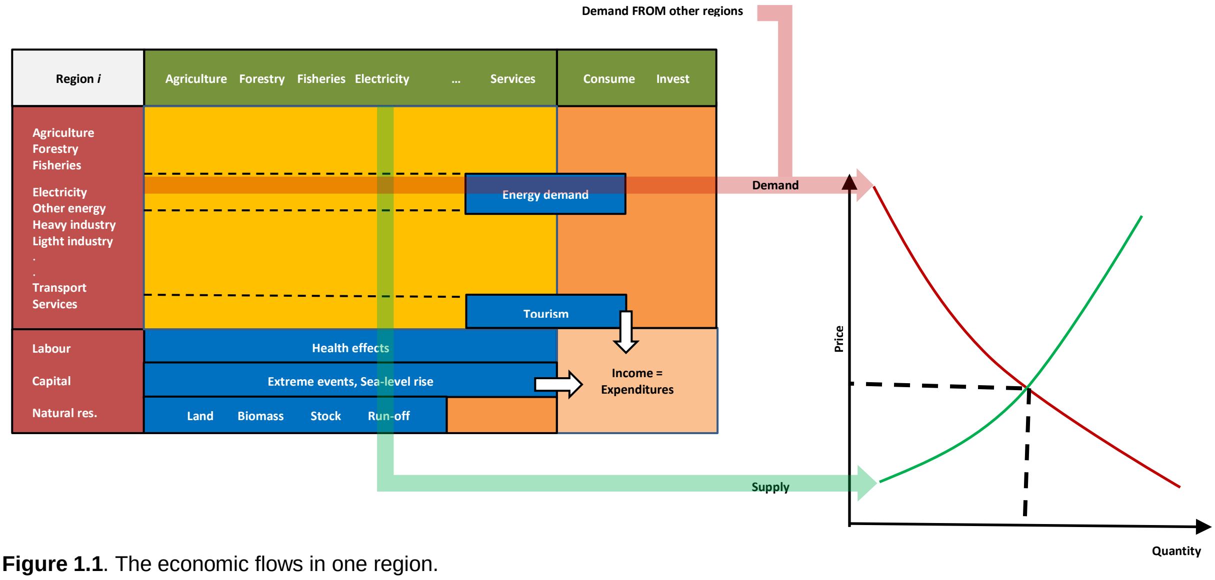


Figure 1.1. The economic flows in one region.

The columns show reported contributions from the different sectors and from primary input factors (labour, capital, and natural resources), measured in values. The rows show the reported use of the different commodities and services in each sector, and in consumption and investments. Consumption is divided into private and public consumption. The numbers refer to deliveries during a year from the national accounts.

The arrows show the main summations of data used for the modelling. The green arrow summarises all factors needed to produce the output from one sector. It comprises input of commodities and services from other sectors, and use of the primary input factors, labour, capital and natural resources. The red arrow summarises the demand for each good and service from all production sectors, from private and public consumers and from investors. Figure 1.1 applies to the flows within one region. Demands from the other regions are added to give the total annual domestic and foreign demand for the output from a sector in a region.

A delivery from one sector to another generates income to the delivering sector, but represents a cost to the receiving sector. In sum, the costs equal the income from these cross deliveries. What is left to the sectors is the income generated by their use of labour, real capital and natural resources. The model attaches this remaining income in all sectors, the gross domestic product (GDP), to these three primary input factors. This implies that no income is generated without being interpreted as exploitation of a production factor. This is called a zero-profit assumption. Every year, the entire GDP is spent on private and public consumption and investments. The model thereby utilizes data that comprise all economic activities in the world to describe how the economies are related.

The aim of the modelling is to explore implications of changes, such as changes in the availability of primary input factors, in the composites of input needed to produce the sector output, or in the composites of consumption. These changes lead to an imbalance between the output produced in a sector and the total demand for its output. To restore market equilibrium, where supply equals demand, the model adjusts the price of the product according to the theory of market behaviour, as illustrated on the right hand side in Figure 1.1. When the price of the output from one sector changes, however, those using this product will change the composite of their use of goods and services. Then, the prices of other products will have to change as well, to restore equilibrium in all markets. A response to a change within one sector thereby propagates throughout the entire economy. The socioeconomic consequences may therefore differ considerably from what is indicated by the response among agents within the sector where the initial price change took place.

The choice of input composites within sectors are derived from production functions, and the choice of consumer goods are derived from utility functions, by use of the theory of market behaviour. This is further described in Section 2. The functions are calibrated to fit the data from the social accounting matrices, but based on general assumptions about the possibility to replace the use of one product with another without changing the produced amount, or the level of utility. These assumptions reflect technologies in the production sectors and preference structures among consumers. When all producers minimize costs in fully competitive markets, and consumers maximize utility, the composites of input factors and consumption patterns are determined by the market prices.

The model thereby links specifications of technologies and descriptions of preferences to the development of the world's economies. In principle, this opens for exploration of the global impacts of changes in technologies, policies and availability of primary input factors to specific economic agents in different countries or regions. Findings from research on responses to policies, changes in preference structures, technological improvements and impacts of climate change may be implemented in the model to indicate how future economic development is affected when considered as one of many drivers of economic growth. In this way, CGE models provide an approach to explore implications for global development of findings in more focused studies. Moreover, the stringency of the model put a lead on how to represent insights from other studies, which reveals knowledge gaps in attempts to draw conclusions about the global consequences from findings in partial studies.

1.2 Addressing climate change

Most anthropogenic drivers of climate change are related to economic activities. The Intergovernmental PaneI on Climate Change (IPCC, 2014) report that CO_2-emissions contribute to 76 percent of greenhouse gas emissions in the world, with extraction and use of fossil fuels as the primary source. 11 percent are due to land use change, which in most cases is motivated by the economic benefits. Agriculture is the primary source of emissions of methane and nitrous oxide, which constitutes 22 percent of greenhouse gas emissions worldwide. The remaining 2 percent are emissions of other gases from various industrial processes. On the other hand, the attention to the impacts of climate change may arise because of other concerns, such as possible health effects or simply because what will happen is unpredictable. However, most of these concerns can be indicated transparently by assessments of possible economic impacts.

Because of the comprehensiveness of economic transactions represented global CGE models, this implies that knowledge about climate change from a broad range of studies can be integrated in the models, in principle, to show how the results contribute to our understanding of the many challenges related to global warming. The process of integration reveals knowledge gaps and difficulties in comparing findings from studies undertaken from different disciplinary perspectives. The point in reinterpreting them and put them into an economic context is, therefore, not to claim that the economic aspects are the most important. The primary aim is rather to offer an approach to integrate insights from different disciplines in a consistent way to show how lessons from more focused studies contribute to the understanding of the global problem that motivated the research, and to identify knowledge gaps that ought to be filled to clarify the linkages.

Drivers of climate change can be related to an economic activity in most cases, and are therefore in some way represented by the flows in Figure 1.1. In its simplest form, the emissions of greenhouse gases can be related to the quantity produced in a sector, or to the quantities from a particular sector used in other sectors and in the final deliveries. For example, extraction and use of the fossil fuels give fixed amounts of CO_2-emissions per unit produced or delivered.

How critical the assumption of a fixed relationship between emissions and sector output or use is depends on two factors. First, the sectors in the model comprise aggregates of several sectors, and the output consists of several products with different emission factors. If, for example, extraction of fossil fuels are aggregated into one sector, the product will be a composite of coal, oil and gas, each with different emission factors. In that case, the model will give the same emissions from each unit produced and used from the fossil fuel sector regardless of how the composite of coal, oil and gas develops over time. To limit such biases, the sector aggregates should specify the main emitting sectors. However, the sectors will always comprise units with different emission factors, meaning that this bias exists even for sectors that produce relatively uniform commodities.

The second weakness in using fixed emission factors for the sectors is that emissions are not always fixed by the production or use of a traded commodity or service. Emissions may be related to the choice of technology in production or use, on how the goods or services are used, or on emissions of other gases, and they may be subject to human and natural surroundings. In these cases, the basic version of GRACE can give just an indication on how economic development will affect the drivers of climate change. However, the emissions may nevertheless be driven primarily by economic incentives, and the general approach taken in CGE models provides guidelines to how insights from more detailed studies on these factors can be interpreted and integrated in the model to examine the global consequences.

The impacts of climate change are represented in GRACE by relationships between selected economic variables from the social accounting matrix, or from calibrated economic relationships and changes in average annual temperatures and annual precipitation. These climate indicators are drawn from climate projections. The model describes nine variables sensitive to climate, shown by the blue squares in Figure 1.1. Most of the economic impacts are due to climate sensitive primary input factors. Health effects change the productivity of the labour force, and capital stocks are affected by damages due to extreme events and by sea-level rise. Some sectors are based on utilization of natural resources, which may be affected in different ways depending on the usage. Agriculture depends on how the productivity of land is affected, forestry is subject to the impacts on forest stocks and growth rates, fisheries to the sensitivity of fish stocks, and production of renewable energy is often based on weather related flows. In addition, the demands for energy and tourism are assumed sensitive to climate indicators.

The impacts are represented by a choice of functional relationships between the selected variables in the model and changes in annual mean temperature and annual precipitation. Some of the functions are drawn directly from Roson and Satori (2016), who estimates impacts on agriculture, health, energy demand, tourism, and from sea-level rise at increasing temperature for all countries in the GTAP data base. The remaining impacts are calibrated by a meta-study of assessments of linkages between annual mean temperature and precipitation, and aggregated value added (or contributions to GDP) in a given sector or on the demand for a specific product (Section 3). The assessments are based on a few studies showing some large differences in the estimated impacts, and they are estimated for different temperature changes in partly overlapping regions. Moreover, the estimates on impacts on value added are used to calibrate impacts on specific input variables in GRACE. This assumes that the estimates apply without adaptation, because adaptation leads to a change in the relationship between use of the input factor and value added, which the model is supposed to take care of. However, it is not always clear from the underlying assessments whether or not adaptation is taken into account.

The apparent weaknesses in the impact estimates used in GRACE require an explanation to why highly uncertain and insufficient estimates are preferred to findings from far more precise studies of the physical impacts of specific climatic changes and weather conditions. One reason is the different scales addressed in a global macroeconomic model and the many studies of physical impacts. Impacts vary considerably over short distances, and it is an overwhelming task to put different estimates together to get a picture of the national, not to speak of the global, impacts. Estimates on the highly aggregated level is helpful at present, because of the lack of summaries of detailed studies on all the impacts represented in the model.

A second, more important, reason for using the assessments of impacts on aggregated sectors is related to the general challenge in translating estimates of impacts on physical quantities to the quantities represented in economic models. The quantities in economic models are collections of goods produced in one sector. Their contents may change depending on the constraints, which producers and consumers have to consider in making their choices. The composite of physical quantities in an aggregate is unknown, but it will change under changing constraints, for example because of climate change. Estimates of the impacts on these aggregates should therefore account for these changes, meaning that they ought to refer to estimates of the impacts on the aggregates rather than to estimates of the physical units.

The gaps between the knowledge provided by assessments of physical quantities and the information needed to estimate quantities in the economic model raises several issues, which the modelling helps to identify. This is useful to explore ways to reduce the problem, but it is not possible to repeal the difference between physical quantities and economic quantities entirely. Different physical quantities cannot be added in a meaningful way unless they can be included in a common physical concept, meaning that it is not meaningful to add apples and cows. Economic quantities are derived from values, which consist of a price term and a quantity term, but neither the prices nor the quantities are known. Instead, prices are used as weights, and interpreted as a reflection of the usefulness of all goods and services to those who buy them. Thereby, the observed value of an aggregate can be interpreted as a measure for the aggregated quantity in the base year, where the price equals 1. From then on, the model takes care of the development of prices. By this approach, we can add all kinds of physical units.

1.3 Usage and possibilities

GRACE represents a consistent system for exploration of the global consequences of changes that make producers and consumers worldwide choose different composites of goods and services, with attention to the impacts on greenhouse gas emissions and resulting climatic changes. The main point in having such a system available is to keep track of the known relationships between people within countries, between people in different parts of the world, and the interdependencies between people and nature. The model helps us understand how climate change and climate policies affect the main concerns related to global warming, that is, how present choices motivated by the benefits to individuals over the coming years may affect the world in the very long run. This contributes to understand some general issues related to global warming. Below, we point out four issues.

1.3.1 The difference between local and global scales

The first issue is the difference between assessing the effect of making a change of technology or behaviour, for example on emissions, when markets are unaffected, and assessing the same effect when market responses are taken into account. Wei and Liu (2017) estimate the global costs and emission reductions by implementing a set of measures suggested by the International Energy Agency (IEA) in GRACE. They thereby take into account the market responses that follow from the shifts in costs and the resulting emission reductions reported by IEA. The study indicates that market responses lower IEAs estimate of reductions in energy use by 70%, and lower the estimate of related emission reductions by 90 % in 2040. The main reasons for this so-called rebound effect are labour movement across sectors, a change in labour supply, and substitution between energy and other goods.

Aaheim et al. (2016) also point at the differences in assessing consequences on a national scale and consequences for single people in a study of impacts of climate change on agriculture in Tanzania. The economic impacts on a national scale is measured based on how indicators in the national accounts represented in GRACE are affected, while most farmers in Tanzania consume most of what they produce, without economic transactions. The consequences therefore differ substantially. However, smallholders are also affected by the changes reflected in national economic indicators, which increases their vulnerability to climate change, and may cause qualitative shifts in the livelihood for some smallholders.

1.3.2 Sources of conflicts

The second general issue that can be addressed by GRACE is to reveal possible sources of conflicts in dealing with climate change. Studies have shown that challenges, which seem large when considering the disagreements between negotiating parties, may be small if the global responses are taken into account, and the time perspective is extended to include the long-run impacts of present emissions. In a study of alternative principles of burden sharing between parties, Underdal and Wei (2015) conclude that the choice of principle has small impacts on how the costs are allocated in the end, despite notable differences in how responsibilities and capabilities are emphasized. They do not find any dichotomy – such as that between ‘rich’ and ‘poor’, or ‘developing’ and ‘developed’ countries – that adequately captures the full range of variance on responsibility and capability indicators among countries.

Aaheim et al. (2017a) use GRACE to identify possible sources of conflicts in climate negotiations. They compare the economic development in world regions under low-emission (RCP4.5) and high-emission (RCP8.5) pathways. Conflicts do not arise primarily between ‘rich’ and ‘poor’ regions, but rather between sectors within regions. Nearly all sectors in all regions benefit from limiting global warming, instead of avoiding emission cuts, except fossil fuel extracting sectors. However, the benefits to the other sectors do not appear before the second half of this century after decades with costs from charges needed to keep emissions under control, which points at the severe conflicts between generations.

1.3.3 Consequences of unilateral actions

The third general issue is how countries can contribute to mitigate climate change without a global treaty. Glomsrød et al. (2016) examine the opportunities for China to cap CO_2 emissions by domestic policies to reduce poverty. Reduction in poverty implies higher domestic consumption and lower coal based exports, and reductions in emissions of both CO_2 and SO_2. Atmospheric modelling shows an immediate local warming effect due to the lower SO_2 emissions, but the cooling due to lower CO_2 emissions dominates in the long term. In addition to the global benefits for the climate, the Chinese economy also benefits by becoming less dependent on exports and investments as drivers of economic growth.

REDD+ allows countries to collaborate in mitigating drivers of climate change bilaterally by improving forest management. Aaheim et al. (2017b) address the potential difference between carbon uptake and costs to an Indian forest manager who engages in REDD+ and the impacts on global emissions and the economic impacts to India, which is the concern of countries investing in REDD+. By facilitating the forestry sector in GRACE for use of results from vegetation models, the study shows large differences between local, national and global impacts on both carbon uptake and on costs. This is due mainly to the responses in other Indian forests, where the increase in carbon uptake in the REDD+ forests are compensated by reduced uptake in other forests. They also find that the leakage to other countries is moderate.

Climate engineering gives a single country a possibility to bring global warming to an end with drastic, but feasible measures. Because of the related risks, it is considered more as a threat than an opportunity. Some of the risks arise because of other climatic changes than the controlled global temperature rise. Aaheim et al. (2015a) use GRACE to assess the economic consequences of these side effects, and show that the benefits of geoengineering are negative or negligible if compared with a control of emissions to keep global warming below 2.0 – 2.5 °C above pre-industrial time. The study also identifies a range of other risks related to climate engineering, including the effectiveness of alternative measures and non-climatic environmental impacts, but do not address these because of the lack of knowledge.

1.3.4 Identification of knowledge gaps

In general, the comprehensiveness of GRACE makes the model useful for identifying knowledge gaps in generalizing conclusions from more focused studies. Aaheim et al. (2015b) aim to integrate lessons from studies of the health effects of climate change and on impacts of climate change on tourism in GRACE to derive the socioeconomic consequences for the EU. The majority of studies on health effects address mortality under heat episodes, and most of the people who die are old. To analyse the socioeconomic consequences, one needs information primarily on other health effects, on how people in working age are affected, and the need for health care among all those affected. As most of this information is lacking, the study lists knowledge gaps to be filled to make reliable assessments of the socioeconomic consequences.

For tourism, the situation is slightly different. There are many relevant studies on impacts on specific tourist destinations in Europe, such as ski and beach resorts. These are clearly relevant for evaluations of socioeconomic consequences, but it is problematic to attach findings from these studies to national statistics, and thereby gain knowledge about impacts to the resorts represented in a national context, on which GRACE is based. A part of the problem is poor and contradictory statistical information on tourism. A second problem is a lack of information on the adaptive capacity within the tourism sector, which in some cases may switch their dependency from climate sensitive to climate insensitive tourism, or vice versa, without notable difficulties.

1.4 GRACE and other integrated assessment models

By aiming to provide a model for integrating results from studies of different aspects related to climate change, GRACE belongs to a category of models called integrated assessment models (IAM). Over the years, many IAMs have been developed, and it may be difficult for others than insiders to distinguish them. What reasons are there for developing a separate model like GRACE instead of using existing, and well-established models, which have been used extensively to combine knowledge from different disciplines, and provided comprehensively based information for practical purposes?

The simple answer is that what model to use depends on the question at hand. For the IAMs, it is necessary to distinguish three categories of models. One category couples models that describe different natural systems and select among technological options to estimate the impacts of chosen socioeconomic scenarios on drivers of climate change and impacts on natural systems. These are called detailed process IAMs (Weyant, 2017). These models are global, but partial in the sense that they focus on selected natural systems and sources of greenhouse gases. Those drivers of climate change not highlighted in the sub-models are amended and linked to general indicators, such as GDP. Three of the IAMs used to develop the Representative Concentration Pathways (van Vuuren et al. 2011), IMAGE (Stehfest et al., 2014), MiniCAM (Brenkert et al., 2003) and MESSAGE (Riahi et al., 2007) belong to this category.

A second category is benefit-cost IAMs, which are extensions of economic growth models. The primary aim of these models is to assess what should be paid at present to avoid damages from climate impacts in the future, or the social cost of carbon. The models deduct damage costs from GDP, which depend on future temperature increase, in different world regions. Emissions are generated by energy use and general economic activity in each region, and the increase in temperature is derived from accumulated emissions by a few equations. One of these models is DICE (Nordhaus and Boyer, 2000), which has been used in several studies and extended in different ways. Other well-known models are FUND (http://www.fund-model.org) and PAGE (Hope, 2006), which was used in the Stern Review (Stern, 2006).

Global CGE models comprise a third category of IAMs. As opposed to the other two IAM categories, they comprise all economic activities in the world. However, they do not recommend policies as the benefit-cost IAMs do, and the physical data used in the detailed process IAMs have to be translated to economic data to be integrated in CGEs. AIM (Matsumoto and Masui, 2010), the fourth model used in the development of RCPs, belongs to this category. The advantage of global CGE models is related to the combination of comprehensiveness and flexibility regarding the choice of scenarios, which makes it possible to derive the socioeconomic consequences of projections from climate models. This is not possible with the other two categories of IAMs. The detailed process IAMs integrate so-called simple climate models, which cover the main properties of global climate models and earth system models, but are far from the original models. These models also focus on a selection of topics of primary importance for emissions, while the impacts of climate change are covered rather weakly and somewhat arbitrarily. The benefit-cost IAMs also cover all the economies in the world, but the economies are represented mainly by GDP and the contributions from energy production. Climate change is modelled by means of a few equations, which provide only very rough indications of the increase in global mean temperature.

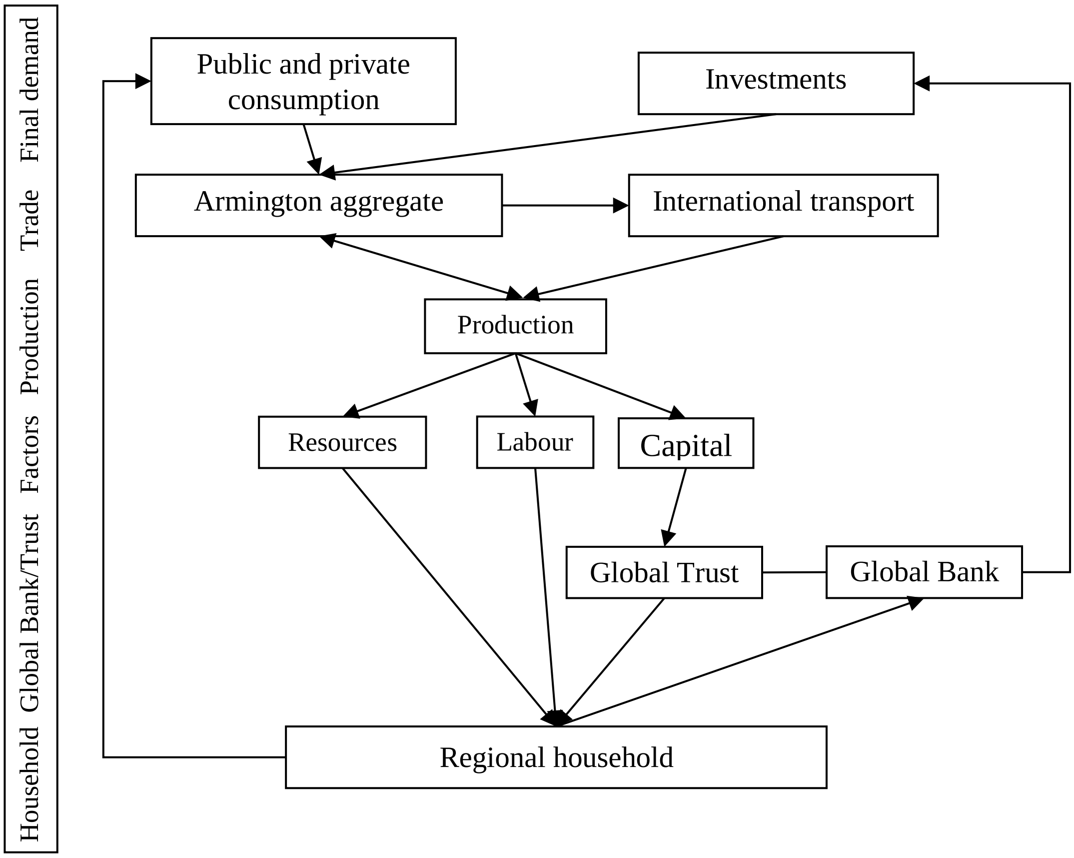
Turning back to the question on what model to choose, the global CGE models apply, in particular, when insights from physical research are evaluated in the light of the needs for the population, and when the influence of social and economic drivers play an essential role for communication of messages from the research. However, the comprehensive approach taken reveals the knowledge gaps behind the messages based on insights from the research to practitioners, and the apparent imperfections of the models show that the messages need to be interpreted with care. GRACE indicates how the relations between people and between people and nature matter to the challenges of climate change. This may be used to derive consequences of actions to limit global warming, and helps to identify knowledge gaps and suggest ways to fill them. Therefore, the model does not reflect the state of the underlying knowledge, but rather the ability to utilize this knowledge in evaluations of the global problems related to climate change.

2 Modelling structure

GRACE belongs to the MPSGE models (Rutherford, 2011), modelled in GAMS. This section presents the general structure of the model, and points out general properties of choices made in the basic version of GRACE. The choice of regions and sectors is flexible, and varies depending on the objective of the study in the applications of the model. This section provides an informative description of the model, before the algebraic description is given. Then follows a presentation of the modelling of the energy sector, which is used in some applications of the model. Modelling of climate impacts is presented in Section 3.

2.1 Informative description of the GRACE model

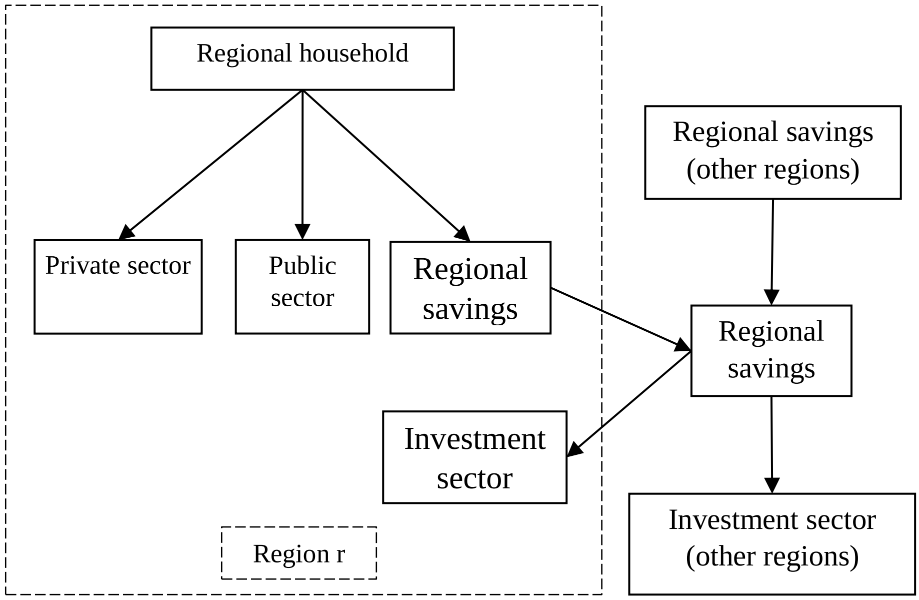
Figures 2.1 and 2.2 illustrate the circular flow of payments among the main components of the model, which explicitly depicts interactions between commodity and factor markets as well as interactions among regions. The Regional Household, which represents private households and government in each region, receives the payments from supplying primary factors. The income of the Regional Household is spent on private and public consumption, and savings.



Source: Aaheim and Rive (2005)

Figure 2.1. Flow of payments in the GRACE model

The Global Bank collects savings from all regions and then provides investments to regions so that the expected return to capital equalises among regions. The Global Trust collects the earnings from installed capital and distributes them among regions, given the assumption of perfect capital mobility. Firms use primary factors and intermediates to produce goods and services. Domestic and imported commodities build the so-called Armington aggregate, which is then distributed among private and public consumption and investments.



Source: based on Hertel (1997)

Figure 2.2. The Regional Household and the Global Bank

2.1.1 Production

Firms are assumed to supply goods and services to maximise their subject to production technologies in perfect competitive markets. Production technologies are described by nested separable constant elasticity of substitution (CES) functions (see below), and inputs are divided into primary input factors (i.e., labour, capital and resources) and intermediate inputs from each sector. Output and the use of all input factors are subject to taxation, reported in the database. Production of primary energy includes natural resources as a sector-specific production factor, with a fixed supply.

Two forms of the nested CES functions are adopted by the core version of the GRACE model. Figure 2.3 illustrates the structure of the functional forms for production of primary energy – crude oil, coal, and gas. The parameters starting with small letter "e" indicate the elasticities of substitution (the same for figures illustrating structures of nested functions below). At the top-level, output is described by a standard CES function of the value-added-intermediates aggregate and the natural resource. The substitution elasticity at the top-level as well as the value share of natural resource determine the price elasticity of supply of fossil fuels. In the basic version of the GRACE model, this substitution elasticity is set to 0.3. At the second level, the value-added-intermediates aggregate is depicted by a Leontief function (with no substitution) of intermediates and the value-added aggregate. The value-added aggregate is a standard CES function of capital and labour. The substitution elasticity between capital and labour is another important parameter, which determines technological flexibilities in production. The empirical literature typically rejects the hypothesis of a Cobb-Douglas function, where the substitution elasticity between capital and labour equals 1, and shows that the elasticity tends to be less than unity (Arrow et al., 1961). In the core version of the GRACE model, we assume a substitution elasticity of 0.3.

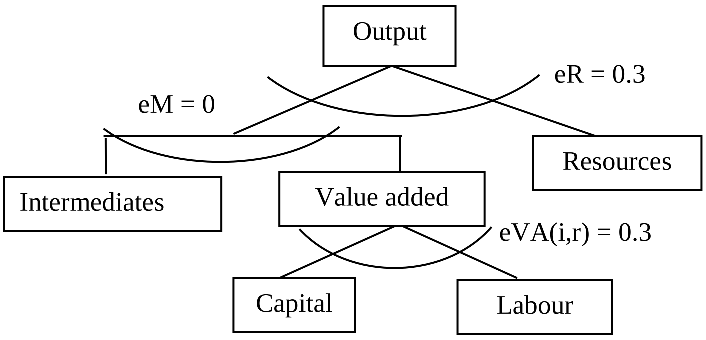


Figure 2.3. Production structure of primary energy goods

The other form of production functions illustrated in Figure 2.4 is for production of goods/services other than primary energy – crude oil, coal, and gas. Output is described assuming no substitution (Leontief function) between intermediates and the value-added-energy aggregate. At the second level, the value-added-energy aggregate is a standard CES function of the energy aggregate and the value-added aggregate, with a substitution elasticity of 0.5. The energy aggregate is formed from a CES function of electricity and non-electric energy inputs. The aggregate of non-electric energy inputs is depicted by a Cobb-Douglas function (elasticity of substitution = 1) of coal, crude oil, oil products, and natural gas. The elasticities of substitution at all nests are adopted from the MIT EPPA model (Paltsev et al., 2005).

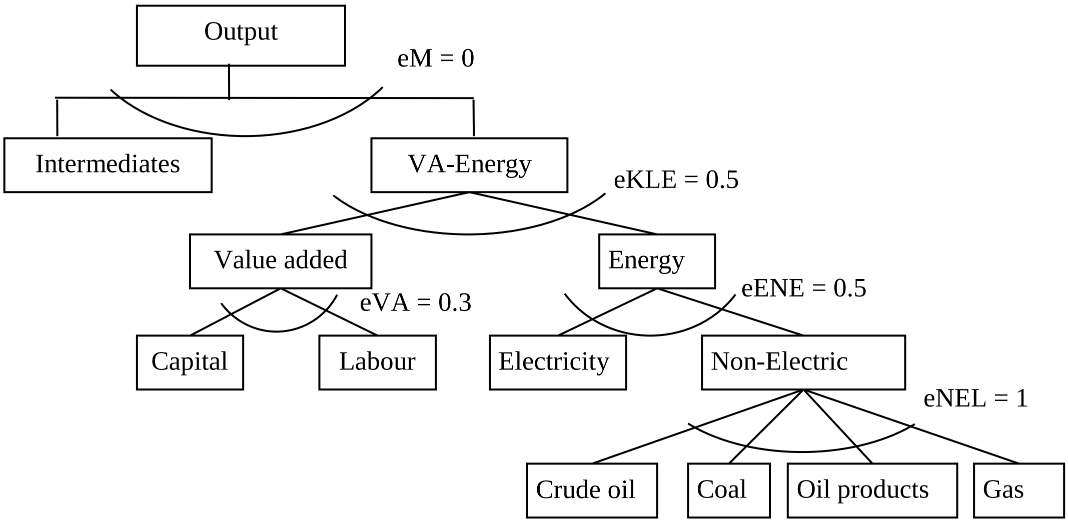


Figure 2.4. Production structure of goods/services other than agriculture and primary energy

In later studies that focus on the energy sector, we employ a more elaborated structure for the power generation sector. The calibration of the power generation sector is based on the GTAP9-Power database, which is an electricity-detailed extension of Version 9 of the GTAP database (Aguiar et al., 2016; Peters, 2016). The GTAP9-Power database depicts the global economy in 2011 and provides data on 140 regions and 68 commodities. In the GRACE model, the power generation sector is divided into the five sub-sectors gas-fired plants, coal-fired plants, nuclear power, hydropower and renewables (see Figure 2.5 and 2.6a, b).

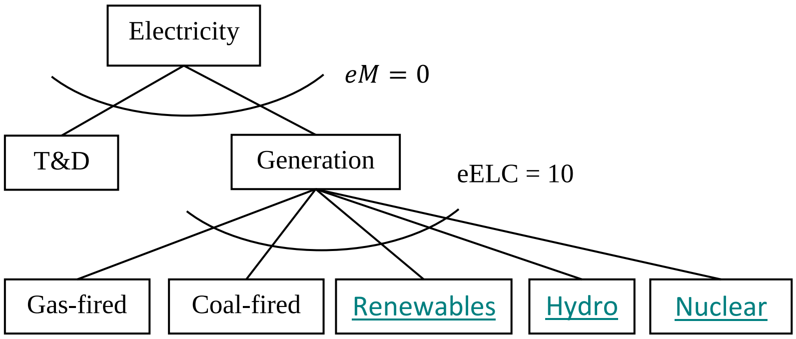


Figure 2.5. The power generation sector

The power generation sector consists of generation, and transmission and distribution (T&D). Transmission and distribution are represented by a service sector, which is consumed in a fixed proportion relative to power generation, as described by a Leontief function (Peters, 2016b). Following many other CGE-based studies (e.g., Peters, 2016b; Sue Wing, 2008; Wing, 2006), we assume imperfect substitutability among technologies to depict market inertias associated with switching from one technology to another. Hence, a stricter climate policy will lead to substitution towards less carbon intensive technologies, without ending up with corner solutions. The choice of elasticity is subject to a compromise between a high elasticity to reflect the homogeneity of the output, and a low elasticity to reflect the incompleteness in switches between technologies.

Following Paltsev et al. (2005), we incorporate a technology-specific factor on the supply side of power generation from renewables, nuclear power, and hydro power. This can be interpreted as a natural resource constraint. The specific factor is assumed substitutable with the value added, meaning that we calibrate the substitution elasticity to achieve an assumed price elasticity of supply. There are only a few empirical estimates of the price elasticity of the supply of renewable electricity generation. For example, Johnson (2011) estimated a value of 2.7 for the price elasticity pertaining to the supply of renewables in the USA. This value was used by Paltsev et al. (2005) and Rivers (2013). In our analysis, we use the same value for renewables, whereas for nuclear power and hydropower, we use a value of 1 for the price elasticity of supply.

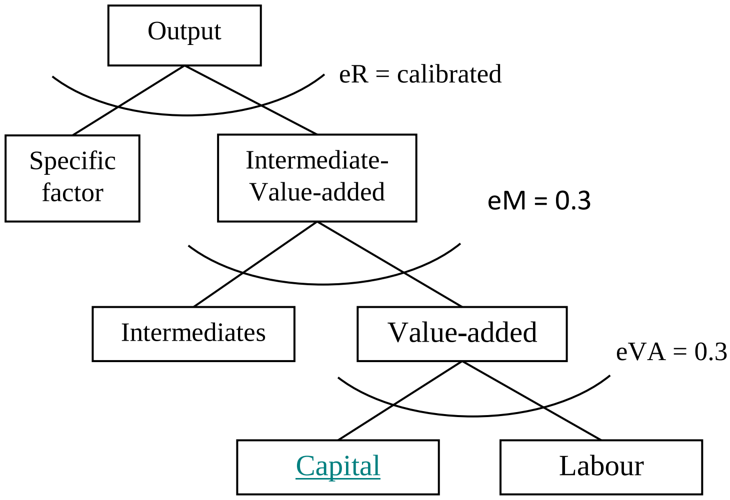


Figure 2.6a. Nesting structure of renewables, nuclear, and hydro power generation

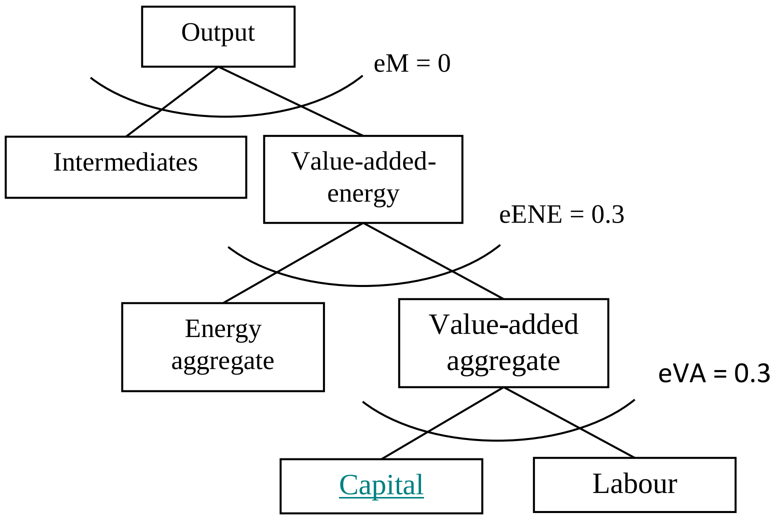


Figure 2.6b. Nesting structure of fossil fuel based power generation

2.1.2 Trade

Total domestic output is distributed between export and domestic markets. In the core version of the GRACE model, domestic and export supplies are treated as perfect substitutes in production. In contrast, imported and domestically produced commodities are assumed imperfect substitutes. Following the Armington approach (Armington, 1969), we use a CES function to depict imperfect substitutability between imports and domestically produced goods, so that domestic and imported goods comprise the so-called Armington aggregate. In a two-level Armington aggregate, the first level depicts substitution in imports between regions, and the second level describes substitution between imported and domestically produced commodities. The Armington elasticities of substitution are obtained from the MIT EPPA model (Paltsev et al., 2005). Furthermore, importing countries pay a price premium to the international transport sector. This price premium is determined by a fixed transport factor derived from the base year data. The supply of international transport services is depicted by a Cobb-Douglas aggregate of the service good from the individual regions. The Armington aggregate is then distributed between private, public, investment, and intermediate consumption.

2.1.3 Consumption

In the basic version of GRACE, private households and the government account in each region are depicted by a representative household, which receives factor payments (i.e., labour, capital, and resource income) and tax revenues and spends them on private and public consumption and savings. The composite of private and public consumption and savings is described by a Cobb-Douglas function. The nesting structure of the consumption composites is illustrated in Figure 2.7. Following the MIT EPPA model, each consumption composite is described by a standard CES function of the composite of energy and non-energy goods, with a substitution elasticity of 0.25. The composite of energy goods is also formed from a CES function of electricity, gas, oil products, and coal, with a substitution elasticity of 0.4. The composite of non-energy goods is also represented by a CES function, with a substitution elasticity of 0.4.

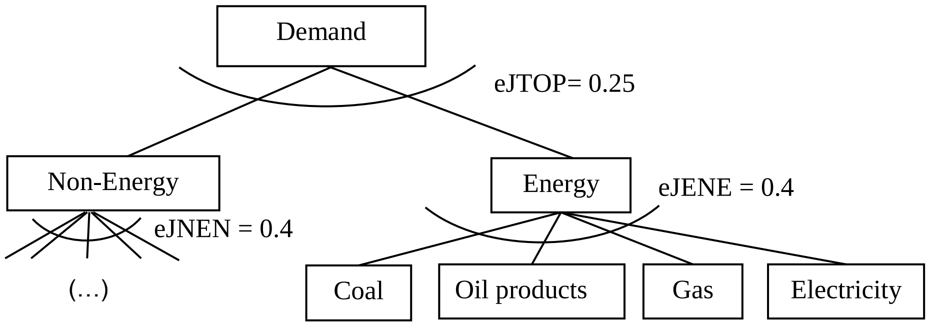


Figure 2.7. Structure of final demand

2.1.4 Emissions

The GRACE model is suitable for analysing different mitigation policies since it can depict many policy instruments, such as carbon taxes and emissions permits. The base year CO2 emissions are provided by the GTAP database. Emissions permits are modelled as fixed-factor inputs (i.e., via a Leontief function). The latest version of the model also includes non-CO2 GHG emissions, such as methane (CH4), nitrous oxide (N2O), fluorinated gases (FGAS), which are provided by the GTAP database.

2.1.5 Dynamics and calibration

Economic growth is driven by investments, population growth, technological change and the availability of natural resources. Labour force growth is exogenously determined in the model and calibrated based on some population projection (e.g., World Bank). In the reference scenario, the real Gross Domestic Product (GDP) is exogenous and calibrated based on some economic growth projection (e.g., World Bank or OECD) by making labour productivity endogenous, i.e., a labour-augmenting technical change. Alternatively, the economic growth in the reference scenario could be calibrated by making total factor productivity endogenous (i.e., labour and capital). In policy simulations, factor endowment is scaled by the calibrated parameters of factor productivity and real GDP is endogenously determined within the model. Following the MIT EPPA6 model (Chen et al., 2017), we assume an annual autonomous energy efficiency improvement of 1.0% for non-electric sectors and 0.3% for the electric sector.

The capital stock in each period is determined by the standard capital accumulation equation:

$$VKE_r = VKBZ_r(1 - dDEP_r) + INV_r \qquad \perp VKE_r$$

where VKE_r is the end of period capital stock in region *r*
$\overline{VKBZ_r}$ is the initial capital stock in region *r*
$\overline{dDEP_r}$ is the depreciation rate in region *r*
INV_r is investments in region *r*

The capital accumulation equation states that the capital stock in each period equals the capital stock in the previous period (net of depreciation) plus investments. Because we assume international capital mobility, investments in region *r* include also international capital inflows. To model international capital mobility, we follow the approach adopted in the GTAP-Dyn model (Ianchovichina and McDougall, 2000). More technically, we incorporate an artificial account called Global Bank, which collects all savings, and then distributes them among regions, so that the expected rates of return to capital are equalised among regions:

$$RORE_r = \sum_{rr} \frac{RORE_{rr}}{card_{rr}} \qquad \perp INV_r$$

$$RORE_r = -\left(\frac{VKE_r}{VKBZ_r} - KHAT_r\right) + 1 \qquad \perp RORE_r$$

where $RORE_r$ is net rates of growth in the expected rates of returns to capital
$card_r$ is the number of regions
$KHAT_r$ is the initial normal rate of growth in the rate of return to capital

Capital income in each region is collected by an artificial account called Global Trust and then distributed to regions at the global rate of return, so that the returns to capital are equalised among regions.

$$p^{CAP}\ GLOBTRUST = \sum_r p^F_{fcap,r}\ FTOT_{fcap,r} \qquad \perp p^{CAP}$$

where p^{CAP} is the global return to capital
$GLOBTRUST$ is the initial global capital stock
$p^F_{fcap,r}$ is the return to capital in region *r*
$FTOT_{cap,r}$ is the capital stock in region *r*

After each recursive solve of the model, savings and investments in the previous period update the savings shares in Global Trust and capital stocks in each region[1]:

$$SAVINGS_r = SAVINGS_r(1 - dDEP_r) + SAVr\_T_{r,sim,t}$$

$$GLOBTRUSTSHARE_r = \frac{SAVINGS_r}{\sum_{rr} SAVINGS_{rr}}$$

$$FTOT_{cap,r} = FTOT_{cap,r}\frac{VKE_r}{VKBZ_r}$$

$$VKBZ_r = VKE_r$$

where $SAVr\_T_{r,sim,t}$ is the savings in each region from the previous period
$SAVINGS_r$ is the regional cumulative savings in Global Trust
$GLOBTRUSTSHARE_r$ is the share of region *r* in global savings

2.2 Algebraic description of the GRACE model

Following Mathiesen (1985) and Rutherford (1995), economic equilibrium in the GRACE model is formulated as a Mixed Complementarity Problem (MCP) of inequalities and associated variables. The model is coded in the General Algebraic Modeling System (GAMS), using the Mathematical Programming System for General Equilibrium analysis (MPSGE) (Brooke et al., 1992; Rutherford, 2011), and is solved by using the PATH solver (Dirkse and Ferris, 1995). Production technologies as

[1] The following equations are not a part of the equation system in the model. These are a part of dynamic re-calibration of capital stocks.

well as consumption preferences are depicted, using Constant Elasticity of Substitution (CES) functions. The newest version of the model is calibrated around the GTAP9 database (Aguiar et al., 2016).

The GRACE model is formulated as a system of nonlinear inequalities, which correspond to three types of conditions for a general equilibrium: (1) zero profit, (2) market clearance, and (3) income balance. The former type determines activity levels, the latter determines price indexes, and the last one determines the income level, i.e., each variable is linked to an associated inequality. The complementarity between inequalities and corresponding variables is indicated by the operator ⊥. For example, zero profit conditions state that prices indexes (on LHS of inequalities) should be less than or equal to the corresponding unit cost functions (on the RHS of inequalities). Unit cost functions are derived from the “calibrated share form” of the CES functions (Rutherford, 2003). Differentiating the unit cost functions with respect to input prices gives compensated demand functions, i.e., by employing Shephard’s lemma. Those compensated demand functions are then used in market clearance conditions, which state that supply should be greater than or equal to demand. Below we provide the algebraic description of the core version of the GRACE model. The MPSGE package constructs zero profit, market clearing, and income balance conditions automatically in the “background”, which implies a strict focus on real economic transactions without disturbances from financial markets. It should be noted that the value-added aggregate ($VA_{i,r}$), the energy aggregate ($IEN_{i,r}$), and the welfare index (W_r) as well as the associated price indexes (i.e., $p_{i,r}^{VA}$, $p_{i,r}^{IEN}$,and p_r^W) do not explicitly appear in the GAMS/MPSGE code. Yet, we incorporated then in the algebraic description of the model for the sake of transparency.

Table 2.1 shows the file structure of the model. Table 2.2-2.8 explain the notations for sets, activity levels, price indexes, cost shares, substitution elasticities, tax rates, factor endowment, and other relevant parameters. The following pages present the equations.

Table 2.1. File structure of the GRACE model

Files	Description
core.gms	Upload all corresponding gams files.
GTAP_input_header.gms	Declares main sets and parameters for the data upload.
GTAP_input_main	Upload the dataset (GTAP) and declares sub-sets.
Zvalues_header.gms	Declares the initial values of parameters.
Zvalues_main.gms	Defines the initial values of parameters to calibrate the base year.
emissions.gms	Declares and defines initial parameters for GHG emissions.
scenarios_declare.gms	Declares policy simulations as well as declares and defines the parameters for factor productivities and energy efficiency.
scenarios_define.gms	Defines policy simulations.
elasticities.gms	Declares and defines substitution elasticities.
mpsge_all.gms	GAMS/MPSGE model code.
time_declare.gms	Declares the parameters to store the model output.
time_define.gms	Store the model output.
intertemporal.gms	Dynamic calibration of the model, i.e., update capital stocks, labour force, factor productivity, energy efficiency.
closure.gms	Declares and defines the model closures.

Table 2.2. Indices and sets

i (alias *ii*)	Set for all commodities
ipep	Sub-set for primary energy goods
efoss	Sub-set for fossil fuel based power generation, i.e., gas-fired, coal-fired, and oil-fired
Ielc	Sub-set for electricity
etech	Sub-set for power generation technologies
ie	Sub-set for energy inputs
ief	Sub-set for energy inputs except electricity
f (alias *ff*)	Set for primary factors
fnat	Sub-set for natural resources
fcap	Sub-set for capital
j (alias *jj*)	Set for consumption categories, i.e., private and public consumption, and investments
jinv	Sub-set for investment goods
r (alias *rr*)	Set for regions

Table 2.3. Activity levels

$XD_{i,r}$	Production of commodity i in region r
$VA_{i,r}$	Demand for the value-added aggregate in sector i in region r
$IFAF_{f,i,r}$	Demand for factor f in sector i in region r
$IEN_{i,r}$	Demand for the energy aggregate in sector i in region r
$IO\_ABS_{ii,i,r}$	Demand for intermediate good ii in sector i in region r
$FD\_ABS_{i,j,r}$	Demand for commodity i in region r
$X_{i,r}$	Armington aggregate of commodity i in region r
$IM_{i,r}$	Demand for imported commodity i in region r
$TRANS$	International transport services
$FD_{j,r}$	Domestic consumption in region r
W_r	Welfare level in region r
VKE_r	End of period capital stock in region r
INV_r	Investments in region r
$RORE_r$	Expected net rate of return to capital in region r

Table 2.4. Price indexes

$p_{i,r}^{XD}$	Producer price index for commodity i in region r
$p_{i,r}^{VA}$	Price index for the value-added aggregate in sector i in region r
$p_{i,r}^{IEN}$	Price index for the energy aggregate in sector i in region r
$p_{ii,i,r}^{IO}$	Price index of intermediate demand for commodity ii in sector i in region r
$p_{i,j,r}^{C}$	Price index for final consumption of commodity i in region r
$p_{f,i,r}^{FA}$	Price index for factor f in in sector i in region r
p^{CAP}	Price index for capital return under int'l capital mobility
$p_{i,r}^{X}$	Price index for Armington aggregate of commodity i in region r
$p_{i,r}^{IM}$	Price index of aggregate import of commodity i in region r
p^{TRNANS}	Price index for transport services
$p_{j,r}^{FD}$	Price index of final domestic consumption in region r
p^{I}	Price index of investments from global bank
p_{r}^{S}	Price index for savings in region r
p_{r}^{W}	Price welfare in region r
p_{r}^{CARB}	Carbon price in region r

Table 2.5. Cost and expenditure shares

$\theta_{i,r}^{RES}$	Cost share of natural resource in production of commodity i in region r
$\theta_{i,r}^{IO1}$	Cost share of intermediate aggregate in production of commodity i in region r
$\theta_{i,r}^{IO2}$	Cost share of intermediate aggregate in production of commodity i in region r
θ_{r}^{TD}	Cost share of transmission and distribution in power generation in region r
$\theta_{i,r}^{POW}$	Cost share of power generation technology i in total power generation in region r
$\theta_{ii,i,r}^{INT}$	Cost share of commodity ii in the intermediate aggregate in sector i in region r
$\theta_{i,r}^{VA}$	Cost share of value added in the value-added-energy aggregate in sector i in region r
$\theta_{f,i,r}^{F}$	Cost share of factor f in the value-added aggregate in sector i in region r
$\theta_{i,r}^{EL}$	Cost share of electricity in the energy aggregate in sector i in region r
$\theta_{i,r}^{A}$	Cost share of imported commodity i in the Armington aggregate in region r
$\theta_{i,rr,r}^{IMP}$	Cost share of imported commodity i from region rr in the aggregate of imports in region r
$\theta_{i,rr,r}^{TRN}$	Cost share of transport margin in export of commodity i from region rr to region r
$\theta_{i,r}^{ITRN}$	Cost share of international transport provided by sector i from region r
$\theta_{j,r}^{JEN}$	Cost share of the energy aggregate in final consumption in region r
$\theta_{i,j,r}^{EN}$	Cost share of commodity i in the energy aggregate of final consumption in region r
$\theta_{i,j,r}^{NEN}$	Cost share of commodity i in the non-energy aggregate in final consumption in region r
$\theta_{i,r}^{NEL}$	Cost share of energy input i in the non-electricity aggregate in sector i in region r
$\theta_{ii,i,r}^{IEN2}$	Cost share of energy input ii in the energy aggregate of power generation technology i in region r

$iocint_{ii,i,r}$	CO2 intensity from usage of fossil fuel ii I in sector i in region r
$fdcint_{i,j,r}$	CO2 intensity from usage of fossil fuel i in final consumption j in region r
$\theta^{W}_{j,r}$	Cost share of final consumption of j in region r

Table 2.6. Substitution elasticities

$\sigma^{eR}_{i,r}$	Substitution elasticity between the natural resource and the value-added-intermediate aggregate in sector i in region r
$\sigma^{eKLE}_{i,r}$	Substitution elasticity between the value-added aggregate and energy aggregate in sector i in region r
$\sigma^{eVA}_{i,r}$	Substitution elasticity among primary factor in sector i in region r
$\sigma^{eENE}_{i,r}$	Substitution elasticity between electricity and other energy inputs in sector i in region r
$\sigma^{eARM}_{i,r}$	Substitution elasticity between domestic and import commodity i in region r
$\sigma^{eIMP}_{i,r}$	Substitution elasticity among region rr in supplying commodity i
$\sigma^{eJENE}_{j,r}$	Substitution elasticity among energy goods in final consumption in region r
$\sigma^{eJNEN}_{j,r}$	Substitution elasticity among non-energy goods in final consumption in region r
$\sigma^{eJTOP}_{j,r}$	Substitution elasticity between energy and non-energy aggregates in final consumption in region r

Table 2.7. Tax rates

$ty_{i,r}$	Output tax rates in sector i in region r
$ti_{ii,i,r}$	Intermediate input tax rates on commodity ii in sector i in region r
$tf_{f,i,r}$	Factor use tax rates on factor f in sector I in region r
$tfd_{i,j,r}$	Tax rates on final consumption of commodity i in region r
$tx_{i,r,rr}$	Export tax rates on commodity i from region r to regions rr
$tm_{i,rr,r}$	Import tariffs on commodity i from region rr to region r

Table 2.8. Factor endowment, incomes, and parameters

$\overline{FTOT_{f,r}}$	Initial endowment of factor f in region
$\overline{IFZ_{f,i,r}}$	Initial endowment of factor natural resources in region r
$\overline{GLOBTRUST}$	Global trust
$\overline{TRNZ_{j,r}}$	Initial public and private income in region r
$\overline{INVZ_{r}}$	Initial investments to region r
$\overline{SAVZ_{r}}$	Initial regional savings in region r
$\overline{VKBZ_{r}}$	Initial capital stock in region r
$\overline{dDEP_{r}}$	Depreciation rate in region r
$\overline{card_{rr}}$	Number of regions
$\overline{KHAT_{r}}$	Initial normal rate of growth in the rate of return to capital in region r
$EMSTOT_{r}$	CO2 emissions

Zero profit conditions:

Production of primary energy goods: $\forall\ i \in (ipep \cup efoss)$

$$p_{i,r}^{XD}\left(1 - ty_{i,r}\right) \leq \left[\theta_{i,r}^{RES} p_{res,i,r}^{FA\left(1-\sigma_{i,r}^{eR}\right)} + \left(1 - \theta_{i,r}^{RES}\right)\left[\theta_{i,r}^{IO1}\left[\sum_{ii} \theta_{ii,i,r}^{INT} p_{ii,i,r}^{IO}\left(1 + ti_{ii,i,r}\right)\right] + \left(1 - \theta_{i,r}^{IO1}\right) p_{i,r}^{VA}\right]^{\left(1-\sigma_{i,r}^{eR}\right)}\right]^{\frac{1}{\left(1-\sigma_{i,r}^{eR}\right)}} \quad \perp XD_{i,r}$$

Production of goods and services except primary energy goods: $\forall\ i \notin (ipep \cup efoss)$

$$p_{i,r}^{XD}\left(1 - ty_{i,r}\right) \leq \left[\theta_{i,r}^{IO2}\left[\sum_{ii \notin ie} \theta_{ii,i,r}^{INT} p_{ii,i,r}^{IO}\left(1 + ti_{ii,i,r}\right)\right] + \left(1 - \theta_{i,r}^{IO2}\right)\left[\theta_{i,r}^{VA} p_{i,r}^{VA\left(1-\sigma_{i,r}^{eKLE}\right)} + \left(1 - \theta_{i,r}^{VA}\right) p_{i,r}^{IEN\left(1-\sigma_{i,r}^{eKLE}\right)}\right]^{\frac{1}{\left(1-\sigma_{i,r}^{eKLE}\right)}}\right] \quad \perp XD_{i,r}$$

Output from the power generation sector: $\forall\ i \in ielc$

$$p_{i,r}^{XD} \leq \left[\theta_r^{TD} p_{TnD,r}^{XD} + \left(1 - \theta_r^{TD}\right)\left[\sum_{i \in etech} \theta_{i,r}^{POW} p_{i,r}^{XD\left(1-\sigma_{i,r}^{ePOW}\right)}\right]^{\frac{1}{\left(1-\sigma_{i,r}^{ePOW}\right)}}\right] \quad \perp XD_{i,r}$$

Value-added aggregate:

$$p_{i,r}^{VA} \leq \left[\sum_f \theta_{f,i,r}^{F} p_{f,i,r}^{FA\left(1-\sigma_{i,r}^{eVA}\right)}\left(1 + tf_{f,i,r}\right)\right]^{\frac{1}{\left(1-\sigma_{i,r}^{eVA}\right)}} \quad \perp VA_{i,r}$$

Capital and labour: $\forall\ f \notin fnat$

$$p_{f,i,r}^{FA} \leq p_{f,r}^{F} \quad \perp IFAF_{f,i,r}$$

Energy aggregate: $\forall\ i \notin (ipep \cup efoss)$

$$p_{i,r}^{IEN} \leq \left[\theta_{i,r}^{EL} p_{elc,i,r}^{IO\left(1-\sigma_{i,r}^{eENE}\right)} + \left(1 - \theta_{i,r}^{EL}\right)\left[\prod_{ii \in ief} p_{ii,i,r}^{IO\ \theta_{i,r}^{NEL}}\right]^{\left(1-\sigma_{i,r}^{eENE}\right)}\right]^{\frac{1}{\left(1-\sigma_{i,r}^{eENE}\right)}} \quad \perp IEN_{i,r}$$

- Energy aggregate in fossil fuel based power generation: $\forall\, i \in efoss$

$$p_{i,r}^{IEN} \leq \sum_{ii \in ie} \theta_{ii,i,r}^{IEN2} p_{ii,i,r}^{IO} \qquad \perp IEN_{i,r}$$

- Intermediates goods:

$$p_{ii,i,r}^{IO} \leq \left[p_{i,r}^{X} + iocint_{ii,i,r} p_r^{CARB}\right] \qquad \perp IO\_ABS_{ii,i,r}$$

- Consumption goods:

$$p_{i,j,r}^{C} \leq \left[p_{i,r}^{X} + fdcint_{i,j,r} p_r^{CARB}\right] \qquad \perp FD\_ABS_{i,j,r}$$

- Armington aggregate:

$$p_{i,r}^{X} \leq \left[\theta_{i,r}^{A} p_{i,r}^{IM^{\left(1-\sigma_{i,r}^{eARM}\right)}} + \left(1-\theta_{i,r}^{A}\right) p_{i,r}^{XD^{\left(1-\sigma_{i,r}^{eARM}\right)}}\right]^{\frac{1}{\left(1-\sigma_{i,r}^{eARM}\right)}} \qquad \perp X_{i,r}$$

- Import aggregate:

$$p_{i,r}^{IM} \leq \left[\sum_{rr} \theta_{i,rr,r}^{IMP} \left(\theta_{i,rr,r}^{TRN} p^{TRNANS} + \left(1-\theta_{i,rr,r}^{TRN}\right) p_{i,rr}^{XD}\right)^{\left(1-\sigma_{i,r}^{eIMP}\right)} \left(1+tx_{i,rr,r}\right)\left(tm_{i,rr,r}\left(1+tx_{i,rr,r}\right)\right)\right]^{\frac{1}{\left(1-\sigma_{i,r}^{eIMP}\right)}} \qquad \perp IM_{i,r}$$

- International transport:

$$p^{TRANS} \leq \prod_i p_{i,r}^{XD^{\theta_{i,r}^{ITRN}}} \qquad \perp TRANS$$

- Consumption aggregate:

$$p_{j,r}^{FD} \leq \left[\theta_{j,r}^{JEN} \left[\sum_{i \in ie} \theta_{i,j,r}^{EN} p_{i,j,r}^{C^{\left(1-\sigma_{j,r}^{eJENE}\right)}} \left(1+tfd_{i,j,r}\right)\right]^{\frac{\left(1-\sigma_{j,r}^{eJTOP}\right)}{\left(1-\sigma_{j,r}^{eJENE}\right)}} + \left(1-\theta_{j,r}^{JEN}\right)\left[\sum_{i \notin ie} \theta_{i,j,r}^{NEN} p_{i,j,r}^{C^{\left(1-\sigma_{j,r}^{eJNEN}\right)}} \left(1+tfd_{i,j,r}\right)\right]^{\frac{\left(1-\sigma_{j,r}^{eJTOP}\right)}{\left(1-\sigma_{j,r}^{eJNEN}\right)}}\right]^{\frac{1}{\left(1-\sigma_{j,r}^{eJTOP}\right)}} \qquad \perp FD_{j,r}$$

- Welfare aggregate:

$$p_r^W \leq \prod_{j \notin jinv} p_{j,r}^{T\ \theta_{j,r}^W} p_r^{S\ \theta_{jinv,r}^W} \qquad \perp W_r$$

Market clearance conditions:

- Value-added aggregate:

$$VA_{i,r} \geq \frac{\partial p_{i,r}^{XD}}{\partial p_{i,r}^{VA}} XD_{i,r} \qquad \perp p_{i,r}^{VA}$$

- Capital and labour: $\forall\ f \notin fnat$

$$IFAF_{f,i,r} \geq \frac{\partial p_{i,r}^{XD}}{\partial p_{f,i,r}^{FA}} XD_{i,r} \qquad \perp p_{f,i,r}^{FA}$$

- Energy aggregate: $\forall\ i \in ie$

$$IEN_{i,r} \geq \frac{\partial p_{i,r}^{XD}}{\partial p_{i,r}^{IEN}} XD_{i,r} \qquad \perp p_{i,r}^{IEN}$$

- Intermediates goods:

$$IO\_ABS_{ii,i,r} \geq \frac{\partial p_{i,r}^{XD}}{\partial p_{ii,i,r}^{IO}} XD_{i,r} \qquad \perp p_{ii,i,r}^{IO}$$

- Consumption goods:

$$FD\_ABS_{i,j,r} \geq \frac{\partial p_{j,r}^{FD}}{\partial p_{i,j,r}^{C}} FD_{j,r} \qquad \perp p_{i,j,r}^{C}$$

- International transport:

$$TRANS \geq \frac{\partial p_{i,r}^{IM}}{\partial p^{TRANS}} IM_{i,r} \qquad \perp p^{TRANS}$$

- Armington aggregate:

$$X_{i,r} \geq \sum_{ii} \frac{\partial p_{ii,r}^{XD}}{\partial p_{i,ii,r}^{IO}} XD_{ii,r} + \sum_j \frac{\partial p_{j,r}^{FD}}{\partial p_{i,j,r}^{C}} FD_{j,r} \qquad \perp p_{i,r}^{X}$$

- Consumption aggregate: $\forall\, j \notin jinv$

$$FD_{j,r} \geq \frac{\partial p_r^W}{\partial p_{j,r}^T} W_r \qquad \perp p_{j,r}^{T}$$

- Consumption aggregate: $\forall\, j \in jinv$

$$FD_{j,r} \geq \frac{\partial p_r^W}{\partial p_r^S} W_r \qquad \perp p_r^{S}$$

- Primary factors (i.e., labour, capital, and resources):

$$\overline{FTOT_{f,r}} \geq \sum_i \frac{\partial p_{i,r}^{XD}}{\partial p_{f,i,r}^{FA}} XD_{i,r} \qquad \perp pfa_{f,i,r}$$

- CO2 emissions:

$$\overline{EMSTOT_r} \geq \sum_{ii,i} \frac{\partial p_{ii,i,r}^{IO}}{\partial p_r^{CARB}} IO_{ABS_{ii,i,r}} + \sum_{i,j} \frac{\partial p_{i,j,r}^{FD}}{\partial p_r^{CARB}} FD\_ABS_{i,j,r} \qquad \perp p_r^{CARB}$$

Income balance conditions:

- Regional income:

$$p_r^W W_r = \sum_{f \in flab} \overline{FTOT_{f,r}} p_{f,r}^F + p^{CAP}\overline{GLOBTRUST}\;\overline{GLOBTRUSTSHARE_r} + \sum_i \overline{IFZ_{fnat,i,r}} p_{fnat,i,r}^{FA} + \sum_{f,i} ty_{i,r} p_{i,r}^{XD} XD_{i,r} + \sum_{f,i} tf_{f,i,r} p_{f,i,r}^{FA} \frac{\partial p_{i,r}^{XD}}{\partial p_{i,f,r}^{FA}} XD_{i,r} + \sum_{ii,i} ti_{ii,i,r} p_{ii,i,r}^{IO} \frac{\partial p_{i,r}^{XD}}{\partial p_{ii,i,r}^{IO}} XD_{i,r} + \sum_{i,j} tfd_{i,j,r} p_{i,j,r}^{C} \frac{\partial p_{j,r}^{FD}}{\partial p_{i,j,r}^{C}} FD_{j,r} + \sum_{i,rr} tx_{i,r,rr} p_{i,r}^{XD} XD_{i,r} + \sum_{i,rr} tm_{i,rr,r}(1 + tx_{i,rr,r}) p_{i,rr}^{XD} XD_{i,rr} + p_r^{CARB}\overline{EMSTOTZ_r}$$

$$\perp p_r^W$$

- Global trust: $\forall\, f \in fcap$

$$\sum_r p^F_{f,r}\overline{FTOT_{f,r}} = p^{CAP}\overline{GLOBTRUST} \qquad \perp p^{CAP}$$

- Final demand: $\forall\, j \notin jinv$

$$p^{FD}_{j,r}FD_{j,r} = p^T_{j,r}\overline{TRNZ_{j,r}} \qquad \perp p^{FD}_{j,r}$$

- Final demand: $\forall\, j \in jinv$

$$p^{FD}_{j,r}FD_{j,r} = p^I\overline{INVZ_r}\, INV_r \qquad \perp p^{FD}_{j,r}$$

- Global bank:

$$p^S_r\overline{SAVZ_r} = p^I_r \sum_{rr}\overline{INVZ_{rr}} \qquad \perp p^I_r$$

- Capital accumulation:

$$VKE_r = \overline{VKBZ_r}\left(1 - \overline{dDEP_r}\right) + INV_r \qquad \perp VKE_r$$

- Investments:

$$RORE_r = \sum_{rr}\frac{RORE_{rr}}{\overline{\overline{card_{rr}}}} \qquad \perp INV_r$$

- Expected rates of return to capital:

$$RORE_r = -\left(\frac{VKE_r}{\overline{\overline{VKBZ_r}}} - \overline{KHAT_r}\right) + 1 \qquad \perp RORE_r$$

- CO2 emissions:

$$EMSTOT_r = \sum_{ii,i} IO\_ABS_{ii,i,r}\ iocint_{ii,i,r} + \sum_{i,j} FD\_ABS_{i,j,r}\ fdcint_{i,j,r} \qquad \perp EMSTOT_r$$

3 The impacts of climate change

GRACE includes impacts of climate change by replacing selected variables that one expects will be affected by climate change in the model with functions. These variables are indicated by the blue boxes in Figure 1.1 in Section 1. Changes in annual mean temperature (dC) and annual precipitation (dT) are calibrated to the observation in the base year, when $dC = dT = 0$. The resulting impact applies to the input from a specific sector to another sector or to consumption. The impacts then express the quantities of aggregates, but they are often based on assessments of physical quantities, and refer explicitly to the physical units, dC and dT. To see what information the impact functions relate to, one needs a transparent explanation of what is measured by the aggregates.

Economic aggregates are meant to express quantities, but there is no way to establish an exact relationship between physical quantities and the quantity of an aggregate, or volume, used in economic models. Below, we explain in detail how the volumes of aggregates are interpreted and how they are affected by climate change in GRACE. This is necessary to see what is expressed by the impact functions, and how to interpret and use results from other studies of climate impacts. Section 3.2 presents the impact functions in the basic version of GRACE.

3.1 The impacts on the volume of an aggregate

Production and welfare functions in GRACE, discussed in Section 2, reflect how a given level of sector output or a given level of welfare can be sustained by substituting the use of one sector product with another sector product. Sector products are in most cases aggregates of a broad range of goods and services, which are unknown to the modeller, and may differ a lot from country to country. The rates of substitution are nevertheless essential for the outcome of the model, but they will change depending on the choice of sectors and regions. Therefore, the choice of rates in a given study can seldom be based on observations, which is why the output of the modelling must be interpreted with care. This underlines the need to keep the purpose of the modelling in mind. It is not to derive implications of a set of known relationships between physical quantities, which models based on natural sciences and technologies do. The aim is rather to help us see what our understanding of economic behaviour and relations between economic agents implies for an evaluation of the drivers of climate change. How to implement estimates of impacts of climate change in the model therefore depends on how the insights affect the aggregates.

The aggregates can be described as convolutions of individual production and consumption opportunities. To illustrate, let each of the two light green curves in Figure 3.1, A (solid) and B (scattered), represent the possibilities for substitution between the use of land and the use of other input in the production of a given composite of crops and livestock under two price regimes. The minimum cost of producing one fixed composite of crops and livelihood represented by curve A is at the point where the relative price between land and other input equals the ratio between the inputs of the two factors. If prices implies that one less unit of land allows producers to buy as many units of other input as indicated by the dotted line in the figure, costs are minimized at point 1.

If the price of land increases, a steeper price line will apply. To sustain the composite of crops and livestock, curve A shows that the agricultural sector will then have to increase the amount of other input quite a lot in order to produce the same amount on slightly less land. However, the agricultural sector can produce the same quantity by changing the composite of crops and livestock. If the price of land increases, it may be less costly to produce more livestock and less crops. Let curve B represent the possibilities of substitution under a new composite. Then, the agricultural sector responds to a higher price of land by changing both input of land and other inputs and by changing the composite of their output. The possibilities for substitution in agriculture can be found as a convolution of substitution possibilities for different composites of crops and livestock, shown by the thick green curve. Cost minimization for the sector thereby gives a composite of input in point 2.

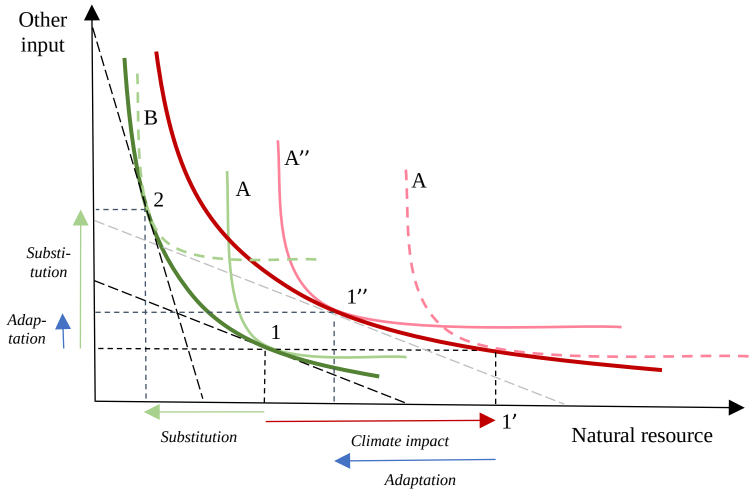


Figure 3.1. Substitution possibilities and convolutions of sub-sectors to sector aggregates

Climate change affects the productivity of land in GRACE. A reduction of this productivity by for example 50 percent would mean that for each input of other goods, one needs twice as much land as initially to sustain the level of production. This is shown by a shift from the green curve for the convolution of substitution possibilities to red curve in Figure 3.1. Then, the immediate impact is a shift from point 1 to point 1', meaning that the agricultural sector produces the same composite of crops and livestock with the same amount of other input, but with twice as much land. If the prices are unaffected, however, the agricultural sector may produce the same volume with lower costs by changing composite of crops and livestock from the curve represented by A' to A'', and use less land and more other input, as in point 1''.

The model thereby takes care of adaptation to climate change within a sector, related both to the use of input factors and to the change of composite within the sector output. This means that the impact functions should reflect impacts of climate change without adaptation. This is advantageous in the sense that it enables integration of results from assessments of physical impacts, and that attention to adaptation, which depends heavily on the perspective taken in each study, is entirely subject to the behaviour described by the model.

On the other hand, it is necessary to keep the general approach taken in GRACE in mind. The quantities are abstract measures, and production possibilities as well as technology options refer to general descriptions with limited empirical basis. For example, the impact functions do not affect the curves that describe the input possibilities to one given composite of output in Figure 3.1. Many adaptation options and impacts may thereby get lost by the impact functions even if they refer to exact physical assessments. This implies that the basic version of the model applies primarily to show how evaluations of the global impacts of climate change are affected by interactions between economic sectors within regions and between regions, but based on a general description of relationships between physical quantities and economic decisions. These interactions play a central role also for evaluations of impacts within sectors and in specific countries, however. For these purposes, GRACE can be expanded by replacing variables with sub-models, or one may focus on specific countries. Section 4 gives some examples.

3.2 Calibration

There is a large body of research estimating the impacts of climate change, and the number of studies is increasing rapidly. The scope of the studies differs substantially. Some studies focus on apparent effects from observations of transparent climatic events, such as mortality under heat waves, while others aim at general assessments, such as the impacts of future sea-level rise on the gross domestic product in a country or a region. All the studies contribute to our understanding of how climate change will matter in the future, and the more insights from the studies that can be represented in GRACE, the better.

Use of results from other assessments to calibrate the impact functions in GRACE requires that the definition of impacts in the other studies matches the definition of impacts in GRACE. Alternatively, it should be possible to make a transparent transformation from the results of other studies to an adequate input in GRACE. From the outset, this limits the usefulness of other studies of impacts of climate change considerably, while at the same time pointing at weaknesses in how impacts of climate change are represented in the model.

Many of the weaknesses are implicit in the criticism of impact functions applied in the integrated assessment models that aim at estimating the social cost of carbon, which is summarized in Diaz and Moore (2017). Not all the issues listed as problematic apply, because some of the criticism refers to a rather clear idea of what the impact functions ought to reflect, but without an equally clear reference to what is modelled. Therefore, some of the issues apply to the models rather than to the calibration of impacts. However, the problems in utilizing quantifications from other studies commented on above apply both for this category of integrated assessment models and for the way impacts are implemented in GRACE. This limits the number of available studies, and makes it challenging to update impact functions with new insights from physical assessments. Moreover, descriptions of how impact estimates are connected to climate projections are in most cases general, and related to changes in annual mean temperature and annual precipitation, only. Finally, the calibration of impact functions in the basic version of GRACE uses results from a relatively few assessments of the impacts at different temperatures on GDP in world regions.

Impact on	Affects	Relationship to climate indicators
Prod. of and in agriculture	Natural resources in agriculture	Function 3.1
Prod. of land in forestry	Natural resources in forestry	Function 3.1
Fish stock	Natural resource in fish stock	Function 3.1
Water cooling and run-off	Natural resources in thermal power	Function 3.1
Run-off	Natural resources in hydro power	Function 3.1
Energy demand	Energy demand in services and consumption	Temperature elasticities
Tourism	Final demand for transport and services	Function 3.1
Extreme events	Real capital in all sectors	Function 3.1
Sea-level rise	Real capital in all sectors	Function 3.1
Health	Labour in all sectors	Function 3.1

Table 3.1. An overview of the impacts relationships

The impacts of climate change are divided into nine impacts in GRACE, listed in Table 3.1. With the exception of impacts on energy demand, which is based on temperature elasticities, and sea-level rise, climate change affect selected variables according to a 2^{nd} order polynomial on the general form

$$dX = \alpha dT^2 + \beta dT + \gamma dP \quad (3.1)$$

Here, dX is the rate of change in the respective variable, dT is the degrees Celsius change in mean temperature, and dP is the rate of change in precipitation, and α, β, and γ are calibrated parameters.

The changes in dT and dP are taken from climate projections from the same emission pathway as the socioeconomic pathway on which GRACE is run. dX refers to the impact on the use of a sector variable in one region over a year. Therefore, dT and dP also refer to the annual changes in temperature and precipitation of relevance for this variable over the year within the region. The regional and the temporal resolutions in climate projections are much higher than in GRACE. An alternative to using annual averages of the climate indicators over the respective regions from the climate projections, one may use weighted averages based on information on how the economic activity is distributed within the region, and possibly over the year. In most applications, the climate indicators for the productivity of land in agriculture is weighted by the area of agricultural land, and for productivity of land in forestry by the area of forested land. For all other impacts, climate indicators are weighted by population density.

The parameters are in most cases calibrated from assessments of impacts on GDP in world regions from a few studies. Updating parameters is a continuous process, however, and which to choose depends on the focus and the choice of regions in each study. To point out some of the challenges related to the calibration, the current impact functions in the basic version of the model is presented below. Here, the world is divided into 11 regions and the economy of each region consists of 15 sectors, listed in Table 3.2.

<table>
<tr><th rowspan="2">Sectors</th><th colspan="3">Regions</th></tr>
<tr><th>Name</th><th>Abbr.</th><th>Comprises</th></tr>
<tr><td rowspan="11">Agriculture
Forestry
Fisheries
Crude oil
Coal
Refined oil
Electricity
Gas
Iron and steel
Non-metallic minerals
Other manufacturing
Air transport
Sea transport
Other transport
Services</td><td>Western Europe</td><td>WEU</td><td>EU15, Nordic, Iberia and Greece</td></tr>
<tr><td>Central and Eastern Europe</td><td>CEE</td><td>Sovereign countries of the former Warsaw pact plus Baltic states and former Jugoslavia</td></tr>
<tr><td>Former Soviet Union</td><td>FSU</td><td>Other former Soviet states</td></tr>
<tr><td>Middle East & North Africa</td><td>MEA</td><td>Mediterranian Africa, and countries in the triangle Turkey – Saudi Aarabia – Iran</td></tr>
<tr><td>Sub-Saharan Africa</td><td>AFR</td><td>States in Sahara and southern Africa</td></tr>
<tr><td>South Asia</td><td>SAS</td><td>Afghanistan, Pakistan, India, Nepal, Bangladesh, Nepal, Maldives, Bhutan</td></tr>
<tr><td>East Asia</td><td>EAS</td><td>China, Mongolia, North Korea</td></tr>
<tr><td>Other Pacific Asia</td><td>PAS</td><td>Asian peninsula and island states</td></tr>
<tr><td>Pacific OECD</td><td>PAO</td><td>Japan, South Korea, Australia, New Zealand</td></tr>
<tr><td>North America</td><td>NAM</td><td>USA and Canada</td></tr>
<tr><td>Latin America</td><td>LAM</td><td>Carribbean, Mexico and further south</td></tr>
</table>

Table 3.2 Sectors and regions

The calibration of the impact functions (3.1) refer to assessments in different studies. Most of the aim at estimating impacts of climate change for use in the benefit-cost IAMs. Here, we use assessments underlying different benefit-cost IAMs, including Mendelssohn et al. (2000), Nordhaus and Boyer (2000), Tol (2002) and the World Bank (2004). Using different assessments reveals challenges related to the comparisons. The studies refer either to a change in mean temperature or to the concentrations of greenhouse gases in the atmosphere. It is unclear what impacts changes in precipitation have, but we interpret them as if changes in temperatures or in concentrations are implicit in the temperature change. The different studies also divide the world into different regions, and the number of regions is less than ten in most of the studies. Therefore, the impacts in a specific region in GRACE is an average of estimated impacts in regions considered representative for that region in other studies.

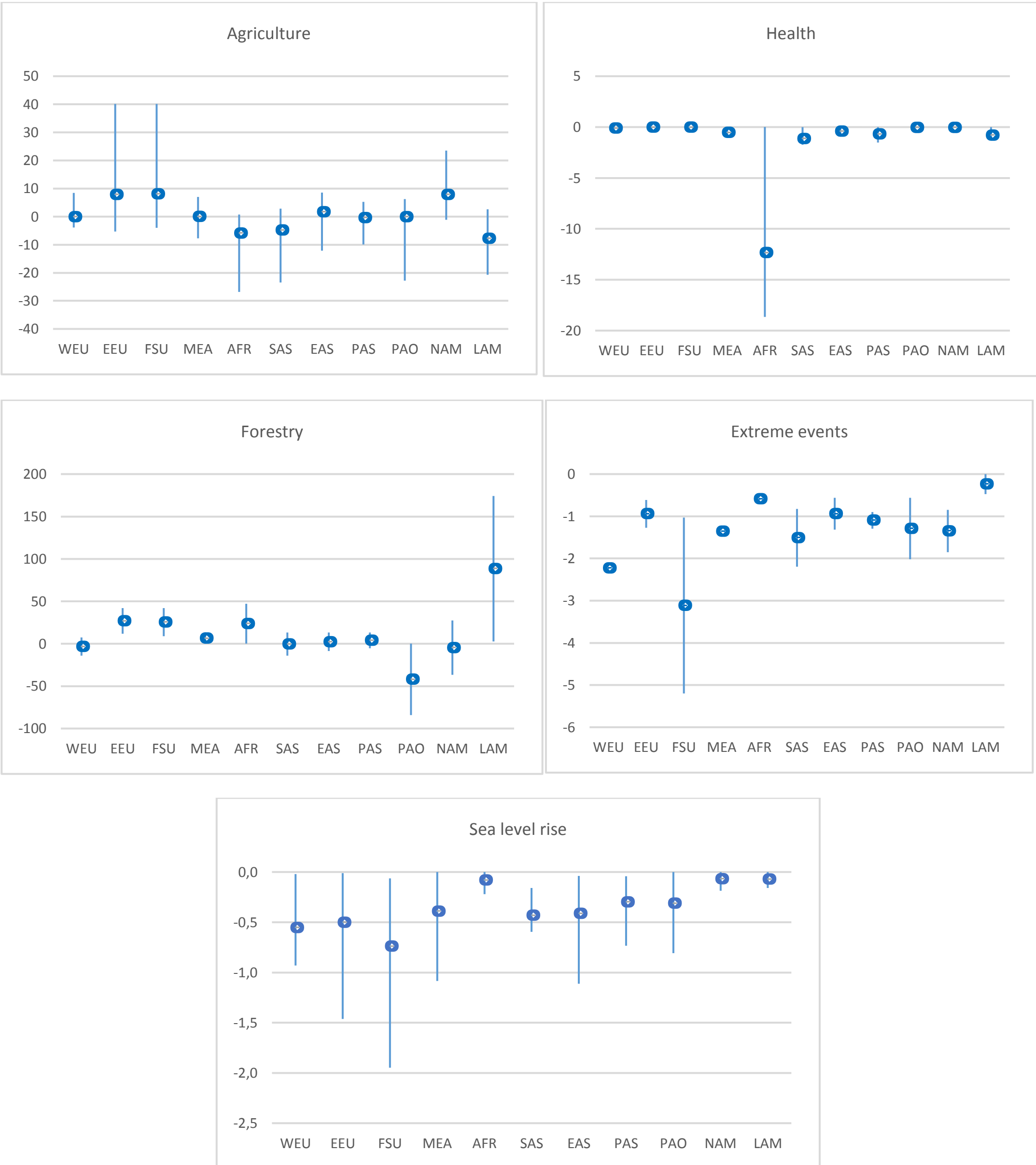


Figure 3.2. Adjusted estimates of impacts by region at + 2.5 °C in reference studies with variations. Percent

The estimates from the different studies were adjusted to make them refer to the same increase in temperature (+2.5 °C) and applying to all regions in GRACE. Five of the impacts were covered by more than one study, and Figure 3.2 shows the variations in the adjusted estimates by region. The dots show the estimates used in GRACE. The large variations are due, partly to the adjustments, but there are still big, and unexplained, differences between the different studies. A possible explanation is that estimation of the costs of climate change on national economies is a rather immature field of research.

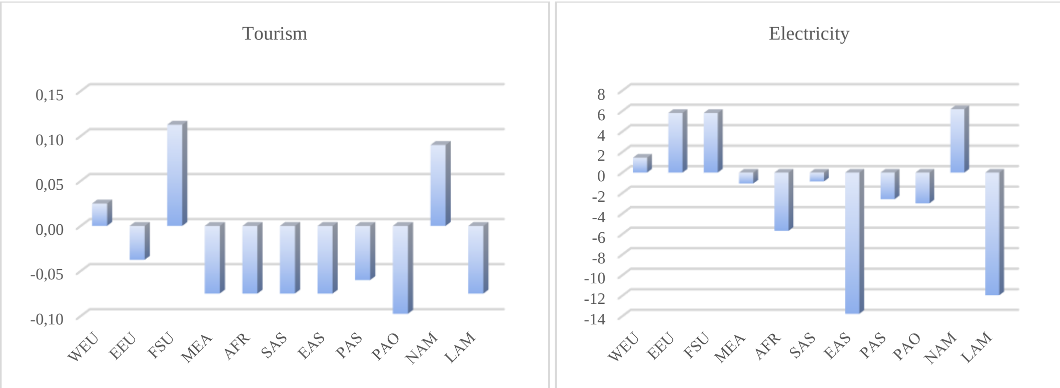


Figure 3.3 Adjusted impacts on demand for services from tourism and on power generation by region at + 2.5 °C. Percent

Impacts on tourism were taken from Ehmer and Heymann (2008) and impacts on power generation were assessed in only one of the studies above. The adjusted impacts used in GRACE are shown in Figure 3.3. None of the previous studies estimates impacts on fish stocks, and impacts are indeed uncertain. The estimates in GRACE refer to an assessment for Europe (Aaheim et al. 2012) where the parameters in the impact functions by regions are adjusted for temperature levels and the share of fish farming. At an increase in global mean temperature of +2.5 °C, the impacts vary from +2.5 % in Europe to – 6 % in Latin America. The impacts on energy demand are taken from de Cian et al. (2007), using the same temperature elasticities in all regions. For electricity, gas, refined oil and coal, the elasticities are 0.5, -2.7 -1.44 and 0.1, respectively.

The estimates above refer to relatively old studies. There are new studies that will be used in coming versions of GRACE. Roson and Satori (2016), in particular, provide estimates for impacts on crop yields, labour productivity and health, energy demand, and tourism for all the 170 countries in GTAP. Further updates will be done in connection with applications of the model in different projects. While the focus in some projects is on the global consequences of policies and related impacts, other projects focus on specific regions and specific sectors in one or more regions. Lessons from these studies contributes to improvements and updates of GRACE. Section 4 gives some examples on how.

The impact estimates used to calibrate the impact functions provide impacts at only one point, where dC = 2.5 and dT = 0. The functional forms in most of the underlying studies are chosen without referring to different changes in the climate indicators, meaning that the functional form is first chosen, and then, the parameters are calibrated to fit the impact assessment at the corresponding change in temperature. Some of the impact functions include variables that are not relevant in GRACE, such as income levels. In GRACE, the parameters are partly based on a study of impacts of climate change in Europe (Aaheim et al., 2012). Then, parameters are adjusted for temperature levels in the different regions, division of fish farming and ocean fishing in fisheries, division of thermal power and renewable power in electricity generation and the share of tourism in service sectors. The impacts of a change in precipitation in some of the sectors are also taken from the study of impacts in Europe.

Table 3.3 displays the parameters in the impact functions (3.1) in the current version of the model. Some impact functions are quadratic (β = 0), and others are unaffected by changes in precipitation (γ = 0). Note also that the parameters for health is multiplied by 100 for readability because of the small numbers (in the model, the actual numbers are used).

	Western Europe	Central and Eastern Europe	Former Soviet Union	Middle East and North Africa	Sub-Saharan Africa	South Asia	East Asia	Other Pacific Asia	Pacific OECD	North America	Latin America
Agriculture											
α	-0.0235	-0.0131	-0.0096	0.0000	0.0044	0.0046	-0.0040	0.0004	0.0003	-0.0373	0.0062
Β	0.0864	0.0440	0.0262	0.0001	-0.0334	-0.0374	0.0179	-0.0034	-0.0017	0.1504	-0.0421
γ	0.5625	0.3139	0.2293	0.0005	-0.1051	-0.1114	0.0952	-0.0102	-0.0083	0.8931	-0.1480
Forestry											
α	0.0071	-0.0030	-0.0030	-0.0030	-0.0030	-0.0001	-0.0033	-0.0030	0.0064	-0.0042	-0.0030
Β	-0.0322	0.0043	0.0047	0.0013	-0.0135	-0.0011	0.0175	-0.0224	-0.0886	0.0012	-0.0103
γ	0.0079	1.0356	0.4187	-0.1883	-25.031	0.0003	0.0072	-0.5702	0.0079	0.0090	4.0205
Fisheries											
α	-0.0059	-0.0042	-0.0042	-0.0036	-0.0031	-0.0036	-0.0036	-0.0036	-0.0048	-0.0048	-0.0053
Β	0.0251	0.0097	0.0096	0.0008	-0.0069	-0.0131	0.0095	-0.0136	0.0093	0.0007	-0.0091
γ	0	0	0	0	0	0	0	0	0	0	0
Electricity supply											
α	-0.0094	-0.0107	-0.0094	-0.0014	-0.0067	-0.0008	-0.0161	-0.0054	-0.0085	-0.0057	-0.0212
Β	0	0	0	0	0	0	0	0	0	0	0
γ	-0.2507	0.7192	0.3497	0.0013	0.0209	0.0017	0.0407	0.0085	0.0125	24.4095	0.3405
Tourism											
α	-0.0064	0.0097	-0.0073	0.0194	0.0194	0.0194	0.0194	0.0155	0.0252	-0.0233	0.0194
Β	0.0188	-0.0573	0.1250	-0.0566	-0.0819	-0.0767	-0.0804	-0.0528	-0.0732	0.1073	-0.0842
γ	-0.0801	0.2680	-0.7174	0.1430	0.1688	0.1497	0.2795	0.1025	0.2280	-0.4171	0.1938
Extreme events											
α	-0.0105	-0.0027	-0.0055	-0.0019	-0.0007	-0.0014	-0.0011	-0.0024	-0.0040	-0.0011	-0.0004
Β	0	0	0	0	0	0	0	0	0	0	0
γ	0	0	0	0	0	0	0	0	0	0	0
Sea-level/coastal											
α	-0.0009	-0.0005	-0.0006	-0.0002	0.0000	-0.0002	-0.0002	-0.0003	-0.0004	0.0000	0.0000
Β	-0.0027	-0.0017	-0.0017	-0.0008	-0.0001	-0.0006	-0.0007	-0.0008	-0.0011	-0.0001	-0.0001
γ	0	0	0	0	0	0	0	0	0	0	0
Health (x100)											
α	-0.0426	-0.0097	-0.0006	-0.0650	-0.2900	-0.1010	-0.0467	-0.1354	-0.0136	-0.0031	-0.1248
Β	0	0	0	0	0	0	0	0	0	0	0
γ	-0.0917	0.0208	0.0014	0.1400	0.6243	0.2175	0.1006	0.2916	0.0293	0.0066	0.2688

Table 3.3. Parameters in the impact functions 3.1. The parameters for health are multiplied by 100

4 Applications

A list of papers based on the use of GRACE is given by the end of this report. This section gives a brief presentation of three studies to illustrate some main usages of the model. The first (Liu and Wei, 2017) highlights the importance of market effects, and shows how the effect on greenhouse gas emissions from improvements of energy efficiency in Europe depend on whether the emission reductions are measured at the source point or by the effects on global emissions. The second study combines climate projections with pathways for economic development to explore what motives policy makers and economic agents may have to reduce greenhouse gas emissions in the light of the economic consequences of climate change. The third study gives an example on how a variable in one region can be replaced by a sub-model to establish a closer link between the economic model and physical models, and thereby derive the socioeconomic consequences of physical changes. In this example, we use results from vegetation models in India to assess the impacts on global carbon uptake of REDD+ initiatives.

4.1 Energy efficiency improvement: Is it reliable for climate mitigation?

The effect of an action taken to reduce emissions of greenhouse gases depend critically on whether the action is taken by one individual, or if it is a part of a policy aimed at reducing national emissions. In the latter case, market responses may reduce effect on national or global emissions considerably compared to the initial, direct effect (Khazzoom, 1980). This is called the rebound effect.

Many regions, including the European Union, have put their faith in energy efficiency improvements to help mitigate climate change, trusting it will reduce emissions of carbon dioxide (CO_2) from fossil fuel combustion. Typically, a ten per cent improvement in energy efficiency by consumers is expected to reduce energy use and related CO_2 emissions by ten per cent in prevailing energy use forecasts (Saunders, 2015). However, reality may perform differently.

Counter-intuitive effect

According to a new study by Wei and Liu (2017), a ten per cent improvement in energy efficiency for all final energy use at the global level may lead to an “actual” reduction in energy use and related emissions in the long term as low as three and one per cent, respectively. The “take-back” or rebound phenomenon at work here implies that the energy efficiency improvement itself will unlikely effectively change global energy use and related emissions, although it *can* promote economic growth.

This counter-intuitive rebound phenomenon occurs due to a series of behavior changes of final energy consumers (Figure 4.1). An energy efficiency improvement reduces the “effective” price of given energy services required by consumers and directly leads to reduced demand for energy goods. At the same time, the consumers can benefit from two channels: One is cheaper energy services and the other is the consumers’ saved expenditures for the same energy services as before.

Consumers spend their money elsewhere

Cheaper energy services may stimulate consumers to increase consumption of energy goods compared to other goods, while energy expenditure savings can be used to increase consumption of both energy and other goods. These behavior adjustments further lead to price changes in energy and other goods markets. As a result, the whole economy responds to the price changes by adjusting production activities, reallocating resources across sectors and regions, creating innovative activities to adapt to the energy efficiency improvement, and increasing effective labor and capital supply to fully utilize the potential energy services associated with the energy efficiency improvement.

Consequently, the final energy use and related carbon emissions deviate from the original situation. At one extreme, consumers may reduce energy consumption by more than the energy efficiency improvement, leading to super-conservation. Alternatively, consumers may consume more energy than the stipulated energy efficiency improvements, leading to an energy efficiency backfire. Most probably, there will be a situation between these two extremes.

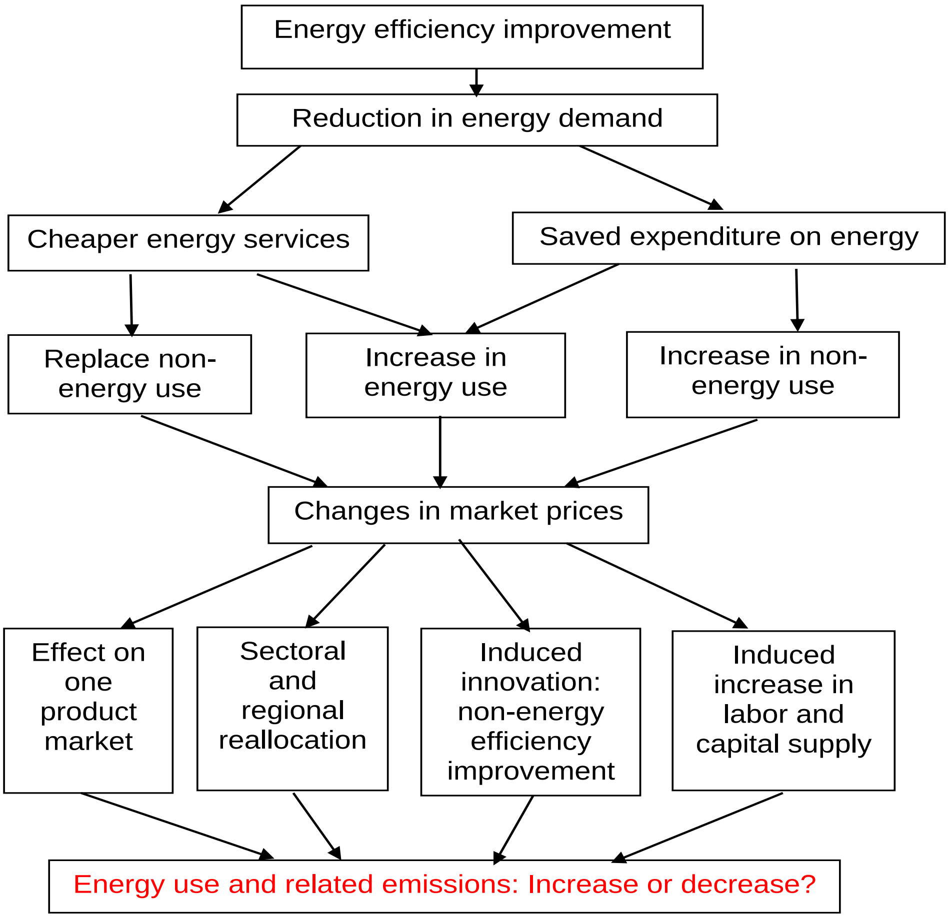


Figure 4.1. The mechanism of economy-wide rebound effect. Source: Wei and Liu [1].

Zooming in on the results

Economists may examine the rebound phenomenon in various scopes and levels. Direct and indirect rebound effects correspond to changes in sectoral (particularly household) energy consumption assuming no effect on other sectors and market prices. Macroeconomic rebound effect refers to regional/global "take-back" effects caused by inter-sectoral links and changes in market prices.

Economy-wide rebound effect refers to the sum of direct, indirect, and macroeconomic rebound effects.

Wei and Liu [1] examine the size of the global economy-wide rebound effect in the long term by use of GRACE. In this study, the model divides the world into eight regions: United States, European Union, Japan, Russia, China, India, Brazil and the rest of the world.

Simulation results indicate that there is a considerable long-term rebound effect[2] in energy, ranging from 55 per cent in Brazil to close to 80 per cent in India, with the global effect close to 70 per cent by 2040. Although at first glance such estimates may seem high, the results are broadly in line with previous estimates. In 2009, Terry Barker and his colleagues [3], for example, reported the global rebound effect in energy to be 31 per cent by 2020 and 52 per cent by 2030. The rebound effects in terms of emissions are significantly higher at between 75 per cent (Russia) to 98 per cent (China) and the global estimate is at 90 per cent.

When we introduce energy efficiency as a parallel increase for all final energy users in the model, fossil fuels – cheap compared to renewable energy sources – will only become cheaper, thereby inducing increased consumption of emission-intensive sources.

The results also illustrate that labour mobility contributes positively to the rebound effect. In fact, when the labour supply is fixed, the global rebound effect on energy falls from 70 per cent to 60 per cent. Interestingly, the rebound effect dropped significantly when the labour supply was fixed in developed countries and China, while experiencing little change in the case of India. This may imply that the labour supply fulfils different roles across regions.

Policy

Energy efficiency improvement in the demand side can serve as an effective policy to promote economic growth, but probably cannot itself be an effective policy to reduce the global energy use and related emissions. In the long term, energy efficiency improvement does not mainly reduce energy use, but instead, promotes considerably economic growth and social welfare through inducing additional supply of other productive resources such as labour and capital. To make energy efficiency improvement an effective policy for reduction in energy use and related emissions, policy to improve efficiency of renewable production and consumption alone could be effective for reduction in fossil fuel use and related emissions, but may still not be effective for reduction in total energy use.

Several steps could improve the estimation of global rebound effect. It might be more relevant to policy making if investment costs to obtain the efficiency improvement are considered in the analysis. Importantly, our results depend on various assumptions on substitution elasticities and other parameters, not based on historical data. Hence, we could validate our simulation model with historical data, and later use them to examine historical rebound effects and re-estimate the long-term global rebound.

4.2 Implications of climate projections for economic development

The huge attention to climate projections in climate research, combined with the clear message from the United Nations' Framework Convention on Climate Change (UN FCCC) that climate policy must refer to science, one might expect a lot of ongoing research to address the implications of climate projections for the development of world economies. This is not the case. Climate projections are being used to study impacts as well as adaptation, but most often with a narrow focus cases, on a specific sector and activities within sectors, and on selected countries and small regions with

[2] A 50% rebound effect refers to the case that the expected reduction in energy use (or emissions) is taken back by 50%. In other words, if the expected reduction is 10%, the same as energy efficiency improvement, then the 50% rebound effect implies the expected reduction is taken back by 50% and the "actual" reduction becomes only 10%*(1-50%) = 5%.

countries. Besides, it is often unclear how climate projections decades into the future match the descriptions of social and economic conditions, which often refers to the present situation.

The main reason is that few methodologies allow results from climate projections to be combined with comprehensive projections of socioeconomic development. As pointed out in Section 1.4, CGE models can be used for this purpose, although with the weaknesses pointed out above. Aaheim et al. (2017a) use GRACE to compare two Representative Concentration Pathways (RCP), RCP4.5 and RCP8.5, which were developed to provide common emission pathways for running climate models. RCP8.5 can be understood as a business-as-usual scenario, where no mitigation takes place. The climate projections indicate an increase in global mean temperature between 4.0 °C and 5.0 °C above preindustrial level in 2100. RCP4.5 presumes that mitigation should have started already, and continue until 2080, when global emissions are half of the present level. This results in an increase in global mean temperature at 3.0 °C in 2100.

The socioeconomic pathway corresponds to Shared Socioeconomic Pathway 3 (SSP3), (Riahi et al., 2017), and uses climate projections from Max Planck ESM (Giorgietta et al, 2013). The study points out three main messages, which might seem intuitive in the first place, but they are seldom addressed in public climate debates.

Trust in the temperature target gives a high return on green investments

The first message is that the cost of emitting greenhouse gases will have to increase steadily between 12 and 15 percent per year on the world scale until 2080 if the increase in global mean temperature is to be limited to 3.0 °C in 2100. To reach the Paris target of 2.0 °C, the increase in the cost of carbon has to be even higher. The estimate presumes fully cost effective emission cuts on the global scale, for example by a fully competitive global trading scheme for emissions, meaning that the estimated increase is probably in the lower end.

An increase in the price of carbon gives a return on green investments, as green solutions save investors for money in the years to come. Investors will choose the green alternatives if they believe that the carbon price will increase by 12 – 15 percent, because this is far above a normal return on capital. However, global emissions have increased much more than presumed in RCP4.5 after 2005, which is the first year a price on greenhouse gas emissions was implemented in the study. The interpretation is that potential investors do not trust that a temperature target of 3.0 °C will be achieved, not to speak of 2.0 °C.

Apparent economic conflicts go between sectors, not countries

The parties in the climate negotiations are countries, and there is much attention to the conflicts of interest between the different parties, and not at least conflicts between developing countries and developed countries. The interest of a country is often associated with their economic interests. Therefore, one might expect that the vulnerability of developing countries is connected to the economic impacts of climate change, while the vulnerability of developed countries is connected primarily to the costs of mitigation.

However, the study does not reveal any clear differences between developing and developed countries in this respect. When comparing sectors within regions, however, the picture become clear. In the very long term, fossil fuel extracting sectors benefit from a continuation of growth in emission, as in RCP85. All other sectors in all regions will lose, except for service sectors in regions with high extraction of coal, oil and gas. The apparent internal conflicts of interests point at severe challenges in addressing adequate issues in climate negotiations.

The present generation has to pay to the benefit of future generations

This last message addresses the allocation of burdens across generations, which is the main issue for studies by the benefit-cost IAMs. A CGE model provides a more transparent linkage both to climate projections and to how climate change affect a broader set of economic activities, but does not address the normative question about the social cost of carbon, raised by the benefit-cost IAMs.

The impact functions in GRACE give moderate economic costs of climate change at a moderate increase in global mean temperature. In fact, the economic impacts at + 3 °C in 2100 under RCP4.5 are positive in some regions and negative in others, but generally small. This does not imply that impacts are negligible, as they may be severe in some parts of some countries and over a period. What is reflected here is that the cost of these impacts does not necessarily affect the economic indicators of the regions represented in the model. The same applies for the high-emission pathway, RCP8.5, until the midst of this century. From then on, the impacts of climate change become visible also on the regional economic indicators, and increase rapidly towards the end of this century, with a likely continuation beyond.

The cost of mitigation in RCP8.5 become apparent much sooner, and will continue until 2080, when emissions are stabilized. After 2080, RCP4.5 gives a higher economic growth than RCP8.5, but the aggregated world GDPs are lower in RCP4.5 than in RCP8.5 throughout the century. The study thereby shows that present generations have no incentives to mitigate climate change, according to the norms of the benefit-cost IAMs, and that this will lead the world into a dramatically unsustainable future. The strong indications of mistrust in assurances that future temperature will be limited to + 3 °C in the first message suggest that this development is to be expected.

4.3 Replacing the value of harvesting forests with forest management

GRACE explains value added in different sectors by the utilization of primary input factors. Contributions from labour is measured by observations of expenditures on wages. The remaining value added is explained as contributions from capital and natural resources, and divided by underlying assumptions. These contributions are interpreted as returns on the capital stock and the stock of natural resources, respectively. All this information is taken from GTAP. In forestry, the returns on the natural resource is the value of the annual harvesting that remains when wages and the returns on investments in the sector are paid.

Preparing the model for integration of results from vegetation models

The basic version of GRACE thereby includes a link between the economic output from the forestry sector and the economic utilization of forests. Findings from studies of impacts of climate change on forests and changes in forest management can therefore be integrated in the model. However, few studies are motivated by assessing the impacts of climate change on the contributions to value added from cutting forests. Most of the research is based on biophysics, and show how the forests are affected by climate change, which can be used in the management of forests.

To make use of this research, a sub-model was developed to explain forest management under changing biophysical conditions, and derive the value of harvesting. In brief, the model is based on economic theory of management of renewable resources, which determines sustainable harvesting, where the harvest equals the growth of the forest. The growth of the forest depends on the forest mass, and an increase in the forest mass yields a higher sustainable income within a certain range. Optimal harvest is at the point where the added income from a marginal increase in mass equals the return on investing the value of the increase in mass in the best alternative.

Management depends on the physical characteristics of forests

The module was integrated in GRACE to study the potential for carbon uptake by protecting forests by REDD+ initiatives (Aaheim et al., 2017b). The uptake can be estimated directly from data from Forest Service of India (FSI, 2014) and from Bala et al. (2013). The price needed to accept protection could be estimated from the resulting economic loss of future forest rents. However, the concern to those paying for REDD+ is the impact on the global concentrations of greenhouse gases. To them, it is essential to know whether and how protection of one forest affects the management of other forests in India, and if it affects foreign trade.

Protection of a forest means that the products previously supplied from the protected area will be demanded from non-protected forests. To meet this demand, the corresponding sustainable mass in non-protected forests will also have to change. The impacts for carbon uptake in the country and on the world scale, depends on how large biomass is needed to adjust the harvest. This differs considerably across regions. Figure 4.2 shows the relationship between harvest and mass in the eight regions in India. The observed harvest constitutes from less than 4 percent of current mass in Karnataka to more than 25 percent in Rajasthan.

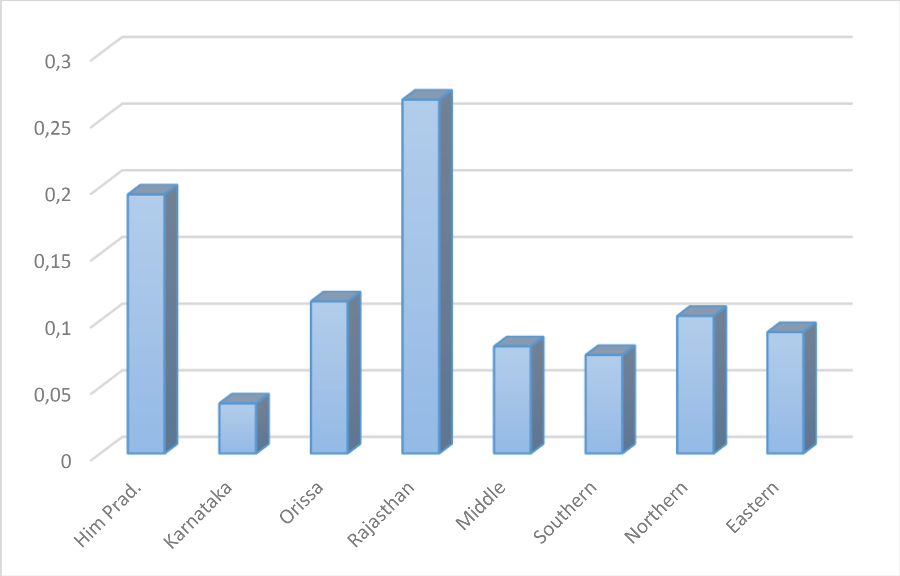


Figure 4.2. Annual growth of forest as a share of total mass by region in India.

The model describes the economies in the four states and the four regions covering the other states in India shown in Figure 4.2 as similar to the average economy of India, but scaled according to regional value added. In addition, the forest sectors vary according to the reported harvest in the physical statistics, which is linked to the standing mass. The rest of the world is represented by one region.

The effect of REDD+ on carbon sequestration depends on the scope

In an experiment, 10 percent of the forest in all regions of India were protected. As expected, the resulting responses depend critically on the on the optimal combination of harvest and standing biomass. Rajasthan and Himachal Pradesh are characterized by a high harvest at a given standing mass. The carbon uptake in protected forests are matured after a relatively short period, and the room for adjusting the amount of harvest is limited in non-protected forests. Therefore, the price effect of protection is high, but with minor impact on the uptake of carbon. Karnataka represents an opposite case. The small harvest at a given stock of biomass implies added carbon uptake over a long period in protected forests. In non-protected forests, the slow growth rate implies flexibility with respect to harvest. The price effect is therefore small, but the impact on carbon uptake is large.

The different price responses in the different regions implies that the price of the same product differs depending on where it is produced. Over time, this levels out, but it takes a long time. The time it takes before carbon storage in the protected forests are mature is shorter, and varies from 10 to 70 years. Thereby, REDD+ may be considered parallel to cutting emissions of short-living gases. The difference between the carbon uptake in protected forests and the net carbon uptake in a national or global perspective is large, however. On average, the net national carbon uptake in India is between 25 percent of the uptake in protected forest in the first year, but increasing to 65 percent after 50 years. At that point, the uptake in most protected forests are close to zero, however. Impacts on foreign trade is small, however, and the “leakage” to other countries is limited to between 4 and 7 percent.

Responses in non-protected forests also raises questions about cost of REDD+ initiatives. The standard recommendation is to calculate the discounted loss of future income from harvesting protected forests. If including benefits from non-protected forests, the cost of REDD+ in this experiment is reduced to between 2 and 50 percent of the discounted loss of future income from protected forests. In the end, the price to be paid is, or course, a question for the parties must negotiate. However, the difference between the cost to the owners of a forest and the cost to the sector of a country illustrates the ineffectiveness in leaving initiatives aiming to solve a global problem to individual managers. This underlines the need to integrate sector studies of climate policy and climate change in a global context by means of models such as GRACE.

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