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Buying Greenhouse Gas Insurance: International Trade and the Adaptation to Climate Change and Variability

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Abstract:

This paper has three messages mainly, which are observed both in a simple theoretical model and its empirical application in a general equilibrium analysis of climate change, international trade and adaptation. First, trade might be viewed as a kind of autonomous adaptation to climate change and variability. In particular, trade can help to reduce direct impacts of global climate change on a region's welfare, but is itself vulnerable to climate change and variability. Second, the less affected and the richer nations are, the more they can profit mostly from moderating the impacts of global climate change through trade. Finally and third, even without cooperation in the solution of the global climate problem, it is in the self-interest of the industrialized nations to fund strategically adaptation in the developing part of the world.

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1 Introduction

There are different reasons, why countries trade. The most important one, economists typically refer to, is that trade is a source of wealth. There is, however, a further reason, which usually is not mentioned explicitly in the economic literature, but is in the center of this analysis. Since the direct impact, which global warming can have on the regional society, considerably varies across countries, trade is a kind of insurance against the risks of climate change and variability. For example, if in some region because of weather extremes food production is reduced, over the short-run the shortfall of domestic supply might be substituted by imports. Over the long-run production could even shift to regions, which have the comparative advantage of being less vulnerable to climate change and variability (see Julia and Duchin, 2007). Seen in this way, trade is mean for adjusting to the increasing risks of global warming.

Moderating climate impacts is one side of the coin. A second one is that trade might spread the cost of climate change across regions. Here is a recent example. After six years of drought Australia's rice production almost collapsed in 2008. This was one of several factors contributing to a doubling of the world market price of rice, which led to panicked hoarding and violent protests in particular in low income countries (see Bradsher, 2008). Indeed, even if free trade curbs the effect of climate change on global supply, output losses in one single country might cause higher world market prices, and the resulting terms-of-trade effects can pertain to real income losses in almost any country. This is a problem for the poorest in particular. On the one hand these countries are heavily exposed to the impacts of climate change, but do not own the necessary resources for coping with the associated risks on the other. And they are hampered in increasing their export earnings in order to pay for imports (see Cline, 2007).

Both the direct impacts and the trade effects of global warming depend on the societies' vulnerability to climate change and climate variability. In particular, the less sensitive production in export oriented sectors is to climate change, the less dependent a country is on imports of vulnerable goods, the lower will be the term of trade effects. Consequently, self-interest of countries seems to suggest that they should invest into measures for reducing the vulnerability of their regional societies. On the one hand this could be mitigation, which refers to policy interventions such as the reduction of anthropogenic greenhouse gases emissions. On the other hand it could be adaptation, which refers to investment into processes, practices, or structures to moderate or offset potential damages of global climate change, as well as to reduce the climate vulnerability of communities, regions, or countries (see Parry et al., 2007).

Generally it is argued that climate policy requires a long-term perspective. Undeniable this applies, if climate mitigation is the policy option under consideration, where, because of the inertia of the climate system, costs are borne early, but benefits accrue in the distant future. For the same reason, however, the global climate will continue to change, even if greenhouse gas emissions are drastically reduced immediately. Therefore, over the mid-term, adaptation is the most important policy option for preventing the negative impacts of global warming. Much adaptation will be done automatically by the market. Much of the rest will require strategic investment into local public goods. However, many poor countries lack the capability to adapt. This is not only because of scarcity of financial resources. Poor countries typically have weaker market institutions, and their governments routinely undersupply local public goods.

Without support by the developed countries through for example adaptation funding climate change could pronounce the already existing inequalities between industrialized and developing countries (see Barrett, 2008). Industrialized countries have already accepted to assist poor countries to adapt. At the 2001 Climate Change Convention (COP6) three funds have been established to support financially adaptation in developing countries: (1) the Least Developed Countries Fund (LDCF), which aims to support the 49 least developed countries, (2) the Special Climate Change Fund (SCCF), which provides financial support to all developing countries, and (3) the Adaptation Fund, which is based on Article 12 of the Kyoto Protocol (for details, see Buob and Stephan, 2011). Since then several other funds were established.

In what follows, we take a mid-term perspective and focus on the interaction between adaptation, climate change and trade. In particular, we will discuss the questions: (1) How does climate change affect international trade, regional welfare and the geographical pattern of production especially in sectors, which are sensitive to climate change. (2) How does regional investment into adaptation affect welfare, the comparative advantage of countries and hence the pattern of international trade flows. (3) Finally, can funding adaptation in developing countries improve welfare?

As was discussed above, over the mid-term mitigation has almost no impact on global climate change. Therefore, for the purpose of this paper climate change and climate variability are taken as exogenously. Based upon this assumption, Section 2 presents a simple analytical framework, which is designed to analyze how global climate change, adaptation and international trade interact. Sections 3 and 4 extend the theoretical discussion both qualitatively and quantitatively. For the purpose of a numerical analysis more details and structure have to be added, and hence the modeling framework of in Section 2 has to be developed further in several directions. Section 3 discusses MITACC, which is the nick-name of the intertemporal general equilibrium model for evaluating international trade and regional adaptation, and Section 4 presents the results of the numerical simulations.

2 A North-South model of climate change, trade and adaptation

Economies in the South are more exposed to global warming than those in the North, and agricultural production is more responsive to climate change and weather extremes than manufacturing personal computers. Moreover, the poor and developing countries are mostly located in the South, and the fraction of economic activities, which are vulnerable to climate change, is larger in poor than in rich countries (see Adger et al., 2003). This motivates dividing the world economy into two regions at least: North (N) and South (S). North corresponds to Annex B countries and represents a region of relatively high wealth, but low exposure to climate change. South covers the rest of the world and is an acronym for the developing part of the world.

Two commodities are traded on internationally: capital and vulnerable, where vulnerable is the nickname for the aggregate of goods and services which are produced in climate vulnerable sectors. Capital and vulnerable are inputs into the regions' gross production, which is characterized by a linear homogenous function $f_n(x_n, k_n)$, n = N,S, and where x_n and k_n denote the inputs of vulnerable and capital, respectively. To simplify the analysis, production of vulnerable is described by a cost function. Costs of supplying vulnerable to the world market are expressed in units of gross output. They are a strictly increasing function $g_n(\theta_n(T, a_n), z_n)$ of the output z_n as well as climate impacts $\theta_n(T, a_n)$. Impacts of climate change are region-specific and depend on the global climate, which is represented by the global mean temperature T, and the region's investment into adaptation a_n. That means, the higher is the global mean temperature and the lower is a region's investment into own adaptation, the higher will the regional climate impact and hence the costs for producing a certain output of vulnerable goods and services.[1]

As mentioned above, countries in the North are less vulnerable to climate change that those in the South. Nordhaus and Boyer (2000) estimate that over the mid-term regional impacts of global warming are essential zero in the US, Japan, Russia and even China. India and many other low-income countries, however, might be confronted with significant damages. Therefore, it is reasonable to assume that over the mid-term the direct impact of climate change on the production of vulnerable commodities is almost negligible in the North. More precisely, let us use the following, close to reality assumption:

[1] More precisely we assume: $\partial\theta_n/\partial T \geq 0$, $\partial^2\theta_n/\partial T^2 \geq 0$, $\partial\theta_n/\partial a_n < 0$, $\partial^2\theta_n/\partial a_n^2 \geq 0$. This takes into account that in some regions such as USA, Russia and Eastern Europe a marginal change of the global climate has only negligible effects on the regional economy.

Assumption 1[2]*: If the global climate changes only slightly, impacts of climate change on costs of producing vulnerable outputs are zero in the North, but positive in the South.*

Each region might support adaptation not only in its own, but also in the other region. That means, $a_n = a_n^n + a_n^s$, where a_n^s denotes the investment of region s into adaptation a_n of region n. Suppose further that both the world market for vulnerable and the world capital market is in equilibrium, i.e.,

(2.1) $z_N + z_S - x_N - x_S = 0$,

(2.2) $\overline{K}_N + \overline{K}_S - k_N - k_S = 0$,

where $\overline{K}_n$ denotes the exogenously given capital endowment of region $n = N, S$.

If p and r denote the world market price of vulnerable and capital, respectively, and if gross production can be consumed domestically and can be used to cover the costs of investing into adaptation as well as of producing vulnerable, then for any region n domestic consumption c_n is determined by

(2.3) $c_n = f_n(x_n, k_n) - g_n(\theta_n, z_n) - t_n(a_n^n + a_s^n) + p(z_n - x_n) + r\left(\overline{K}_n - k_n\right)$.

$t_n(a_n^n + a_s^n)$ are the expenses of region n for investing into its own and the other region's adaptation. $p(z_n - x_n)$ is the deficit from trading vulnerable products and $r\left(\overline{K}_n - k_n\right)$ is the possible deficit from trading capital.

Let sectors behave as price takers, then profit maximization leads to the following optimality conditions for an interior solution, which are both sufficient and necessary

(2.4) $\dfrac{\partial f_n}{\partial x_n(x_n, k_n)} - p = 0$, $n = N, S$,

[2] Formally means: $\dfrac{\partial \theta_N}{\partial T} = 0$, but $\dfrac{\partial \theta_S}{\partial T} > 0$.

(2.5) $p - \frac{\partial g_n}{\partial z_n} = 0$, $n = N, S$,

(2.6) $\frac{\partial f_n}{(\partial k_n)(x_n, k_n)} - r = 0$, $n = N, S,$

(2.7) $\frac{\partial g_n}{\partial a_n} + t_n'(a_n^n + a_s^n) = 0, n = N, S$.

All conditions are well-known. (2.4) and (2.5) together state that the marginal productivity of vulnerable goods equals the world market price, which in turn is equal to the marginal costs of supplying vulnerable. Condition (2.6) implies that the marginal productivity of capital has to be identical across regions, and condition (2.7) indicates that he marginal costs of adaptation must be equal the marginal reduction of costs of supplying vulnerable. These conditions allow to define: (1) capital inputs $k_n = K_n(r, x_n)$ as function of capital prices r and inputs of vulnerable products x_n, (2) imports of vulnerable products as function $x_n = X_n(p, k_n)$ of the world market price p and capital inputs k_n, and (3) exports z_n as function of both the world market price p and the region's climate impact $\theta_n(T, a_n)$, i.e., $z_n = Z_n(\theta_n(T, a_n), p)$, respectively.

How does climate change as well as the investment into adaptation affect the international prices of vulnerable? The following proposition gives a first answer.

Proposition 1: Let Assumption 1 be satisfied, then

(2.8)

$dp = ((\partial z_1 S)/\partial T)/((\partial x_1 N)/\partial p + (\partial x_1 S)/\partial p - (\partial z_1 N)/\partial p - (\partial z_1 S)/\partial p)\, dT + ((\partial z_1 N)/(\partial a_1 N))/((\partial x_1 N)/\partial$

.

Proof. See Appendix

At first glance, Proposition 1 is no surprise. Global climate change drives the costs of producing vulnerable goods. Hence, the higher (lower) is the impact of climate change on the regions' production of vulnerable, the less (more) will be supplied to the world market, and hence, the world market price must rise (fall). At second glance, however, the Proposition 1 presents a surprise as it suggests that there is no reallocation of capital (for a proof, see Appendix).

Corollary 1: A marginal change in either the atmospheric stock Q of carbon dioxide or adaptation investment does not lead to a reallocation of capital across regions.

An immediate consequence is that the input of vulnerable into regional production is not immediately affected by climate change

$$(2.9) \quad dx_n = \frac{\partial x_n}{\partial p} dp \, , \; n = N, S \, .$$

There are, however, indirect effects. For example, if the world market price of vulnerable rises due to climate change, less will be put into regional production.

By differentiating $z_n = Z_n(\theta_n(Q, a_n), p)$ totally we get

$$(2.10) \quad dz_n = \frac{\partial z_n}{\partial Q} dT + \frac{\partial z_n}{\partial a_n} da_n + \frac{\partial z_n}{\partial p} dp \, .$$

The first term on the right side corresponds to the direct effect, which climate change has on the export of vulnerable. This effect is negative (see Appendix (A6)). The second term indicates that the region's investment into adaptation affects the supply of vulnerable goods to the world market. This effect is positive (see Appendix (A7)). Finally, the third term represents what results from changing world market prices. Depending on the interplay between climate change and regional adaptation this effect can be negative, positive or zero. Now, since we are interested in analyzing the interplay between international trade, regional adaptation and climate change, let us discuss two cases separately. First, consider the pure trade case. This means, there is no strategic investment in regional adaptation, neither in the North and the South. Second, let us suppose that there is policy intervention. This means, the North strategically supports investment into that South's adaptation infrastructure.

2.1 *The pure trade effect*

In what follows, there is no investment into adaptation, i.e. $da_n = 0$, $n = N,S$. Then because of Assumption 1 a Proposition 1 it follows from condition (2.10) that the North expands its exports of vulnerable products,

$$\frac{dz_N}{dT} = \frac{\partial z_N}{\partial p}\frac{dp}{dT} > 0 ,$$

whereas

$$\frac{dz_S}{dT} = \frac{\partial z_S}{\partial T} + \frac{\partial z_S}{\partial p}\frac{dp}{dT} = \frac{\partial z_S}{\partial T}\frac{\frac{\partial x_N}{\partial p} + \frac{\partial x_S}{\partial p} - \frac{\partial z_N}{\partial p}}{\frac{\partial x_N}{\partial p} + \frac{\partial x_S}{\partial p} - \frac{\partial z_N}{\partial p} - \frac{\partial z_S}{\partial p}} < 0 .$$

That means, in contrast to the North, the South, where direct effects matter, will now reduce its output of vulnerable products. Or to phrase it differently, there is a change in the terms of trade in favor of the North. This gets even more obvious, if we consider

$$\frac{dz_N}{dT} - \frac{dx_N}{dT} = \frac{\left[\frac{\partial z_N}{\partial p} - \frac{\partial x_N}{\partial p}\right]dp}{dT} > 0 ,$$

$$\frac{dz_S}{dT} - \frac{dx_S}{dT} = \frac{\partial z_S}{\partial T} + \frac{\partial z_S}{\partial T}\left[\frac{\frac{\partial z_S}{\partial p} - \frac{\partial x_S}{\partial p}}{\frac{\partial x_N}{\partial p} + \frac{\partial x_S}{\partial p} - \frac{\partial z_N}{\partial p} - \frac{\partial z_S}{\partial p}}\right] < 0 ,$$

since $\frac{\partial z_S}{\partial T} < 0$ and $\frac{\frac{\partial z_S}{\partial p} - \frac{\partial x_S}{\partial p}}{\frac{\partial x_N}{\partial p} + \frac{\partial x_S}{\partial p} - \frac{\partial z_N}{\partial p} - \frac{\partial z_S}{\partial p}} \in (-1,0)$.

Finally, taking the last three equations and condition (2.8) together gives

$$\frac{d(z_N + z_S)}{dT} = \frac{\partial z_S}{\partial T} + \left(\frac{\partial z_N}{\partial p} + \frac{\partial z_S}{\partial p}\right)\frac{dp}{dT} = \frac{\partial z_S}{\partial T}\frac{\frac{dx_N}{dp} + \frac{dx_S}{dp}}{\frac{\partial x_N}{\partial p} + \frac{\partial x_S}{\partial p} - \frac{\partial z_N}{\partial p} - \frac{\partial z_S}{\partial p}} < 0.$$

which is negative because of conditions (A2), (A5) and (A6) (see Appendix).

Summing up we have

Proposition 2: Let assumption 1 be fulfilled and assume that there is no investment into adaptation. Then the production of vulnerable products is shifted from the South to the North and overall the supply is reduced.

2.2 *Strategic adaptation*

The results from above indicate that it might be in the self-interest of the North to support strategically adaptation in the South. For adaptation can reduce the adverse impact of climate change on the South's production of vulnerable, and hence might reduce the terms of trade effects. As such financing adaptation in the South would be a kind of facilitative adaptation. For testing this hypothesis, let us assume:

Assumption 2: The global climate changes marginally, i.e., $dT > 0$ *, and there is strategic investment into adaptation in the South only, i.e.,* $da_S > 0$ *, but* $da_N = 0$.

Let in addition Assumption 1 be satisfied, then Proposition 1 implies

$$dp = \frac{\frac{\partial z_S}{\partial Q}dT + \frac{\partial z_S}{\partial a_S}da_S}{\frac{\partial x_N}{\partial p} + \frac{\partial x_S}{\partial p} - \frac{\partial z_N}{\partial p} - \frac{\partial z_S}{\partial p}} \quad (2.11)$$

Now, since $\frac{\partial z_S}{\partial a_S} > 0$ (see (A2.7)), the question of what are the price effects of both climate change and investment into adaptation depends which of the two effects dominates. If the negative impact of climate change dominates the positive ones of adaptation, i.e., $\frac{\partial z_S}{\partial T}dT + \frac{\partial z_S}{\partial a_S}da_S < 0$, then we are back in a situation, which has in principle the same features as the one discussed in Section 2.2.1. Therefore, let us assume that investing into adaptation can totally outrage the negative effects of climate change on the production of vulnerable goods in the South. Hence

(2.11a) $$dp = \frac{\frac{\partial z_S}{\partial T} dT + \frac{\partial z_S}{\partial a_S} da_S}{\frac{\partial x_N}{\partial p} + \frac{\partial x_S}{\partial p} - \frac{\partial z_N}{\partial p} - \frac{\partial z_S}{\partial p}} \leq 0$$.

Or in words: If there is investment into adaptation, marginal costs of producing vulnerable in the South will be reduced, which leads to rising supply and falling prices. Furthermore, since, for the same reasons as in Section 2.2.1, there in no reallocation of capital across regions, we now have for any region $n = N, S$

(2.12) $$dx_n = \frac{\partial x_n}{\partial p} dp > 0,$$

(2.13) $$dz_N = \frac{\partial z_N}{\partial p} dp < 0$$,

(2.14)

$$dz_S = \frac{\partial z_S}{\partial a_S} da_S + \frac{\partial z_S}{\partial T} dT + \frac{\partial z_S}{\partial p} dp = \frac{\left[\frac{\partial z_S}{\partial a_S} da_S + \frac{\partial z_S}{\partial T} dT\right]\left[\frac{\partial x_N}{\partial p} + \frac{\partial x_S}{\partial p} - \frac{\partial z_N}{\partial p}\right]}{\frac{\partial x_N}{\partial p} + \frac{\partial x_S}{\partial p} - \frac{\partial z_N}{\partial p} - \frac{\partial z_S}{\partial p}} > 0$$,

(2.15)

$$dz_1(S) + dz_1(N) = [(\partial z_1 S)/(\partial a_1 S)\, da_1 S + (\partial z_1 S)/\partial T\, dT][(\partial x_1 N)/\partial p + (\partial x_1 S)/\partial p - (\partial z_1 N)/\partial p]/((\partial x_1 N)/$$
.

Conditions (2.12) and (2.13) are intuitively clear. Since adaptation reduces the costs of supplying vulnerable goods, prices of vulnerable fall (see condition (2.11). Hence, demand (see (2.12)) increases in all regions, but supply is reduced in the North (see (2.13)). The sigh of condition (2.14) is intuitively also clear: Adaptation makes the production of vulnerable more profitable.

3 A Numerical Model for Evaluating International Trade, Adaptation and Climate Change

The following numerical analysis extends our theoretical discussion on the interaction between adaption to climate change and international trade both quantitatively and qualitatively. It is based on MITACC, which is an intertemporal general equilibrium Model for evaluating International Trade and regional Adaptation to Climate Change. In common with its predecessor (see Schenker, 2009), it integrates sub-models, which provide a reduced-form description of the regional economies, international trade and damage assessment. But in contrast to the former, where the focus was on the spillover of climate impacts across regions, and where adaptation was captured only implicitly, MITACC includes a detailed representation of the regions' adaptation to climate change together combined with a top-down perspective on the remainder of their economies. This in particular is important for studying the interaction between adaptation and international trade in presence of global climate change.

The model is formulated as a mixed complementarity problem (MCP) with the GAMS software package (see Rutherford, 1995)[3]. Its current application has a mid-term perspective of forty years. Time periods are each five years in length. Starting point is 2010. Reports end at 2050 although for minimizing end-of-horizon effects, calculation exceed through 2075.

3.1 *Key features of the economic sub-model*

MITACC divides the world economy into nine regions, which are linked economically through trade and capital flows. These are (see Appendix, Table 3): North America (NAF), Europe (EUR), Oceania (OCE), and the former Soviet Union (GUS). Under the Kyoto Protocol these regions roughly constitute "Annex B". Further regions are: Middle East and North Africa (MEN), Sub-Sahara Africa (SAF), South America (SAM), East Asia (EAS) as well as South Asia (SOA). These are mostly known as developing regions and enclose nearly all "non-Annex B" countries (for details, see Table 3).

Each region is represented by a single agent, who maximizes the discounted utility of consumption subject to an intertemporal budget constraint. Each

3 A detailed explanation of the model and the production structure can be found in (Schenker, 2009). Parameter values are denoted in the Appendix.

region's wealth includes capital and labor. Other than in Schenker (2009), climate impacts are assumed to be sector specific. As in Section 2 this allows for discerning between two categories of goods and services: (1) Vulnerable, which refers to the aggregate of commodities that are produced in climate vulnerable sectors such as agriculture, fishery and forestry. (2) Non-vulnerable, which denotes the aggregate output of sectors that are almost insensitive to climate change like industrial goods and services (for details, see Appendix, Table 4). MITACC considers international trade in both vulnerable and non-vulnerable commodities and takes international capital flows as endogenous. Thereby a region may have a positive or negative trade surplus in any one time period, but the present value of these surpluses must balance off to zero over the entire planning horizon.

For the sake of simplicity let us assume that all regions share the same production technology and that there is no technological progress. Production is modeled through nested constant elasticity of substitution (CES) functions. These functions determine how the regional output of either vulnerable or non-vulnerable goods and services is determined by the inputs of capital, labor and a macro good, which is region-specific and is produced through inputs of vulnerable and non-vulnerable. In this way, the model allows for macroeconomic feedbacks. Environmental damages in one sector can spillover into the other ones and will lead to fewer resources being available for current consumption and for investment in the accumulation of capital stocks.

For being more detailed let us consider, how vulnerable production is described:

(3.1) $$z_{r,t} = \theta_{r,t} \left(\alpha_r y_{r,t}^{\rho} + (1-\alpha_r)(\beta_r k_{r,t}^{\varepsilon} + (1-\beta_r) l_{r,t}^{\varepsilon})^{\frac{\rho}{\varepsilon}}\right)^{\frac{1}{\rho}}.$$

$z_{r,t}$ denotes the output of vulnerable in region r and period t. $y^z_{r,t}$ denotes the intermediate input of the macro good into vulnerable production, $k^z_{r,t}$ and $l^z_{r,t}$ are capital and labor inputs, respectively.[4] $\alpha_r, \beta_r, \rho, \varepsilon$ are the usual parameters

4 For better readability, the superscript z is omitted in equation (3.1).

of a CES production function. As in Section 2, θ_{rt} represents the climate impact, which depends on climate change and adaptation investments. We will return to this issue in the next section. Note that production of non-vulnerable outputs has a similar structure, but by definition is not affected directly by climate change and adaptation.

A region's output of vulnerable and non-vulnerable can either be exported and/or be used domestically. We apply an Armington (1968) formulation and suppose that imports and the domestic outputs are imperfect substitutes in the regional macro production. The region-specific macro output then is used for consumption, can be invested into capital formation and adaptation and is intermediate input into the production of both vulnerable and non-vulnerable commodities (see (3.1)). We assume that labor is mobile across sectors, but not across regions. Capital is traded on open international markets. This allows reallocating capital across and hence shifting production to regions with highest comparative advantage. As such capital mobility can be viewed as some kinds of a substitute for adaptation funding.

In principle MITACC can be used for either cost-effectiveness or cost-benefit analysis. However, in what follows, greenhouse gas emissions as well as climate change are exogenously given. Projections are taken from the SRES A1B emission scenario (see Nakicenovic and Swart, 2000), which is the mostly used IPCC emission scenario and predicts an atmospheric CO2 concentration of about 550 ppm by 2050. Furthermore, the only options for responding to climate change are investment into adaptation, international trade and the reallocation of production across regions. For the latter purpose (the application presented here), the model translates global warming into its market impacts. Market effects are measured in units of GDP and are intended to measure direct climate impacts on the production of vulnerable commodities such as agricultural products and timber. In contrast non-market effects, which refer to those not traditionally included in the national income accounts, for example, the impacts on biodiversity, environmental quality, and human health, are not included.

All further parameter values such as the elasticity of substitution, the population growth rate and depreciation rate are displayed in Tables 5 and 6 (see Appendix). The regional economies, their sector production structure as well as trade flows are calibrated using data from the GTAP6 project (Dimaranan, 2006).

3.2 *Modeling adaptation*

Research on how to make adaptation explicit in the integrated assessment of climate change still is at an early stage (for a literature survey, see Patt et al., 2009). Currently, the literature distinguishes between two approaches mainly. On the one hand there are models such as AD-WITCH (see Bosello et al., 2010), where adaptation is viewed an anticipatory measure like for example the building of a dike for protecting against flooding. This in particular requires accumulating a suited capital stock, and consequently there is a time-lag between the decisions to invest into adaptation and first benefits from adaptation. On the other hand, de Bruin et al. (2009) consider adaptation a reactive measure, which will be effective almost instantaneously. Typically, this applies to agriculture, where the negative impact of climate change can be moderated almost immediately through changing crops or adjusting planting and harvesting times. Because of the mid-term perspective of our analysis, and since we are interested in the interplay between adaptation and international trade rather than in the timing of the costs and benefits of adaptation, let us focus on reactive adaptation only.

Just as in de Bruin et al. (2009) assume that impacts of climate change and costs of adaptation are separable and can be expressed in units of vulnerable products. Let $\mathrm{GD}_{r,t}$ denote gross impacts, i.e., losses of region *r* in the production of vulnerable goods in period *t* in absence of any adaptation measure. Furthermore, let $a_{r,t}$ denote the fraction of losses, which are avoided in region *r* at time *t* because of adaptation. Then, the net-impact $\theta_{r,t}$ is given by

(3.2) $$\theta_{r,t} = \mathrm{GD}_{r,t} \left(1 - a_{r,t}\right) + \mathrm{t}_{r,t}\left(a_{r,t}\right).$$

As is obvious from equation (3.2) net impacts are determined by the costs of adaptation $t_{r,t}$ as well as residual damages. Both costs and residual damages depend on adaptation $a_{r,t}$, but are independent of each other. Residual damages are gross impacts times the fraction of output losses, which have not be avoided through adaptation. Adaptation costs in region *r* and period *t* are a strictly increasing function of adaptation $a_{r,t}$

(3.3) $t_{r,t}(a_{r,t}) = \gamma_r a_{r,t}^{\tau_r}$.

Note that the parameters γ_r and $\tau_r > 1$ will be calibrated from data of adaptation costs.

3.3 *Calibrating the climate and adaptation sub-model*

Two variables are important for the assessment of climate impacts on vulnerable goods and services. This is temperature change on one hand and daily precipitation change on the other. The general circulation model ECHAM5 (see Roeckner et al., 2005)[5] has a spatial resolution of about 200 km and delivers per grid cell monthly averages for both variables. We aggregate these data to get average temperature and precipitation per region. Based on that we observe that by mid of the century the former Soviet Union (GUS) and North America (NAF) must expect an increase of average surface temperature of about 3 to 3.5 °C.[6] MENA and Sub Saharan Africa (SAF), which are already at the climate margin in agricultural production, are awaiting an increase of about 2.3 °C, whereas for Oceania (OCE) a more moderate temperature increase of about 1.6^{0}C is expected.

Projections on precipitation are more uncertain and trends are not as linear as in the case of temperature. In South Asia (SOA) for example precipitation will raise by 4% only, whereas North America (NAF) and GUS might expect an increase of approximately 8 - 11%. An exception is MENA. Today Middle East

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[5] Output from ECHAM5 experiments can be downloaded from http://www.ipcc-data.org.

[6] Polar regions will face a higher temperature increase than those in lower latitudes, but since these regions are sparsely populated we probably overestimate the impact of climate change on these regions.

and North Africa are already dry regions and a further decline in precipitation is expected until mid of the century.

Changes in temperature and precipitation primarily affect agricultural production, which is the most important one among vulnerable sectors (see Appendix, Table 4). For estimating market damages of climate change it seems legitimate, therefore, to use the reduced form of a climate impact function, which Mendelsohn and Schlessinger (1999) have established. This response function is based upon Adams et al. (1999), who examine the impact of climate change on US agricultural production. As such the Mendelsohn - Schlessinger (MS) function performs well for the agricultural sector of the US economy, but cannot correctly explain the effects of climate change on agriculture in other regions of the world.

To overcome this problem, we adopt the approach of Cline (2007) and assume that the changes in output per hectare are predicted accurately by the MS function, but the base-line averages are wrong. In other words, we are adding a regional-specific constant to the response function of each country in order to equalize for the difference between the estimated and the actual average output. Since the derivative is independent from such a constant, the output change per hectare will remain unchanged. The total derivative of the response function is then (see Cline, 2007)

(3.4) $$d\Theta_{r,t} = 116dT_{r,t} - 9.9T_{r,t}dT_{r,t} + 0.47dP_{r,t}.$$

$d\Theta_{r,t}$ denotes the change in output per hectare in region r at time t, $dT_{r,t}$ and $dP_{r,t}$ are the changes in temperature $T_{r,t}$ (degree Celsius) and precipitation (mm per year), respectively. Other than in the original MS study and also different from Cline (2007), we neglect the carbon fertilization effect of climate change, which is seriously debated in literature and seems highly uncertain in quantities. This might imply, however, that we overestimate the adverse impacts of climate change on agriculture.

4 Results from Numerical Simulations

Four scenarios are discussed in the following. The first one is called BASE. It serves the purpose of a reference scenario and is founded on the assumption that the world economy develops without being affected by climate change and variability.

The second scenario is called TUMB. It reflects what might happen, if there are impacts of climate change, but agents behave as “dump farmers”. That means, global warming distresses the regional economies, but economic agents do not respond and hence do not invest into adaptation for reducing the impact of climate change and vulnerability. Obviously this is an unrealistic assumption, but allows assessing the effectiveness of adaptation measures.

As was mentioned earlier, adaptation can create benefits, which are private to the single region. Therefore, self-interest suggests that some adaptation is made autonomously, quasi by the markets. Our third scenario, which we call AUTO, explicitly incorporates autonomous adaptation to climate change and variability. That means, in AUTO regions invest into adaptation until regional marginal benefits from adaptation are equal to the region’s marginal costs of adaptation.

Finally, FUND is the short-cut of the fourth scenario. As was mentioned in the introduction three funds exist for supporting adaptation in the developing countries. Overall it is to be expected that most of adaptation funding goes through the same channels as classical development assistance does. The UN Millennium Development Goals demand that the developed countries should provide 0.7% of their Gross National Income (GNI) as development assistance. To keep our analysis simple, we follow that rational and suppose that the “Annex B” regions such as Europe (EUR), North America (NAF), and Oceania (OCE) transfer 0.1% of their gross national income to the “non-Annex B” ones Sub-Sahara Africa (SAF), South America (SAM) as well as South Asia (SOA). In 2050 this would imply a transfer of total 27 billion $ US, and hence almost half of what world-wide is spent autonomously on adaptation. We further assume that the funds then are equally shared among the recipient region. The transfer can be exclusively used for adaptation measures in the recipient regions. We rule out the possibility of crowding-out effects and assume that the developing regions chose their autonomous adaptation level independently from any funding. That means in particular that the foreign contributions are additional, going beyond the adaptation level, which was chosen autonomously by the developing regions.

4.1 TUMB: climate impacts, trade but no adaptation

If there is no investment into adaptation, the ECHAM5 SRES A1B scenario predicts that by the mid of the century world-wide damages of climate change will account to 8.4 % of the Gross World Product (GWP). These damages are not equally distributed across regions. The more exposed a region is to climate change, the higher is the impact, which climate change directly has on agriculture and other vulnerable sectors. This implies in particular that those regions, where agricultural production is an important source of national income, are confronted with significant economic losses. In Oceania (OCE) for example, where the productivity in agriculture is already low, the output of food production per hectare will be reduced by more than 68%. In Sub-Saharan Africa (SAF), South America (SAM) and in South Asia (SOA) a cut-back of 66%, 63% and 20%, respectively, is to be expected. This is in sharp contrast to the former Soviet Union (GUS) and North America (NAF), where the output of vulnerable sectors will increase by 5% and 7%, respectively. In these regions agriculture can benefit from global climate change. And since these two regions are huge and produce a significant fraction of the world foods supply, the output of agriculture world-wide will decline by 1% only till in 2050.

By definition the production of non-vulnerable goods such as personal computers is not directly affected by climate change. Nonetheless, indirect impacts, which result from inter-sector spillover, can be important. In Europe (EUR), for example, non-vulnerable production will decrease by approximately 4%. Sub-Sahara Africa (SAF) as well as South America (SAM), which already suffer from a decline in vulnerable production, might face losses of about 22% in the output of non-vulnerable. As such these regions are not able to compensate the shortfall of income from vulnerable production through selling more non-vulnerable to the world market. This makes the argument that shifting agricultural production to more northern latitudes could be a kind of adaptation to climate change (see Julia and Duchin, 2007), a questionable one. In contrast, our calculations show that the adaptation-through-trade-argument has a "let them eat cake"-flavor as Cline (2007) has stated it.[7]

4.2 AUTO: climate change, trade and autonomous adaptation

Let us start by considering, how autonomous adaptation can moderate the impact of climate change on world GDP.

Given that most of the developing countries are confronted with the financial constraints and lack advanced institutions, the assumption that all regions are able to implement autonomously the optimal level of adaptation is obviously is a heroic one. Nonetheless, let us stick to that assumption. Even then optimal adaptation does not completely help avoiding the negative impact of climate change on the world's gross production (GWP). As Figure 4.1 shows there still is a decrease of more than 4 % GWP by 2050.

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[7] Applying Hicksian equivalent variation exhibits that those regions, which are confronted with large impacts on agriculture, might loose high fractions of their welfare. In case of Oceania this would be 16%, in developing regions, such as Sub Saharan Africa and South America, even 41% and 32%, respectively. Europe, which is a less vulnerable region, welfare looses are in the order of 1.4%, while North America and the GUS region slightly can profit.

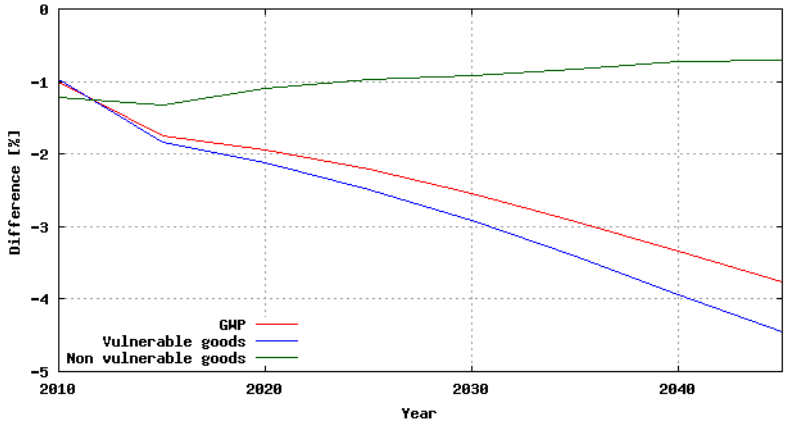

Figure 4.1: Percentage change of the Gross World Product, world output in vulnerable goods, and world output in non-vulnerable output with autonomous adaptation (relative to BASE).

A was mentioned above, economic rationality suggests to invest into adaptation until marginal benefits are equal to marginal costs. Therefore scenario AUTO assumes that each region autonomously chooses a level of adaptation such that marginal damages or benefits are equal to marginal adaptation costs. For any *t* and *r* equations (3.2) and (3.3) therefore imply that optimal adaptation expenditure $\bar{t}_{r,t}$ is given by

$$(4.1) \qquad \bar{t}_{r,t} = \gamma_r \left(\frac{\gamma_r \tau_r}{GD_{r,t}} \right)^{\frac{\tau_r}{1-\tau_r}} .$$

Note that optimal adaptation depends only on the gross impacts and parameters of the adaptation cost function. Neither regional income nor output plays a role for the optimal expenditures.

Based on equation (4.1), our calculation show that by the mid of the century Oceania (OCE) will contribute 1.46% of its GDP autonomously to adaptation (see Figure 4.2 left side, bottom). This would account to 1.7 billion $US. Worldwide expenditures for autonomous adaptation are expected to be in the order of magnitude of 56 billion $US by 2050. This is significantly higher than what the World Bank (2007) has estimated, and which would be in the range of 10 to 40 billion $US, but below the UNFCCC (2007) estimate of 46 to 171 billion $US in 2030.

As follows from equation (3.2) benefits of adaptation correspond to fraction of damages avoided. As Figure 4.2 (top) shows, Europe is able to prevent 13% of climate damages in the vulnerable good sector by 2050. Regions, which will be more heavily affected such as Oceania (OCE), Sub Saharan Africa (SAF), and South America (SAM) can reduce their damages by one third approximately. GUS and NAFTA, the two regions, which already benefit in the medium term from climate change, can additionally increase these benefits through investing into adaptation by 26% and 14%, respectively.

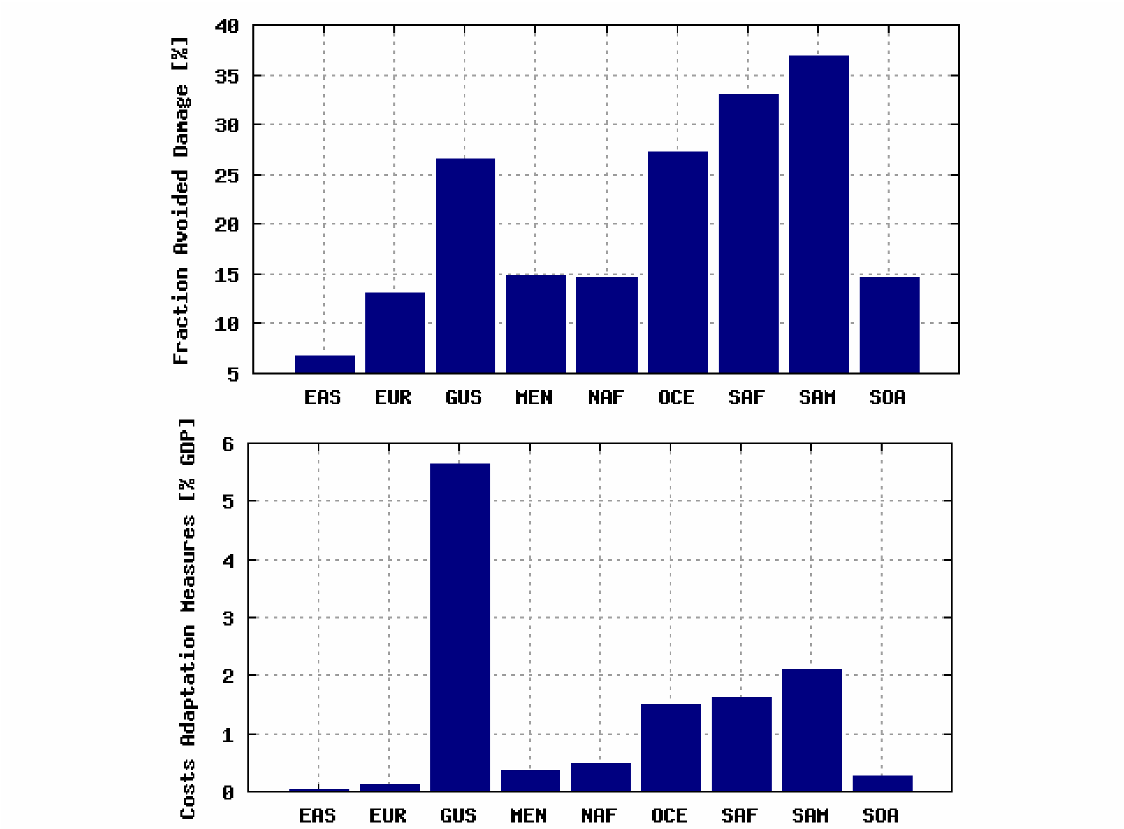

Figure 4.2: The top figure shows the autonomous chosen level of adaption for each region, whereas the corresponding costs are showen in the bootom figure

Moderating the impact of climate change immediately affects the production of vulnerable products and services, as equation (3.1) indicates. Therefore, autonomous adaptation has largely positive effects on the regional production. Regions, which highly depend on agricultural production, such as South America (SAM) and Sub Sahara Africa (SAF) can increase their vulnerable output by 21% and 19%, respectively. Oceania (OCE) is able to raise the output of agricultural goods by 10% relative to the TUMB scenario. But if the compare the results, we get for a world with autonomous adaptation (AUTO), with a the results, we would observe in absence of climate change (BASE), then the heavily affected regions still have to cope with large losses in the production of vulnerable goods (see Figure 4.3).

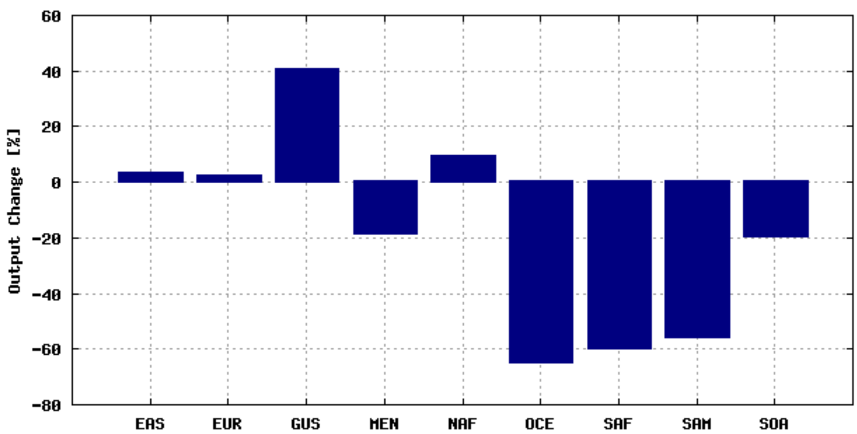

Figure 4.3: 2050 differences in vulnerable output with autonomous adaptation relative to outputs in absence of climate change.

Climate change creates comparative advantages in producing vulnerable goods for those regions, which are less affected. Consequently, adaptation reduces the comparative advantage of the less affected regions. They will increase their output only slightly (NAF 1.9%, MENA 0.8%) or even reduce the production of those goods (EUR:1.8%, EAS:1.1%). Only GUS can even increase the benefits and increase their production of vulnerable goods by again almost a 40% relative to the outcome without climate change (see Figure 4.3).

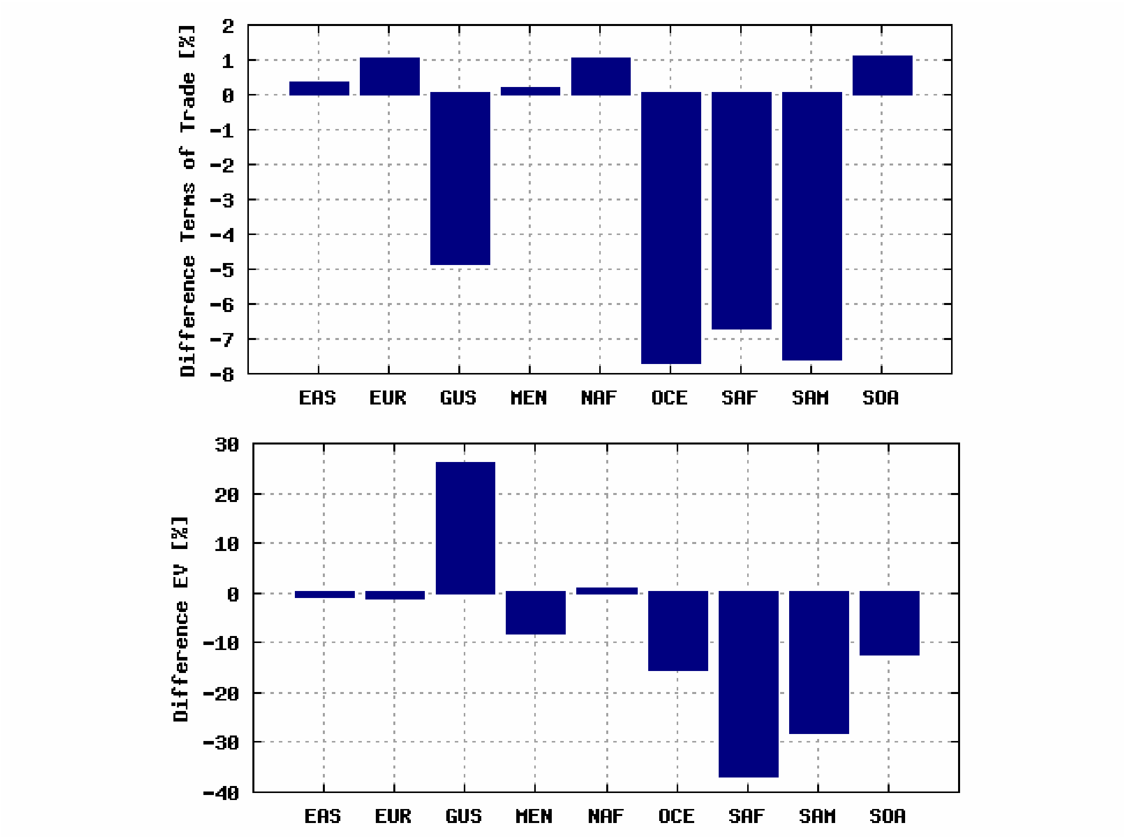

Figure 4.4: Change in terms of trade and welfare, measured by Hicksian Equivalent Variation

Changes in comparative advantage because of climate change and adaptation affect the Terms of Trade (ToT). At first glance we would expect that the main agricultural exporters can gain from terms of trade effects, since vulnerable commodities are becoming scarcer and hence will be more expensive. But as our calculations reveal, the world-wide decrease in agricultural output in small and hence prices for vulnerable change only slightly. On the other hand we observe a large reduction in output of non-vulnerable goods, making these goods relatively more expensive. Hence in contrast we observe that the main-agricultural exporters have to cope with a significant reduction in ToT (see the top of Figure 4.4). Oceania (OCE) looses almost 8% relatively to the counterfactual benchmark scenario without climate change. Also SAF and SAM loose 6.7% and 7.5%, respectively. In contrast EUR and NAF gain each almost one percent in ToT.

Together with the reduced direct impacts through adaptation the change in terms of trade causes indirect changes in welfare of the considered regions (see the bottom of Figure 4.4). Whereas GUS gains 25% of welfare in terms of Hicksian Equivalence Variation, highly vulnerable developing regions such as Africa and South America are confronted with losses of 37% and 28% welfare. For the high developed regions EUR and NAF welfare effects are rather moderate.

4.3 FUND: climate impacts, trade and the funding of adaptation

As was mentioned at the beginning of this section, for the purpose of FUND it is assumed: (1) the developed world annually spends 0.1% of its Gross National Income for funding adaptation in the developing world regions, (2) funds are equally shared among the recipient region, and (3) the transferred resources are exclusively used for adaptation without crowding-out autonomous adaptation in these regions.

Adaptation funding, as described above, has a positive effect on total output. Compared to the outcome of our simulation in the AUTO, i.e. the scenario with autonomous adaptation only, the world gross production (GWP) is increased by 1.46% in 2050. If we look on sector output, both the vulnerable and non-vulnerable sector shows almost identical changes in output relative to AUTO. These are 1.4% in vulnerable goods, and 1.47% in non-vulnerable outputs. In other words, although the production of non-vulnerable is not directly affected, it nevertheless profits from the increase in adaptation (for an extensive research on that argument, see Fankhauser and Tol, 2005).

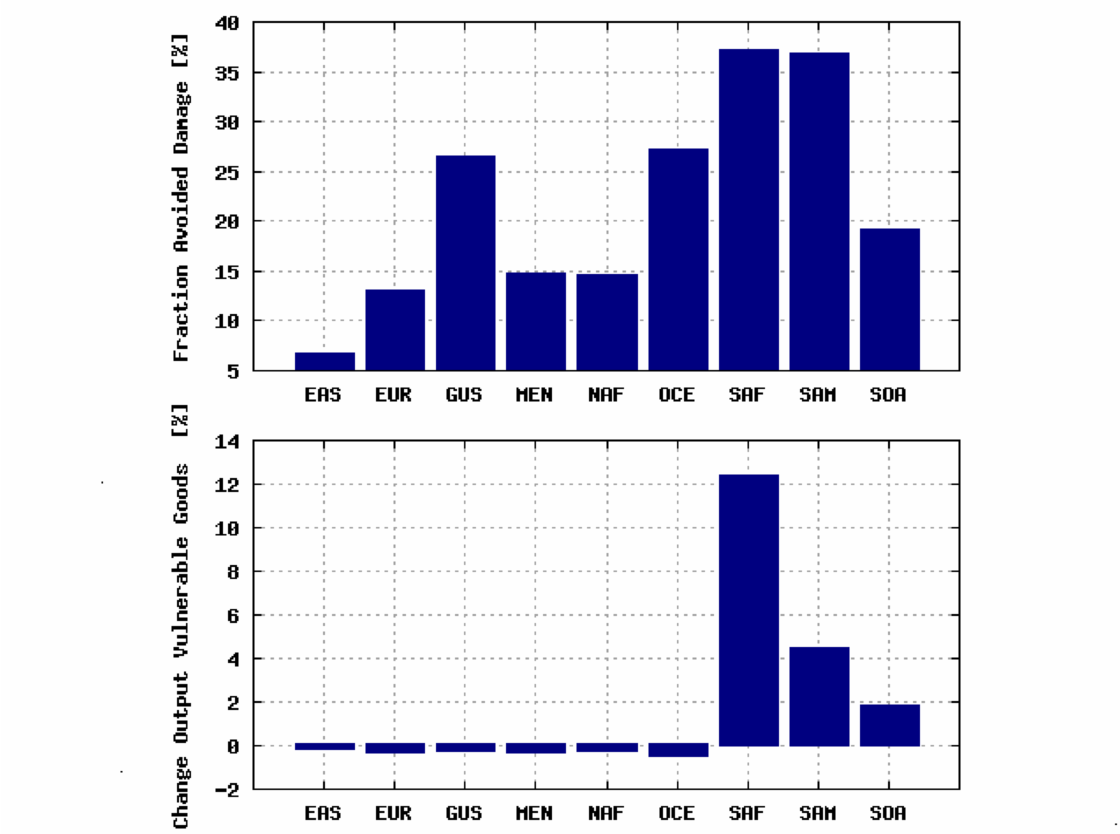

Figure 4.5: Damages avoided (per region in 2050) and percentage changes in output of vulnerable. Results from comparing FUND and AUTO.

Funding of adaptation mot only positively affects the world's output of vulnerable and non-vulnerable commodities and services. It also leads to a shift of production capacities across regions. The recipient regions are gaining comparative advantage in the production of vulnerable goods, since productions costs are reduced because of additional adaptation. Consequently, there is an increase in the output of vulnerable goods in all regions, which are financially supports through the funding of adaptation. As shown in Figure 4.5 the output of vulnerable goods is increasing by 4.3% in South America (SAM) and by 1.78% in South Asia (SOA), respectively. In Sub-Sahara Africa (SAF) these changes in output compared to AUTO are even more significant. Under FUND assumptions in 2050 the output of vulnerable goods is more than 12% higher than in the scenario with autonomous adaptation (AUTO). In all other regions, the output of vulnerable goods is decreasing.

Finally, let us have a look on terms of trade (ToT) as well as welfare effects. If production is reallocated across regions, this must have an impact of the terms of trade.

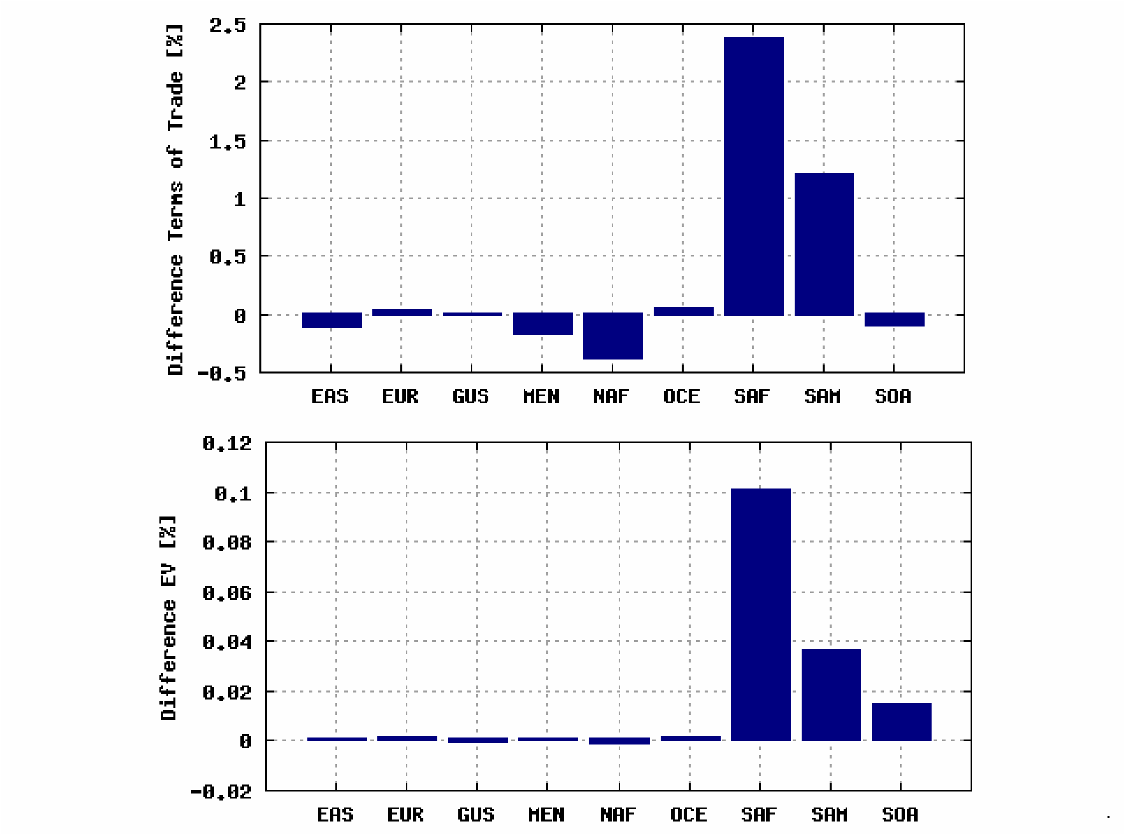

Figure 4.6: Changes in terms of trade and welfare, measured by Hicksian Equivalent Variation

Whereas the main exporters of agricultural products such as GUS and North America (NAF) have to cope with a decrease in their ToT, other regions such as Europe (EU), Oceania (OCE), Sub-Sahara Africa (SAF), and South America (SAM) can profit from an improvement in their ToT. This of course has effects on regional welfare. There are two effects mainly funding adaptation has on the regions' welfare. On the one hand we have a direct income transfers and regions might profit from an increase in their terms of trade on the other. This implies the following welfare effects, which are measured by Equivalence Variation and hence are expressed in units of national income: For East Asia

(EAS) and Middle East and North Africa (MEN) welfare are negligible. The two biggest exporters of vulnerable products, GUS and NAF will be confronted with a decrease of welfare in the range of 0.03% -0.1% of their income. The other regions, however, can benefit from the funding adaptation. The biggest benefits are observed in by the recipients Sub-Sahara Africa (SAF) gains 5.8%, South America (SAM) 2% and South Asia can at least realize welfare gain of SOA 1%. Positive but small benefits are observed for two of the funding regions, namely Oceania (OCE) and Europe (EUR). That means that the welfare loss due to the financial funding of adaptation is smaller than the welfare gain due to the reduction of the indirect costs of climate change for those regions. This shows that the funding of adaptation might be beneficial even for the funder. However, this does not apply to any of the funding regions: Since North America (NAF) is a net-exporter of vulnerable goods and looses comparative advantages relative to the adaptation recipients it has to cope with a small welfare decrease.

5 Final remarks

Generally one might conclude that trade can greatly reduce losses from global climate change. This is consistent to what the existing literature on global warming and agriculture reports (for references, see Julia and Duchin, 2007). But as Cline (2007) notes this has a “let them eat cake” flavor, since the developing nations are most likely to experience greater losses in the production of vulnerable commodities among which agriculture is the most important one. A focus on trade implicitly argues that these countries can limit losses from global warming by shifting to imports rather than producing vulnerable goods at home. The problem is that they may face difficulties increasing export earnings from other goods in order to pay for their new food import needs. Incorporation of world trade moderation of global warming damage should at the minimum include corresponding estimates of the terms-of-trade losses of the poorer countries

Finally, it must be mentioned that the analysis is based on the assumption that vulnerable products are traded on open and perfect world markets. Reality is far away from such a situation. In particular, this is not the case regarding international trade of agricultural products. For example, in 1973 the United States imposed an embargo on soybean exports in order to avoid inflationary effects of rising prices, and many nations are inclined to impose agricultural import barriers in the name of food self-sufficiency.

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Appendix 1

Remember that conditions (3.4), (3.5) and (3.6) implicitly define: (1) capital inputs $k_n = K_n(r, x_n)$ as function of capital prices r and inputs of vulnerable products x_n, (2) imports of vulnerable products as function $x_n = X_n(p, k_n)$ of the world market price p and capital inputs k_n, (3), exports z_n as function of both the world market price p and the region's climate exposure $\theta_n(T, a_n)$, i.e., $z_n = Z_n(\theta_n(T, a_n), p)$, respectively. This implies for $n = N, S$

(A1) $$\frac{\partial k_n}{\partial r} = \frac{1}{\frac{\partial^2 f_n}{\partial k_n^2}} < 0,$$

(A2) $$\frac{\partial x_n}{\partial p} = \frac{1}{\frac{\partial^2 f_n}{\partial x_n^2}} < 0,$$

(A3) $$\frac{\partial k_n}{\partial x_n} = -\frac{\frac{\partial^2 f_n}{\partial x_n k_n}}{\frac{\partial^2 f_n}{\partial k_n^2}} > 0$$

(A4) $$\frac{\partial x_n}{\partial k_n} = -\frac{\frac{\partial^2 f_n}{\partial x_n k_n}}{\frac{\partial^2 f_n}{\partial x_n^2}} > 0$$

(A5) $$\frac{\partial z_n}{\partial p} = \frac{1}{\frac{\partial^2 g_n}{\partial z_n^2}} > 0,$$

(A6) $$\frac{\partial z_n}{\partial T} = -\frac{\frac{\partial^2 g_n}{\partial z_n \partial \theta_n}}{\frac{\partial^2 g_n}{\partial z_n^2}}\frac{\partial \theta_n}{\partial T} < 0,$$

(A7) $$\frac{\partial z_n}{\partial a_n} = -\frac{\frac{\partial^2 g_n}{\partial z_n \partial \theta_n}}{\frac{\partial^2 g_n}{\partial z_n^2}}\frac{\partial \theta_n}{\partial a_n} > 0.$$

These conditions are almost immediately obvious. If the world market price of vulnerable products ceteris paribus rises, less is put into production, but more is exported to the world market. Furthermore, if the regions' direct exposure changes but the world market price p of vulnerable products ceteris paribus stays constant, then the supply is reduced because of rising marginal costs of production. In other words, the direct effect, an increased direct exposure to climate change and variability has on the regional exports of vulnerable products, is negative.

Finally note that

(A8) $$\left(\frac{\partial^2 f_n}{\partial x_n k_n}\right)^2 = \frac{\partial^2 f_n}{\partial k_n^2}\frac{\partial^2 f_n}{\partial x_n^2},$$

which, because of the linear homogeneity of the production functions $f_n, n = N, S,$ directly follows from Euler's equation.

Proof of Proposition 1:

By taking the total differential of condition (3.1) we get

$$\left(\frac{\partial z_N}{\partial T} + \frac{\partial z_S}{\partial T}\right)dT + \frac{\partial z_N}{\partial a_N}da_N + \frac{\partial z_S}{\partial a_S}da_S - \frac{\partial x_N}{\partial k_N}dk_N - \frac{\partial x_S}{\partial k_S}dk_S =$$

$$\left(\frac{\partial z_N}{\partial p} + \frac{\partial z_S}{\partial p} - \frac{\partial x_N}{\partial p} - \frac{\partial x_S}{\partial p}\right)dp$$

or, since $dk_N = -dk_S$ (see condition (3.2))

$$\left(\frac{\partial z_N}{\partial T} + \frac{\partial z_S}{\partial T}\right)dT + \frac{\partial z_N}{\partial a_N}da_N + \frac{\partial z_S}{\partial a_S}da_S - \left(\frac{\partial x_N}{\partial k_N} - \frac{\partial x_S}{\partial k_S}\right)dk_N =$$

$$\left(\frac{\partial z_N}{\partial p} + \frac{\partial z_S}{\partial p} - \frac{\partial x_N}{\partial p} - \frac{\partial x_S}{\partial p}\right)dp$$

Recall that condition (3.6) implies

$$\frac{\partial f_N}{(\partial k_N)(x_N, k_N)} = \frac{\partial f_S}{(\partial k_S)(x_S, k_S)},$$

and hence by taking the total differential

$$\frac{\partial^2 f_N}{\partial k_N^2} dk_N + \frac{\partial^2 f_N}{\partial x_N \partial k_N} dx_N = \frac{\partial^2 f_S}{\partial k_S^2} dk_S + \frac{\partial^2 f_S}{\partial x_S \partial k_S} dx_S \, .$$

Now, since $dx_n = \frac{\partial x_n}{\partial k_n} dk_n + \frac{\partial x_n}{\partial p} dp$ and since conditions (A4) and (A8) together imply

$$\frac{\partial^2 f_n}{\partial x_n \partial k_n} \frac{\partial x_n}{\partial k_n} = -\frac{\partial^2 f_n}{\partial k_n^2} \, ,$$

we observe

(A9) $$\frac{\partial^2 f_N}{\partial x_N \partial k_N} \frac{\partial x_N}{\partial p} dp = \frac{\partial^2 f_S}{\partial x_S \partial k_S} \frac{\partial x_S}{\partial p} dp \, ,$$

which means (see (A2) and (A4))

(A10) $$\frac{\partial x_N}{\partial k_N} = \frac{\partial x_S}{\partial k_S} .$$

Consequently

$$dp = \left((\partial z_\downarrow N)/\partial T + (\partial z_\downarrow S)/\partial T \right) / \left((\partial x_\downarrow N)/\partial p + (\partial x_\downarrow S)/\partial p - (\partial z_\downarrow N)/\partial p - (\partial z_\downarrow S)/\partial p \right) dT + \left((\partial z_\downarrow N)/(\partial a_\downarrow N \right.$$
.

Proof of Corollary 1:

Consider the first order conditions

(3.4) $$\frac{\partial f_n}{\partial x_n (x_n, k_n)} - p = 0 \, , \quad n = N, S \, ,$$

(3.6) $$\frac{\partial f_n}{(\partial k_n)(x_n, k_n)} - r = 0 \, , \quad n = N, S \, .$$

which implies

$$\frac{\partial f_N}{\partial x_N} - \frac{\partial f_S}{\partial x_S} = 0$$

$$\frac{\partial f_N}{\partial k_N} - \frac{\partial f_S}{\partial k_S} = 0 \; .$$

By taking the total differential and by taking into account that $dk_N = dk_S$, this gives the following system

.

Let A denote the determinate of the above matrix, i.e. $A = \frac{\partial^2 f_N}{\partial x_N^2}\frac{\partial^2 f_S}{\partial k_S^2} - \frac{\partial^2 f_N}{\partial x_N \partial k_N}\frac{\partial^2 f_S}{\partial x_S \partial k_S}$, which under the usual condition that cross derivatives do not dominate is positive. Then by using Cramer's rule, we obtain

$$dk_N = \frac{1}{A}\left[\frac{\partial^2 f_N}{\partial x_N^2}\frac{\partial^2 f_S}{\partial x_S \partial k_S} - \frac{\partial^2 f_N}{\partial x_N \partial k_N}\frac{\partial^2 f_S}{\partial x_S^2}\right] dx_S \; .$$

Condition (A9), however, implies $\frac{\partial^2 f_N}{\partial x_N^2}\frac{\partial^2 f_S}{\partial x_S \partial k_S} - \frac{\partial^2 f_N}{\partial x_N \partial k_N}\frac{\partial^2 f_S}{\partial x_S^2} = 0$, and hence $dk_N = 0$.

Appendix 2

1 *Data Aggregation*

Regional Aggregation:

Region	**Composition**
Oceania	Australia, New Zealand, Rest of Oceania
East Asia	China, Hong Kong, Japan, Korea, Taiwan, Rest of East Asia
South Asia	Indonesia, Malaysia, Philippines, Singapore, Thailand, Vietnam, Bangladesh, India, Sri Lanka, Rest of South and South East Asia

Region	Composition
North America	Canada, United States, Mexico, Rest of North America
South America	Colombia, Peru, Venezuela, Rest of Andean Pact, Argentina, Brazil, Chile, Uruguay, Rest of South America, Central America, Rest of FTAA, Rest of Caribbean
Europe	Austria, Belgium, Denmark, Finland, France, Germany, United Kingdom, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, Switzerland, Rest of EFTA, Rest of Europe, Albania, Bulgaria, Croatia, Cyprus, Czech Republic, Hungary, Malta, Poland, Romania, Slovakia, Slovenia, Estonia, Latvia, Lithuania
GUS	Russian Federation, Rest of Former Soviet Union
MENA	Turkey, Rest of Middle East, Morocco, Tunisia, Rest of North Africa
Sub Sahara Africa	South Africa, Rest of South Africa CU, Malawi, Mozambique, Tanzania, Zambia, Zimbabwe, Rest of SADC, Madagascar, Uganda, Rest of Sub-Saharan Africa

Table 3: Aggregation of region r out of GTAP6

Sectoral Aggregation

Sector in model	GTAP6 Sector
Vulnerable Goods	Paddy Rice, Wheat, Cereal grains, Vegetables, Fruit, Nuts, Oil Seeds, Sugar Cane, Plant-based bers, Crops, Cattle, Sheep, Goats, Horses, Animal Products, Raw milk, Wool, Silk-worm cocoons, Forestry, Fishing, Meat, Vegetable oils and fats, Dairy products, Processed rice, Sugar, Food products, Beverages,

Sector in model	GTAP6 Sector
	Tobacco, Transport, Sea Transport, Insurance, Recreation and other services
Non Vulnerable Goods	Coal, Oil, Gas, Minerals, Textiles, Wearings apparel, Leather products, Wood products, Paper products, Publishing, Petroleum, Coal Products, Chemical, Rubber, Plastic prods, Mineral products, Motor vehicles, Transport equipment, Electronic equipment, Machinery, Manufactures, Electricity, Gas manufacture, distribution, Water, Construction, Trade, Air Transport, Communication, Financial Services, Business Services, Public Administration, Defence, Health, Education, Dwellings

Table 4: Aggregation of sector i out of GTAP6

2 *Parameters*

Elasticities of Substitiution	Value
Aggregate Commodities to GDP σ^Q	0.2
Capital - Labor in Vulnerable Goods	0.4
Capital - Labor in Nonvulnerable Goods	0.6
KL - Intermediates in Vulnerable Goods	0.7
KL - Intermediates in Nonvulnerable Goods	0.2
Armingto Foreign - Domestic Vulnerable Goods σ^A_V	4.27
Armington: Foreign - Domestic Nonvulnerable Goods σ^A_{NV}	4.66
Intertemporal Elasticity of Substitution	5

Table 5: Elasticities of substitution

Parameter	**Value in per cent**
Annual Discount Rate	5
Annual Depreciation Rate	5
Annual Population Growth Rates:	
Oceanina	1.8
East Asia	4.5
South Asia	4.5
NAFTA	1.92
South America	4.1
Europe	2
GUS	3.1
Sub Sahran Africa	4.1

Table 6: Fundamental Parameters in per cent