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On Interactions of Optimal Climate Policy and International Trade. An Assessment of Border Carbon Measures.

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Abstract

Not only after the failure of the Copenhagen climate conference 2009, border carbon adjustment (BCA) has received growing attention in the climate policy debate as a measure to combat “carbon leakage” and force non-abating countries to tighter climate policies.

In this paper, we study the strategic interactions between international trade and climate policy with a focus on the effectiveness of border measures. First, we analyze the main principles of unilateral climate policy with international trade in a small analytical model. Second, we examine welfare effects of WTO compatible carbon import tariffs in a stylized numerical integrated assessment model with explicit trade in commodities and analyze if BCA is a credible threat to force non-abating countries to implement stricter climate policies.

We show that the terms of trade effects can, depending on trade patterns, ease or boost the prisoners dilemma of mitigating greenhouse gases. We further demonstrate that WTO conform BCA increases the effectiveness of climate policy and forces trading partners to reduce emissions. But as the results of the numerical model illustrate, welfare effects are depended on trade flows and are negative for realistic parameter values.

Keywords: International Trade, Environmental Policy, Border Tax Adjustment

JEL-Classification: H20, F18, Q54

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1 Introduction

After the failure of the Copenhagen climate conference 2009 the difficulty to coordinate international climate policy became once more evident. Unilateral climate policy measures have several international dimensions, which makes it challenging to reach an joint agreement.

First, the mitigation of greenhouse gases is a typical example of a public good. The warming potential of greenhouse gas (GHG) emissions and its impact on the environment is uncorrelated to the location of the emitter. Hence, if country A mitigates, country B profits from the abatement effort by the same amount as A does.

Second, unilateral climate mitigation policies may rise production costs and prices of carbon intensive goods, which may endanger domestic competitiveness in international markets. Furthermore, this price increase might be an incentive for producers in countries with less tighten abatement policies to extend the production of carbon intensive goods and hence increase emissions, counteracting the others abatement efforts.

Several studies estimated the size of this *carbon leakage* problem. The range in estimations is large and uncertainties seem to be high. But most analyses conclude that the efforts of *Annex B* countries, which have committed themselves to reduce GHG emissions in the *Kyoto Protocol*, cause a "leakage" between 5% to 20% in *Non-Annex B* countries (Metz, Davidson, Bosch, Dave, and Meyer 2007, Ch. 11).

As an approach to overcome this problem, trade policy instruments such as *border carbon adjustments* (BCA) came into the debate. Such a border measure could be a tax on imported carbon intensive products or a requirement for the exporting country to buy domestic emission permits and to offset so carbon emissions incorporated in the imported good. BCA should so counteract the negative competitiveness effects of GHG mitigation policies by leveling the playing field between domestic and foreign producers and force countries without substantial commitments to reduce GHG emissions. Early contributions on border tax adjustments in general show that they guarantee trade neutrality if goods are different taxed in different regions (Bhagwati and Srinivasan 1973). In his seminal paper, Markusen (1975) applied such border measures on environmental problems and showed that import tariffs are part of the optimal policy set for transboundary pollution problems. Copeland (1996) has generalized this work for variable abatement technologies. He concludes that the affected country should levy an tariff, which varies with the pollution content of the imports. He further shows that even if Foreign reduces pollution as a respond to Homes trade policy, Home should adhere to the import tariff to maximize rents.

It also seems that such measures may increase the political enforceability of climate policy and becoming even a *conditio sine qua non* in certain countries. In Europe, the *European Commission* (EU) is working on a proposal for an internal minimum carbon tax by updating the *EU Energy Taxation Directive* (2003/96/EC). In the United States, *The America Clean Energy and Security Act* wants to force importers of carbon-intensive products to buy emission permits analogue to domestic producers.[1] The US delegation claimed also at the Copenhagen *UN Climate Conference* that such border measures should be an integral component of a Post-Kyoto agreement. This may indeed increase the size of the coalition in favor of an abatement agreement, as the work of Lessmann, Marschinski, and Edenhofer (2009) and Barrett (1997) shows.

It remains the question if such border measures are conform with World Trade Organization (WTO) constraints. Ismer and Neuhoff (2007) argue that if carbon tax adjustment at the border is based on the carbon content of the imported good as if it would be produced with the best available production technology in the levying country, then the measure should be compatible with WTO obligations. I.e. not the actual carbon content of the imported commodity is taken into account as the assessment basis of the tariff, which obviously reduces the efficiency of the instrument.

Alexeeva-Talebi, Löschel, and Mennel (2008) show with a numerical general equilibrium model that border measures might improve the efficiency of EU's climate policy and increase the competitiveness of European energy-intensive industries. However, the distinction between sectors covered by emission trading and a border tax adjustment scheme and non-covered sectors has some problematic consequences. BCA causes a shift in emissions and puts a higher burden on non-covered sectors. Since marginal abatement costs in the non-covered sectors are higher, welfare effects are ambiguous. In an earlier contribution Babiker and Rutherford (2005) studied the economic effects of border measures under the targets of the Kyoto agreement. They show that the introduction of BCA is welfare improving.

However, this studies differ in their setup from ours (and hence in their conclusions) since they assume an exogenous given climate policy and then compare the effectiveness of BCA. We use a different approach. Our starting point is an optimal unilateral climate policy and we add BCA as an additional policy instrument for the regulator.

Under this assumptions we want to examine the question if such border carbon measures are an effective instrument to minimize carbon leakage under optimal climate policy and if BCA is a credible threat for the taxed countries to adopt stricter mitigation policies. First, we illustrate the main principles behind the interaction of trade and environmental policy in a small analytical model. For a quantitative assessment of the effects and a comprehensive welfare analysis, we use then an extended version of the RICE integrated assessment framework. We distinguish in our analysis between two regions: Annex B and Non-Annex B of the Kyoto protocol, whereas both choose their optimal unilateral climate policy. The model allows us to extend the effects of explicit trade in commodities on optimal climate policy and vice versa in an integrated assessment framework.

The analysis shows that BCA is effective in combating leakage and improves the ef-

[1] The *America Clean and Energy Security Act* plans to introduce an GHG emission trading scheme for the US industry. The bill was passed by the *House of Representatives* on June 26, 2009 and is still in consideration in the *Senate*.

fectiveness of Annex B's unilateral abatement policies. But due to existing trade pattern, BCA has a negative effect on the terms of trade under optimal unilateral climate policies and hence causes relevant welfare costs for Annex B. Therefore, such measures are not obvious a credible threat to force other regions to implement stricter environmental policies.

The remainder of the paper is organized as follows: Section 2 explains the set up of the analytical model, provides in sections 2.1 to 2.3 the results of the analytical model, and discusses the effectiveness of carbon tariffs in section 2.4. Section 3 explains the numerical model. The results of the numerical simulation are provided in section 4. Finally we conclude.

2 A Small Analytical Model

In this section, we set up an illustrative model to analyze the main characteristics of climate policy in open economies and explain the mechanisms behind carbon leakage, the efficiency of border carbon adjustment as measure against leakage, and the opportunity to manipulate terms of trade with climate policy. The knowledge gained from this exercises will help to understand the rationale behind the results of the numerical model, presented in section 3.

We are interested in the interaction between two interconnected regions. The two main blocks of countries in climate politics are the Annex B countries (mainly members of OECD), which have binding mitigation targets under the Kyoto protocol, and Non-Annex B countries without binding targets. We refer to this two groups and abbreviate Annex B (Non-Annex B) with A (N).

Figure 1 explains the main characteristics of the model. The two regions A and N are linked through two channels. First, emissions generate a negative trans-boundary externality and mitigation is a public good, which creates an incentive to free ride on the others abatement efforts. Second, the two regions are linked through trade in goods and border measures might affect this flow of goods.

We focus our analysis on two types of commodities: A carbon-intensive, dirty good and a clean good, which is vulnerable to climate change. We suppose that the production of the carbon-intensive good causes an externality and affects the production of the vulnerable good.

Examples for goods produced in the carbon-intensive sectors are the production of energy with fossil fuel, cement or steel. All this sectors are responsible for a significant amount of CO_2 emissions from economic activities. The output of the carbon-intensive good in region $i \in \{A, N\}$ can be denoted as

$$D_i = D(e_i), \tag{1}$$

where e_i are the GHG emissions of region i.[2] As for any other input factor we assume

[2] Although emissions are an undesirable joint product of production, we could imagine the input of

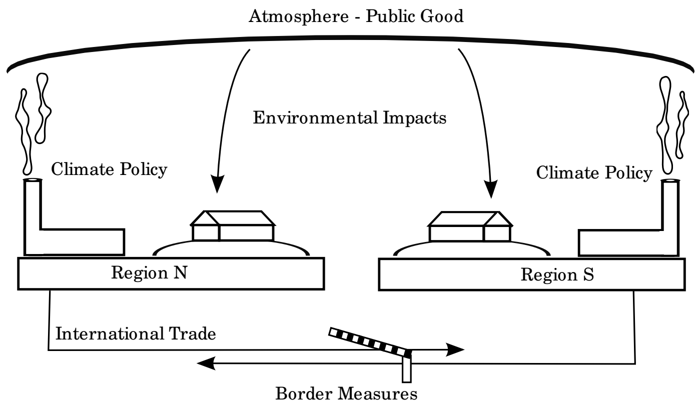

Figure 1: The main characteristics of the analytical model. We distinguish between two regions which are connected through the use of a common public good and international trade in two commodities.

decreasing marginal returns of emissions: $\frac{\partial D_i}{\partial e_i} > 0$ and $\frac{\partial^2 D_i}{\partial e_i^2} < 0$.[3]

The CO_2 emissions from producing the carbon-intensive good, regardless in which region, affect the state of the climate system and causes a degradation of environmental quality. The second sector, which produces the clean, affected good, uses environmental services as an input and has hence to cope with productivity losses from GHG, emitted by the carbon-intensive sector. Examples are sectors such as as agriculture and forestry, which are negatively affected by higher probabilities of droughts and increasing climate variability as consequences of climate change (Parry, Canziani, Palutikof, van der Linden, and Hanson 2007).

The production of the clean, affected good C_i in region i can be denoted as:

$$C_i = C(E(e_i, e_j)), \tag{2}$$

with $i \neq j$. The output of the affected good sector depends negatively on GHG emissions from both regions, neglecting other input factors. As it is the case for GHG, we assume that emissions are perfect substitutes in their damage potential, regardless of their origin, i.e. $E(e_i, e_j) = e_N + e_A$. From the discussion above follows that $\frac{\partial C_i}{\partial E} < 0$. We further assume increasing marginal damages with respect to emissions, $\frac{\partial^2 C_i}{\partial E^2} < 0$.

The assumption on increasing marginal damages due to climate change is consistent with most empirical findings on the climate vulnerability of societies (e.g Stern (2007) and Nordhaus and Boyer (2000)). Furthermore, it influences the *production possibility frontier* (PPF) of the regional economies. As shown by Baumol and Bradford (1972), market externalities might often cause non-convex production sets, which aggravates the application of standard microeconomic tools.[4] The above discussed properties of the production function ensure that the production set is convex.

emissions as the use of environmental services to deposit the joint product.

[3]Note that if $\frac{\partial D_i}{\partial e_i} > \frac{\partial D_j}{\partial e_j}$, region i has a more carbon efficient production technology than j.

[4]In the *fundamental theorems of welfare economics*, non-convexity is one of the required conditions.

Proposition 1 *Despite of negative market externalities the production set is still convex, if we assume that* $\frac{\partial D_i}{\partial e_i} > 0$ *and* $\frac{\partial^2 D_i}{\partial e_i^2} < 0$ *in the carbon-intensive sector and* $\frac{\partial C_i}{\partial e_i} < 0$ *and* $\frac{\partial^2 C_i}{\partial E(e_i)^2} < 0$ *in the affected good sector.*

The proof for proposition 1 can be found in Appendix A.1.

The value of a region's total production can be denoted by a national income function

$$G_i = p \cdot D(e_i) + C(E(e_i, e_j)) \text{ with } i \neq j, \tag{3}$$

where p denotes the world market price of the carbon-intensive good. The world market price of the affected good is the *numéraire.* For low levels of foreign emissions, G_i is humped shaped, since marginal benefits from emissions are relatively large compared to the damages. G_i is increasing until marginal benefits are equal to the marginal damages.

Both regions simultaneously choose their optimal climate policy. We define *optimal climate policy* as the level of emissions, which maximizes welfare within the region. The climate policy regulator of a region issues e_i emission permits to carbon-intensive producers, such that regional welfare is maximized. Or in other words: The regulator maximizes the indirect utility function V_i with respect to the number of emission permits e_i:

$$\max_{e_i} V(p, G_i(p, e_i)). \tag{4}$$

Then the following first order condition has to hold for an utility maximum:

$$\frac{\partial V_i}{\partial e_i} = \frac{\partial V}{\partial p}\frac{\partial p}{\partial e_i} + \frac{\partial V}{\partial G_i}\left[\frac{\partial p}{\partial e_i} D_i + p\frac{\partial D_i}{\partial e_i} + \frac{\partial C_i}{\partial E}\frac{\partial E}{\partial e_i}\right] = 0. \tag{5}$$

Following *Roy's Identity*, the domestic demand for the carbon-intensive good $H(p, G_i)$ is defined as $H(p, G_i) \equiv -\frac{\frac{\partial V}{\partial p}}{\frac{\partial V}{\partial G_i}}$. So we can rearrange equation (5) to

$$p\frac{\partial D_i}{\partial e_i} + \frac{\partial C_i}{\partial E}\frac{\partial E}{\partial e_i} + \frac{\partial p}{\partial e_i} X_i = 0, \tag{6}$$

whereas X_i denotes carbon-intensive net exports of region i. Condition (6) represents the standard equimarginal Pigouvian principle, plus a Terms of Trade (ToT) term. If the domestic demand for the carbon-intensive good is smaller than production, X_i is positive. Thus, assuming that $\frac{\partial p}{\partial e_i} < 0$, a net exporting region has to take into account that an increase in emissions deteriorates Terms of Trade.

Before discussing the effectiveness of border carbon measures, we take a closer look on international spillover effects of unilateral climate policy. To do so, we distinguish between three different cases. In the first case, we assume that both Annex B and Non Annex B are small open economies, i.e. commodity prices are exogenous and independent from policy decisions for both regions. In the second case we slacken this assumption for Annex B and suppose that A's policy decisions affects commodity prices, which is a necessary assumption to study leakage. In the third case, we assume that both regions are large open economies and Terms of Trade effects are taken into account for optimal policy responses.[5]

We assume that the different countries, which belong to one group, act as homogeneous entity. We focus the analysis on responses of Non-Annex B on marginal reductions of Annex B's GHG emissions. This should reflect the current debate about stricter environmental policies in Annex B countries and the respective carbon leakage effect in Non-Annex B countries.

2.1 Two Small Open Economies - The Free Rider Effect

As described above, both regions take prices as exogenously given. Therefore, $\frac{\partial p}{\partial e_i} = 0$ and the first order condition for Non-Annex B 's optimal emission policy in equation (6) is simplifying to $p\frac{\partial D_N}{\partial e_N} + \frac{\partial C_N}{\partial E}\frac{\partial E}{\partial e_N} = 0$. Hence, trade considerations play no part and only the effect of the trans-boundary externality matters. Then N's optimal response to a marginal change in A's emissions is

$$\frac{\partial e_N}{\partial e_A} = \frac{-\frac{\partial^2 C_N}{\partial E^2}}{p\frac{\partial^2 D_N}{\partial e_N^2} + \frac{\partial^2 C_N}{\partial E^2}} < 0. \tag{7}$$

The nominator shows the change in marginal damages if A abates an additional unit of emissions. The denominator shows the change in N's marginal profits from a change in own emission. Crucial for the analysis is the sign of expression (7). We find that the sign is negative. If Annex B countries raise its mitigation efforts, Non-Annex B will emit more GHG.

Proposition 2 *Neglecting price effects, mitigation in Annex B countries causes an increase of emissions in Non-Annex B countries. Emissions are strategic substitutes.*

Proof: The numerator is positive by definition. The two terms in the denominator are negative for positive prices. Thus, the denominator is negative and so the sign of equation (7). □

The negative relationship between the emissions of both regions can be considered as classical free-rider problem. Increasing mitigation efforts in Annex B decrease marginal damages and thus increase the incentive to raise emissions in Non-Annex B (and vice versa).

Note that gradient of the response function is between -1 and 0. N never increases emissions by more than A's abatement. Global emissions are not increased in the margin due to the free rider effect.[6]

[5] The terms "small" respective "large" open economies are eventually misleading, since output-levels and the relative size of the externality do not change over the cases. "Small"and "large" differ only in the way in which Terms of Trade effects will be taken into consideration for climate policy making. However, since these terms are often used in this context, we stick to this terminology.

[6] It is obvious that the resulting equilibrium not maximizes social welfare. A social planner would take

2.2 One Small and one Large Open Economy - Leakage

As seen in the section above the free-rider effect counteracts Annex B's mitigation efforts, if we neglect effects from climate policy on commodity prices. We release now this assumption for A, so that $\frac{\partial p}{\partial e_A} = 0$ only by accident. Now N's optimal response if A marginally reduces emissions is now as follows:

$$\frac{\partial e_N}{\partial e_A} = \frac{-\left(\frac{\partial^2 C_N}{\partial E_N^2} + \frac{\partial p}{\partial e_A}\frac{\partial D_N}{\partial e_N}\right)}{p\frac{\partial^2 D_N}{\partial e_N^2} + \frac{\partial^2 C_N}{\partial E^2}}. \tag{8}$$

Compared to the reaction as derived in the small open economy configuration, an additional term appears in the response expression. The second term in the numerator indicates the effect of changing world market prices of the carbon intensive goods due to mitigation in Annex B on marginal emission benefits in the Non-Annex B. From the international market clearance condition for the carbon-intensive good $\sum_i H(p, G(e_i, e_j)) - \sum_i D_i(p, e_i) = 0$, we can show that:

$$\frac{\partial p}{\partial e_A} = \frac{\frac{\partial Y_A}{\partial e_A} - \sigma\theta\left(\frac{\partial G_A}{\partial e_A} + \frac{\partial G_N}{\partial e_A}\right)}{(\varepsilon - \eta)Z} < 0, \tag{9}$$

whereas σ denotes the income elasticity of the demand of the carbon-intensive good, ε is the price elasticity of the demand and η stands for the price elasticity of the supply of carbon-intensive goods. θ describes the value share of carbon-intensive goods in the utility function and Z denotes the respective market size. It easy to show that equation (9) has a negative sign, $\frac{\partial p}{\partial e_A} < 0$.[7] Emission taxes or emission trading schemes raise the production costs and prices of carbon-intensive goods.

Note that elasticities play a crucial role for the strenghtness of the price change and hence for leakage. Higher demand elasticities cause lower price changes, whereas higher supply elasticities obviously leads to larger price effects.

A's emission reduction raises the price of carbon-intensive commodities. This leads to larger marginal profits, which induces leakage. Hence, relative to equation (7) in the first case, the nominator is larger, so that, compared to the first case, N responds more vigorously on mitigation in A.

Figure 2 illustrates the previous findings. Because of decreasing marginal damages, Non-Annex B increases emissions if Annex B intensifies mitigation efforts, since N profits from A's contribution to a better climate state. Further, if mitigation in A increases the world market price of carbon-intensive goods, N has additional incentives to raise emissions, since it becomes more profitable to produce carbon-intensive goods.

Proposition 3 *If Annex B's abatement efforts affect the price of the carbon-intensive good on the world market, Non-Annex B will raise emissions by more than in the absence*

into account that emissions affect both regions. Hence, from the Samuelson condition on the optimal provision of public goods, the first order condition for a social optimum would be $p_i\frac{\partial D_i}{\partial e_i} = -\sum_r \frac{\partial C_r}{\partial E}\frac{\partial E}{\partial e_i}$.

[7]The derivation of expression (9) can be found in the Appendix A.2.

of those induced price effects. Leakage increases the negative response of N' on A's abatement efforts.

Proof: Since $\frac{\partial p}{\partial e_A} < 0$ as shown in the Appendix and $\frac{\partial D_N}{\partial e_N} > 0$ by definition, expression (8) is always smaller than expression (7). Hence, mitigation in A increases the incentive to raise emissions by N more than in the first case. □

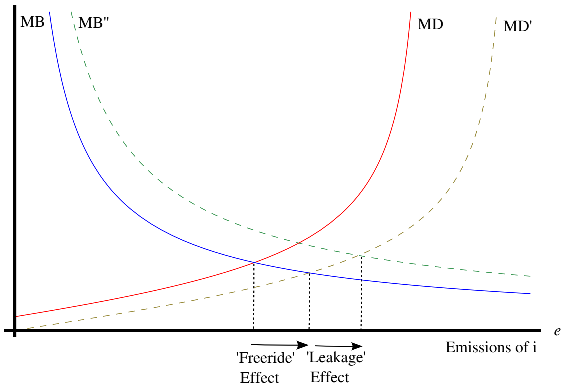

Figure 2: If region i is increasing the world market price of the carbon-intensive good by mitigating, climate policy in region i leads to an increase of region j emissions because of the free-rider effect and the leakage effect.

Note that if $\frac{\partial p}{\partial e_A}\frac{\partial D_N}{\partial e_N} > p\frac{\partial^2 D_N}{\partial e_N^2}$, i.e. the increase in marginal benefits of emissions due to the increase in prices is greater than the change in marginal benefits due to increasing emissions, expression (8) can get smaller than -1. Total emissions may increase due to a marginal reduction in the North.[8]

We define now the leakage rate, i.e. marginal change in N emission due to marginal changes in A abatement policy, induced by commodity price change, $L_N = \frac{\partial p}{\partial e_A}\frac{\partial e_N}{\partial p}$. Thus, the leakage rate denotes the marginal change of the price due to a decrease of emissions in the Annex B times the marginal increase of emissions in Non-Annex B due to the price change and so we get for L_N:

$$L_N = \frac{-\frac{\partial D_N}{\partial e_N}\left(\frac{\partial D_A}{\partial e_A} - \sigma\theta\left(\frac{\partial G_A}{\partial e_A} + \frac{\partial G_N}{\partial e_A}\right)\right)}{\left(p\frac{\partial^2 D_N}{\partial e_N^2} + \frac{\partial^2 C_N}{\partial E^2}\right)(\varepsilon - \eta)Z}. \tag{10}$$

Equation (10) indicates that larger marginal profits of emissions ($\frac{\partial Y_N}{\partial e_N}$) in the Non-Annex B cause more leakage. And the higher elasticities of demand the smaller is the leakage rate. And obviously the more vulnerable N's C sector is, the lower is leakage. We see as well that increasing market sizes reduced leakage.

As several authors have shown (e.g. Kennedy (1994)), imperfect competition causes a strategic interaction of environmental policies between countries. In the presence of

[8]But such an equilibrium might be unstable.

leakage have countries an incentive to set CO_2 taxes below the Pigouvian level to capture additional rents. This *environmental dumping effect* additionally tempers the ability of climate policy instruments to internalize the pollution problem.

In the next section we examine this terms of trade effects of unilateral climate policy more in detail.

2.3 Two Large Open Economies - Take Terms of Trade into Account

In contrast to the case before, where Non-Annex B only responds to the price effect caused by mitigation in Annex B, we take now changing terms of trade into consideration in the formulation of the own climate policy. Climate policy is no longer only a tool to internalize externalities from CO_2 emissions, but might serve as device to manipulate Terms of Trade.

If we let the two regions trade and assume that both regions are no longer price takers, the first order condition (6) holds for both regions. Therefrom we derive again the optimal response of N on an marginal emission reduction in A.

$$\frac{\partial e_N}{\partial e_A} = \frac{-(\frac{\partial^2 C_N}{\partial E^2} + \frac{\partial p}{\partial e_A}\frac{\partial D_N}{\partial e_N} + \frac{\partial p}{\partial e_N}\frac{\partial X_N}{\partial e_A} + \frac{\partial^2 p}{\partial e_N \partial e_A}X_N)}{p\frac{\partial^2 D_N}{\partial e_N^2} + \frac{\partial^2 C_N}{\partial E^S} + \frac{\partial p}{\partial e_N}\frac{\partial D_N}{\partial e_N} + \frac{\partial^2 p}{\partial e_N^2}X_N + \frac{\partial p}{\partial e_N}\frac{\partial X_N}{\partial e_N}}. \tag{11}$$

Now, effects on terms of trade and net exports play a crucial role for responses on each others abatement decisions. The region which net-exports the carbon-intensive good has an interest in high relative prices of this good. Let us assume that Non-Annex B is a net-exporter of carbon-intensive goods and Annex B marginally reduces his emissions. As we have seen in the section above the abatement effort of A increases the carbon-intensive good price. Since N is a net-exporter of this good, As effort improves the Terms of Trade of N. Therefore N has only limited incentives to expand production of the carbon-intensive commodity (and raise emissions), since this lowers the price and deteriorates Terms of Trade.

The fourth term in the numerator of expression 11, $\frac{\partial^2 p}{\partial e_N \partial e_A}X_N$ shows how the marginal Terms of Trade change if A changes emissions. For a net-exporting country this term is positive and reduces the numerator relative to cases, which do not take into account Terms of Trade effects. The two additional terms in the denominator $\frac{\partial^2 p}{\partial e_N^2}X_N + \frac{\partial p}{\partial e_N}\frac{\partial X_N}{\partial e_N}$ are both positive for net-exporting countries. Hence the denominator increases. Take the two effects together and we observe that a net exporter of carbon-intensive goods responds with less large increase in emissions if the other region abates one unit of emissions.

The sign of expression (11) is no longer clear by definition. If the responding country is a net-exporter of carbon-intensive goods and ToT considerations dominate the leakage and the free rider effect, a marginal reduction emission reduction by the opponent can cause a reduction in emissions by the acting region. The opposite holds if N is a net-importer of carbon-intensive goods. In this case will N further increase emissions to reduce the price of carbon-intensive goods to improve ToT.

It is not a new result that environmental policy is used to alter Terms of Trade. Krutilla (1991) showed that an export reduction due to environmental policy generates a monopolistic surplus on the reduced exports volume and so it might be in the interest of the regulator to emit less than the Pigouvian level.

But besides establishing unilateral climate policies and exploit the trade effects of these policies, the climate policy regulator has also the possibility to explicitly target foreign emissions by imposing a tariff on carbon-intensive imports. We discuss the effects of such an instrument in the next section.

2.4 Border Carbon Adjustment to Combat Leakage

Climate policy instruments only target domestic polluters. But climate change is a global scale externality and GHG mitigation is a public good. As shown in the sections 2.2 and 2.3, such problems may be enforced through carbon leakage and, depending on trade patterns, Terms of Trade effects.

A measure to face carbon leakage are border taxes on the import of carbon-intensive goods. They raise the consumer price for carbon-intensive imports, reduce demand for those goods and hence foreign production, which goes along with less foreign emissions. In this section, we analyze the effect of border carbon adjustment on carbon-intensive goods and discuss if BCA has the potential to increase the efficiency of unilateral climate policy in open economy regimes.

Among lawyers it is heavily debated if border carbon adjustment is conform with WTO rules. Ismer and Neuhoff (2007) propose that the implementation of BCA is feasible under certain conditions. They argue that all products of a certain sector, regardless of the production method, have to be considered as homogeneous. Hence, to not violate the non-discriminatory principle of Art. III GATT, the levying country is only allowed to take the lowest GHG charges incurred by any domestic producer. This means that the calculation basis for the level of BCA is the amount GHG emitted during the production process as if the good would be produced with the best available technology in the implementing country.

Since the representation of production technologies is as simple as possible in our model, we do not distinguish between different production methods within a region, hence we simply assume that the tax rate by which an imported carbon-intensive good is levied, is based on the domestic carbon intensity. In contrast to a pollution content tariff as in Copeland (1996), the tariff level does not depend on the carbon content of the imported good itself and the production technology abroad. This reduces the policy efficiency of the tariff, since abatement efforts of the exporters do not directly reduce the tariff. But it should represent an WTO conform implementation as it was pointed out by Ismer and Neuhoff (2007).

For the analysis of BCA we concentrate for the sake of simplification on the second case discussed above in which only Annex B's policy actions influence prices, whereas the Non-Annex B takes them as given. We extend then the model by Annex B's imposition of a border tax τ_A on imported carbon-intensive goods. Let us again assume that Non-Annex B countries are net exporters of carbon-intensive goods. The exports to Annex B are taxed on the border. The first order condition for the optimal emission level in Non-Annex is now as follows:

$$p\frac{\partial H_N}{\partial e_N} + (p - \tau_A(e_A))\frac{\partial X_N}{\partial e_N} + \frac{\partial C_N}{\partial E}\frac{\partial E}{\partial e_N} = 0. \tag{12}$$

$\frac{\partial H_N}{\partial e_N}$ denotes the change in domestic demand for carbon-intensive goods in Non-Annex B if own emissions marginally change, $\frac{\partial X_N}{\partial e_N}$ denotes the respective change in net exports. The implementation of BCA in A affects the first order condition of N: Marginal profits from emissions are now split up in benefits from domestic consumption and in profits from exports. The higher the foreign tariff, the smaller the marginal profits from carbon-intensive exports and hence from emissions.

A small rearrangement of the expression 12 and an exploiting of the implicit function theorem leads to the following response of N on a marginal reduction of A's emissions:

$$\frac{\partial e_N}{\partial e_A} = \frac{-\left(\frac{\partial^2 C_N}{\partial E_N^2} + \frac{\partial p}{\partial e_A}\frac{\partial Y_N}{\partial e_N} - \frac{\partial \tau_A}{\partial e_A}\frac{\partial X_N}{\partial e_N} - \tau\frac{\partial^2 X_N}{\partial e_N \partial e_A}\right)}{p\frac{\partial^2 D_N}{\partial e_N^2} + \frac{\partial^2 C_N}{\partial E^2} - \tau_A\frac{\partial^2 X_N}{\partial e_N^2}} \tag{13}$$

We detect three additional terms in the marginal response expression 13, which are of importance: (i) $\frac{\partial \tau_A}{\partial e_A}\frac{\partial X_N}{\partial e_N}$ is the tax rate effect of the border measure. If A marginally reduces his emissions, A's carbon-intensive industry produces more carbon-efficiently. Since the assessment basis of the tax rate depends on A's production technology, τ_A is increasing. This reduces the profits from N's carbon-intensive net-exports and hence the incentive to respond with an expansion of GHG emissions. (ii) The term $\tau\frac{\partial^2 X_N}{\partial e_N \partial e_A}$ captures changes in net-exports due to a decrease in A's emissions. A reduction in A's emission affects only the demand side of the net-export balance and is only of second-order importance. We ignore therefore this effect for the further analysis and draw our attention on additional terms in the denominator. If we again neglect demand-side effects, we can state $\tau_A\frac{\partial^2 X_N}{\partial e_N^2} = \tau\frac{\partial^2 Y_N}{\partial e_N^2}$. It now becomes obvious that the border measure reduces the marginal profits from emissions for the Non-Annex B countries and hence reduces negative leakage incentives.

Proposition 4 *Assume that N is a net-exporter of carbon-intensive goods and that changes in climate policy do not affect the demand side of the trade balance. Then border carbon adjustment measures reduce the negative response of N on a marginal change in A's GHG emissions.*

If we neglect demand-side effects on the trade-balance for carbon-intensive good, then $\tau\frac{\partial^2 X_N}{\partial e_N \partial e_A} = 0$, $\frac{\partial \tau_A}{\partial e_A}\frac{\partial X_N}{\partial e_N} = \frac{\partial \tau_A}{\partial e_A}\frac{\partial Y_N}{\partial e_N} > 0$, and $\tau_A\frac{\partial^2 X_N}{\partial e_N^2} < 0$. This reduces the numerator and enlarges the denominator compared to the marginal response expression 8. Hence, in a regime, where A imposes border taxes on N's carbon-intensive exports, N responds to a marginal reduction in A's emissions with a less pronounced emission increase than in absence of border measures. □

The nominator in equation (13) on the right hand side shows the limitation of BCA to combat leakage. While mitigation in Annex B influences the world market price and hence the total production of the carbon-intensive goods in Non-Annex B ($\frac{\partial p}{\partial e_A}\frac{\partial Y_N}{\partial e_N}$), the import tariff affects only N's net exports ($\frac{\partial \tau_A}{\partial e_A}\frac{\partial X_N}{\partial e_N}$). Hence, the bigger the export share of the N's carbon-intensive production, the more effective is BCA.

To examine full general equilibrium effects and to get a quantitative assessment of the effects, we turn now our attention to the numerical model. Annex B profits from a better environmental quality, because the incentive of Non-Annex B to increase emissions is smaller than without import tariffs. But at the same time, A suffers from terms of trade changes, depending on trade patters. BCA is only a credible threat, if N is convinced that the A profits in terms of welfare from the measure. However, welfare effects are not captured in the analytical model. To answer the question of the credibility of WTO conform BCA measures and examine a more detailed representation of the problem, we analyze a parametrized numerical integrated assessment model in the next section.

3 An Integrated Assessment Model with International Trade in Commodities

To gain more accurate evidence about welfare effects of BCA and to assess quantitatively trade flows and optimal climate policies, we need to parametrize the generic model of section 2. The analytical model has some shortcomings since it does not account for the dynamics of global climate change and neglects other production factors. And since the production and utility functions in the analytical model are kept general, we can not characterize the exact equilibrium outcome. For this reason we analyze the findings from above in a numerical integrated assessment model (IAM). An IAM combines a simple mathematical representation of the global carbon cycle with an general equilibrium representation of the economy. We require a model, which is able to represent optimal climate policy under second-best solutions (border taxes) with regional and sectoral disaggregation and international trade in goods.

Most policy optimizing IAMs are casted as nonlinear programs. Prominent examples are the *Dynamic Integrated Climate Economy* (DICE) model by Nordhaus (1991) and the *Model for Evaluating Regional and Global Effects of GHG reduction policies* (MERGE) by Manne, Mendelsohn, and Richels (1995).

Nonlinear programs have the disadvantage that the first-order conditions only correspond to equilibrium conditions where the shadow prices of the constraints coincide with market prices. Since our examination of BCA induces a second-best equilibrium other approaches are necessary.[9] Böhringer, Löschel, and Rutherford (2007) have developed

[9] Applying Negishi-weighted objective functions and sequential joint maximization algorithms (see e.g. Rutherford (1992)) may relax this so-called integrability problem. However, convergence to an

a mixed complementarity formulation of DICE, which overcomes these problems and allows to deal straightforward with the representation of several regions and inefficient market allocations. A second advantage of the reformulation by Böhringer, Löschel, and Rutherford (2007) is the possibility to run the climate and economic sub-models on different time scales. This allows to cope with the moderate speed of climate dynamics on the one hand and a higher degree of complexity in the economic system over a shorter, more policy-relevant time-horizon on the other hand. Due to this properties we use this modified, reformulated version of DICE and add to the model a multi-regional representation of the economy with explicit trade in commodities. To our knowledge, this is the first policy optimization IAM which incorporates explicitly international trade in commodities.

3.1 The Structure of the Numerical Model

As in the theoretical analysis above we divide the world into two regions, the Annex B countries and the Non-Annex B countries.[10] And similar as well, two different products are produced: carbon-intensive goods such as coal, oil and chemicals, and a non-carbon-intensive, clean, good, which enfolds sectors such as agriculture and services.[11]

Both goods are produced with the two factors capital and labor, which are mobile across sectors but not across regions. The two commodities can be traded on international markets. To model sectoral trade flows in both directions (a difference to the analytical model, but obviously closer to the reality), we use the Armington (1968) assumption, proposing that foreign and domestic goods are not perfect substitutes. The sectoral Armington goods are then aggregated to the regional gross GDP $Q_{r,t}$ in period t of region r.[12]

As in our theoretical model presented above, we suppose that GHG emissions,$E_{r,t}$, are linked to the production of carbon-intensive goods, $O_{D,r,t}$ only.

$$E_{r,t} = \phi_{r,t}(1 - \Upsilon_{r,t})O_{D,r,t}, \tag{14}$$

whereas as in DICE $\phi_{r,t}$ denotes the exogenous emission-output ratio[13] and $\Upsilon_{r,t}$ is the endogenously chosen emission control rate. But reducing emissions is costly, so the abatement costs can be denoted as

$$AB_{r,t} = \gamma_r^1 \Upsilon_{r,t}^{\gamma_r^2}, \tag{15}$$

where γ_r^1 and γ_r^2 are the parameters of the abatement cost function.[14]

The state of the climate system then depends on the accumulation of emissions in the atmosphere. Our climate sub-model is similar to the model used in DICE and is described

equilibrium is not established.

[10] Appendix A.5 shows the regional aggregation.

[11] Appendix A.6 shows the full sectoral aggregation.

[12] All elasticities of substitution are depicted in Appendix A.8.

[13] Appendix A.9 presents the energy-technology more in detail.

[14] See Appendix A.8 for parameter values.

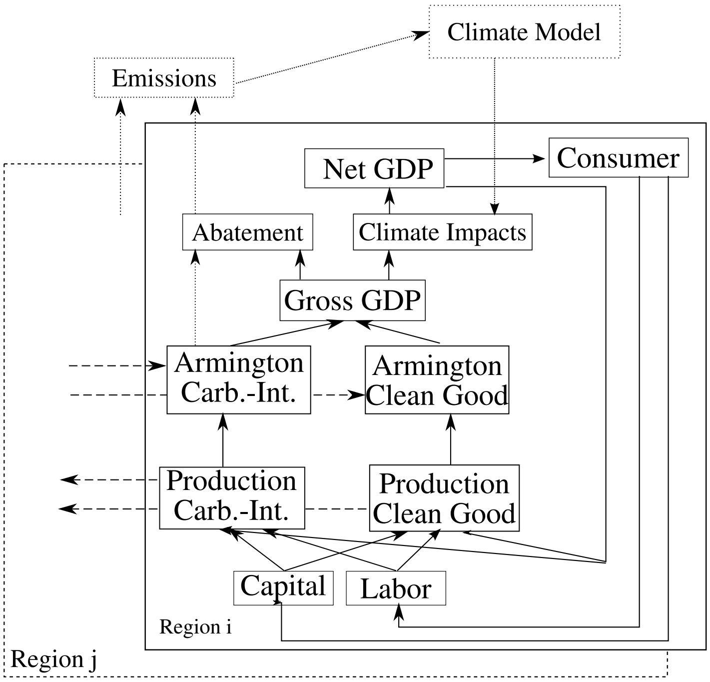

Figure 3: The main properties and characteristics of the numerical integrated assessment model.

in Appendix A.7 in detail. Changes in the state of the climate system then causes impacts on the economy. Other than in the theoretical model the externality affects the economy as a whole and not only one sector. To calibrate the impact function, the same data as in Nordhaus and Boyer (2000) is used and rearranged due to the differences in regional aggregation. The damage representation of the numerical model is explained in detail in Appendix A.4.

Climate damages $D_{r,t}$ and expenditures for mitigation efforts $AB_{r,t}$ reduce the gross output of the economy,

$$Y_{r,t} = (1 - AB_{r,t})Q_{r,t} - D_{r,t}Y_{r,t}. \tag{16}$$

The remaining net output may be used for consumption, investment or as intermediate good in the production of the two commodities. For an detailed explanation about the production structure of the model see Schenker (2009). Figure 3 gives an overview about the structure of the numerical model.

The representative agents choose now the factor allocation, trade flows and abatement efforts, such that the own regional welfare is maximized. I.e. they both choose a policy which is optimal given the others decisions. To mirror the current state in international climate politics, we assume that Annex B chooses the optimal climate policy with respect to future costs of climate change, whereas Non-Annex B does not contain GHG emissions at all.

To assess BCA, we will now compare the outcome of two different policy cases: In the first case, the optimal climate policy is chosen in the absence of border measures. In the second case, Annex B countries implements a WTO-conform BCA measure on imported carbon-intensive goods from Non-Annex B.

4 Results from Numerical Exercises

While the Annex B countries committed themselves to reduce GHG emission by 5.2 percent until 2012 compared to the 1990 level, the Non-Annex B countries have no constraints regarding GHG emission constraints.

To reduce the resulting leakage from Annex B's climate policy, the policy regulator in Annex B imposes in the second scenario a border tax on carbon-intensive imports from Non-Annex B. We argue that the implementation of border tax measure is conform with WTO constraints. The policy regulator has now a second instrument at hand to affect the future state of the climate. Note that these two instruments interact with each other. This is also the main difference to the situation in the real world, where first a decision was made about the climate policy target and then the instruments were chosen to fulfill this targets. We do it the other way around and compare the outcomes of the optimal policies with a different number of instruments at hand. It is clear that the assessment of a policy depends strongly on the chosen baseline case.

4.1 Optimal Climate Policy without Border Carbon Adjustment

Figure 4 illustrates the results of our *baseline scenario*. The top left panel of the figure 4 shows the development of GDP for both regions. In the year 2010, the two regions start with almost the same level of GDP. But Non-Annex B grows faster and has in the year 2100 a nearly three times higher GDP than Annex B. One reason for this development are the higher exogenous population growth rates of the Non-Annex B countries. The other reason is illustrated in the panel in the top right of that figure: Non-Annex B firms can expand the production of carbon intensive goods with less costs than producers in Annex B, since they are not bounded by an emission reduction target and will therefore emit more CO_2. As a result, the mean global surface temperature increases by 5 °C until 2100 and the climate damages in the Annex B countries amount to over 5% of GDP in 2100 (see panel in the bottom right of figure 4).

The graph in the bottom left of Figure 4 shows the price of CO_2 emissions in the Annex B countries. The price of a tCO_2-equiv. raises from 6 \$ in 2010 to 22 \$ in 2100.[15] Since the Non-Annex B countries do not have a mitigation policy at all, the price of emissions in the Non-Annex B countries is zero.

But despite of the advantage of less regulation in Non Annex B's carbon-intensive sector, Annex B stays a net exporter of those goods. The higher capital intensity in the carbon-intensive production ensures that although the additional regulation costs, Annex

[15] This regional social cost of carbon is in line with results from other assessments based on the RICE (see Tol (2005))

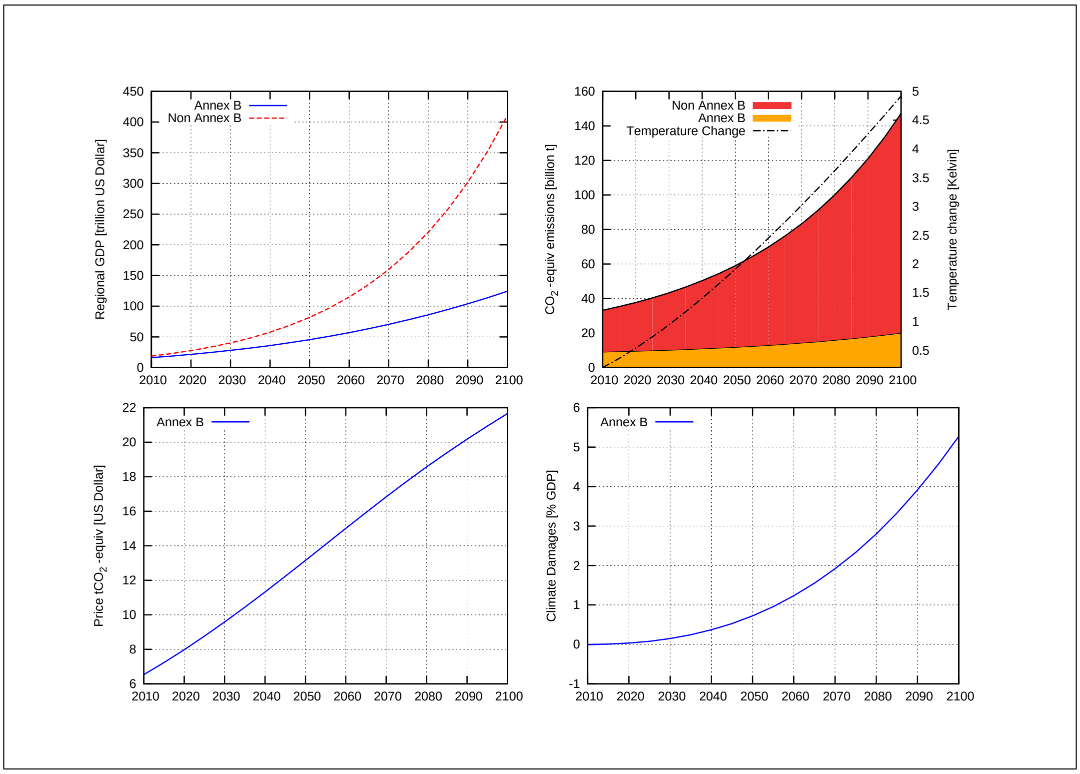

Figure 4: Results of the baseline scenario. Since the Non-Annex B countries neglect climate damages, Non-Annex B CO_2 emissions grow strongly.

B still has an comparative advantage in the carbon intensive sector. Since Annex B has the more efficient technology regarding emissions in the carbon-intensive sector, this has positive effects for the environment. But as we learned from the theoretical analyis in section 2.3, the regulator will in case of beeing net exporter of the carbon-intensive good set the emission price above the Pigouvian level to stint the supply of this goods and generate additional rents. So note that we in our economy two market failours occur: On the one hand are GHG emissions responsible for trans-boundary adverse economic impacts, which were not taken into account by the climate policy regulator. On the other hand, commodity markets are imperfect and the regulator can use climate policy instruments to generate generate rents.

In the next section we will give the climate policy regulator an additional instrument at hand. To combat carbon leakage a border measure will imposed.

4.2 Optimal Climate Policy with Border Carbon Adjustment

The difference between emissions prices in both regions is the basis to calculate the border carbon measure. To minimize leakage, reestablish competitivness of domestic producers of the carbon-intensive good in the domestic market and to level the playing field between producers of those goods in both regions, Annex B will impose a border tax adjustment. But since today international trade is organized along rules based on international law, the implementation of such measures is limited.

The representation of technologies in the our model is very simplified. We distinguish only between two different ways to produce the carbon-intensive good and we further assume that the North has the more carbon efficient production method. Then the level of the border carbon adjustment on dirty good imports from Non-Annex B into Annex B, $\tau_{A,t}$, is calculated as follows:

$$\tau_{A,t} = (p^e_{A,t} - p^e_{N,t})\frac{E_{A,t}}{O_{D,A,t}}, \tag{17}$$

whereas $(p^e_{A,t} - p^e_{N,t})$ is the difference in prices of emissions between Annex B and Non Annex B and $\frac{E_{A,t}}{O_{D,A,t}}$ is the GHG content of one carbon-intensive good, produced with Annex B technology. Obviously it would be more efficient to use the real carbon intensity of Annex B's import, but apart from the potential non-conformity of such a scheme with WTO rules, monitoring the actual carbon content of imports would also be a major challenge.

Figure 5 shows the main consequences of such a BCA implementation by Annex B. As can be seen in the panel in the top right and as proposed by the theoretical analysis the border measure does the job and causes a reduction in foreign emissions. But the additional goal of the tariff to reestablish competitivness in the carbon-intensive good sector is succesfull as well and leads to an increase of domestic emissions.[16] The production of carbon-intensive goods in the Annex B countries increases due to the import tariff, since BCA rises the comparative advantage of dirty good production in Annex B. The Non-Annex B countries decrease the production of those goods. For the clean goods, the effects are vice versa: The Non-Annex B countries increase the production of clean goods and the Annex B countries decrease the production of these goods.

Since the Annex B produces carbon-intensive goods more emission-efficently, overall emissions are reduced. This leads to less climate damages in the Annex B countries. Compared to the damages in the baseline scenario, the damages in the Annex B countries are reduced by 0.5% due to the reduction in emissions induced by the border measure.

To study the efficency of the border measure more in detail we constructed a truncated one-region version of the original model where the prices and quantities of the other region were exogenously given and examined how the considered region responds on marginal changes in the other regions values. As in the theoretical model we focus our analyis on the leakage rate in the Non-Annex B region which is defined as $\frac{\partial p_{D,A,t}}{\partial E_{A,t}}\frac{\partial E_{N,t}}{\partial p_{D,A,t}}$, i.e. the change in Non-Annex B emissions triggered by a price change of dirty goods, which is triggered by a change in Annex B emissions.

Figure 6 shows the leakage elasticity, i.e. the change in Non Annex B GHG emissions due to a price response triggered by a change in Annex B emissions for the case with and without border carbon adjustment. Without BCA an one per cent reduction in Annex B

[16]Note that this adjustment of Annex B emissions makes our analysis different from other studies about the efficiency of border measures, where the emission target is given and BCA are used to achieve this target.

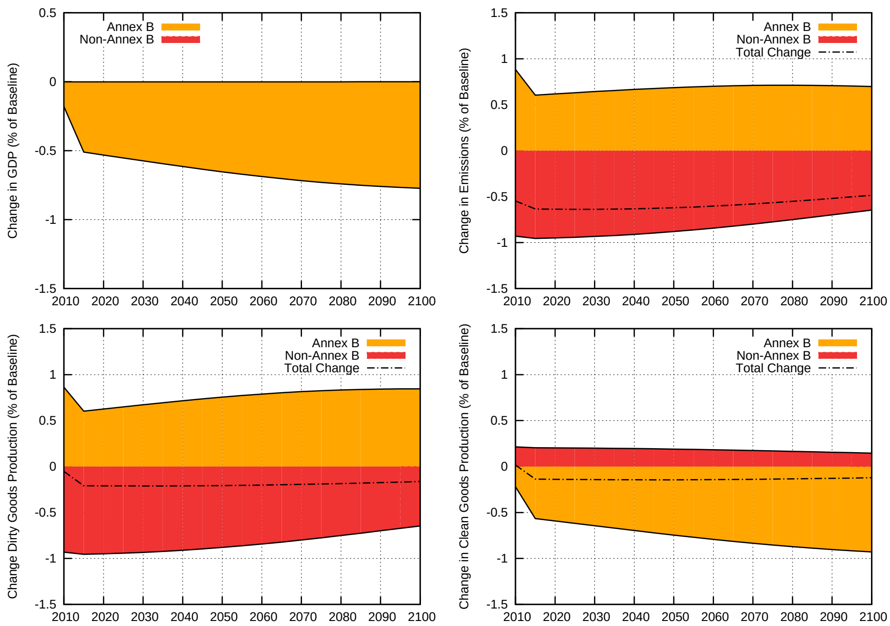

Figure 5: Results of the BCA scenario. BCA leads to a decrease in GDP in the tariff imposing Annex B region. The main goal of the import tariff is reached, since it forces Non-Annex B to reduce emissions. It also improves the competitiveness of Annex B's carbon intensive industries and shifts production of those goods to A and clean goods to N.

emissions raises Non-Annex B emissions through the leakage channnel from 0.1 to 0.35 per cent. Leakage is higher for later periods. If Annex B imposes a carbon tariff, leakage becomes even negative. Now an one per cent reduction of Annex B emissions causes a reduction in Non Annex B emissions in the range of 0.12 and 0.06 per cent. The border measure does efficently reduce leakage.

As we argued above in section 2.4, the credibility of Annex B countries to implement BCA and to use it as a stick and force Non Annex B countries to GHG emission reductions depends on the welfare effects of such a policy. The graph in the top left of Figure 5 shows the change in Net GDP from imposing BCA compared to the *baseline scenario*. The GDP in the Non-Annex B is almost not affected by the measure, while the GDP in the Annex B decreases. The same holds for welfare: An examination of the Equivalence Variation between the scenarios shows that the Annex B suffers small welfare losses on 0.01 per cent of their income, whereas Non-Annex B profits from the measure in Non-Annex B and gains 0.07 per cent income if the measure is introduced. Imposing the import tariff is thus not a credible threat for the Non-Annex B countries. Or in other words: The benefits from the better climate in the future do not cover the costs due to the distortion of free trade. The reason for this negative welfare effect

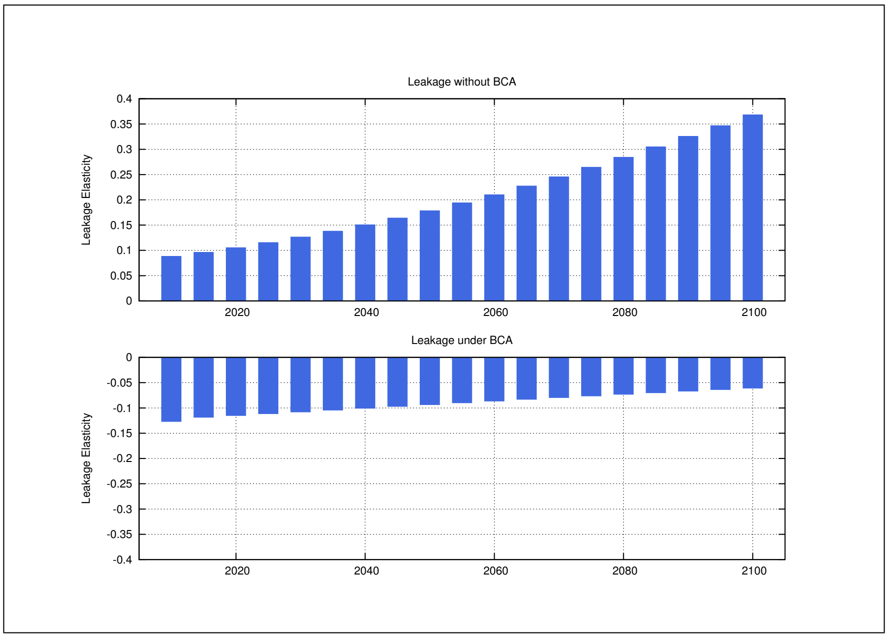

Figure 6: The leakage elasticity in Non-Annex B under the two scenarios with and without border measures. The figure shows the price induced response of Non-Annex B emissions to an one percent reduction in Annex B emissions.

becames clear after a closer inspection of effects on trade from BCA.

Figure 7 presents the main effects of Annex B's BCA implementation on trade between both regions. The panel in the bottom left shows the markup from the BCA on carbon-intensive dirty good imports from the Non-Annex B in Annex B. Carbon-intensive imports from Non-Annex B become 3 percent more expensive. Since the emission price increases over the time horizon, the BCA and the markup raise as well up to 5 per cent in 2100. This allows Annex B producers to increase production capacities of carbon intensive goods and hences pricees of D produced in Annex B slightly fall about 0.25 percent below the baseline level. Since the BCA only captures the domestic market, there is almost no effect on prices of Non-Annex B carbon-goods net of tariff.

To analyze the effects of the import tariff on the net GDP in the two regions in more detail, we concentrate on the production levels of the carbon-intensive good sector and the clean good sector as well as on the import and export levels in figure 7. On the top left of figure 7, the change in carbon-intensive good production due to the import tariff is plotted. The panel in the top right of figure 7 illustrates the effects on net exports induced by BCA. The Annex B countries decrease the net exports of the clean good and increase the net exports of the carbon-intensive good. Note that the Annex B countries are net exporter of carbon-intensive goods and net importer of the clean good in the *baseline scenario*. Thus, BCA boosts the original ratios: The Annex B countries concentrate their production and their exports even more on carbon-intensive goods than in the baseline scenario. The Non-Annex B countries concentrate their production and their exports on clean goods.

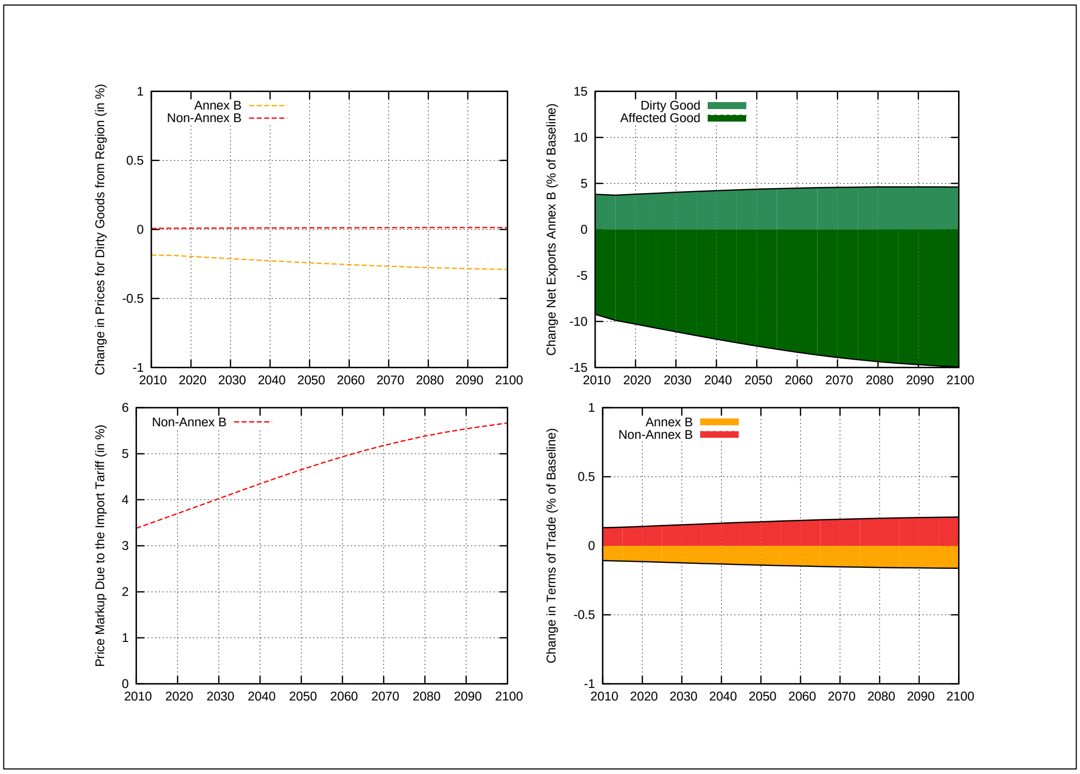

Figure 7: Trade effects of the BCA. The implementation of carbon border measures leads to a small reduction in prices for Annex B's carbon intensive goods. Since Annex B is a net exporter of this goods, the price decrease deteriorates terms of trade of Annex B and hence welfare. For Non-Annex B the effects are vice versa.

But since Annex Bs carbon-intensive good prices fall, Terms of Trade are also deteriorated for Annex B and improved for Non Annex B as it is shown in the panel in bottom right of figure 7. This small changes in Terms of Trade are responsible for the welfare effects we observed above.

But as the sensitivty analysis has shown are the observed welfare effects are not constant over the whole range of elasticities. A crucial role plays the Armington elasticitiy for carbon-intensive goods, which determines the substitutability between domestic and foreing goods.

Figure 8 shows exemplary the differences for a low and a high Armington elasticity of substitution. Whereas for large elasticites, as in the case above, Annex B reacts on the implemation of border measures with an increase in emissions, is the reaction in case of low elasticies reversed. BCA leads to a more tighten climate policy in Annex B and to almost no reaction of GHG emissions in Non-Annex B. Low elasticities allow Annex B a better exploitation of their market power in the carbon-intensive sector and run short the supply of the respective good. The border measure supports this strategy since it makes it less attractive for Non-Annex B to expand production of dirty goods. Climate and trade policies pull now both in the same direction. Under such a configuration the implementation of border measures becomes welfare increaseing for Annex B.

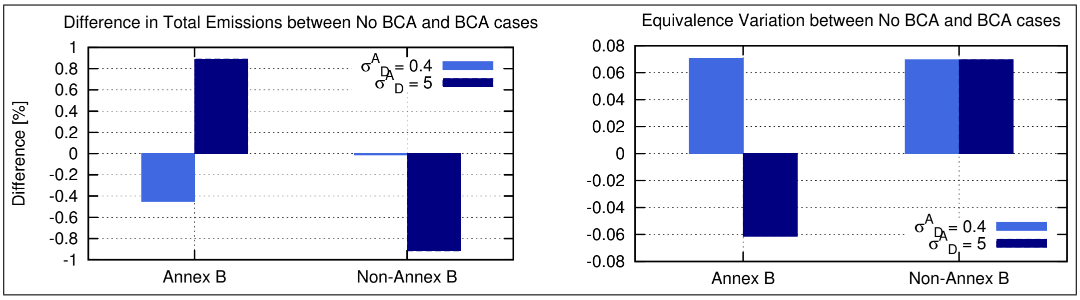

Figure 8: Effects of BCA on emissions and welfare for different Armington elasticities of substitution for carbon-intensive goods.

5 Concluding Remarks

Climate policy must prove itself in an international environment. Besides the cross-border externality of GHG emissions and the corresponding public good problem of mitigation, an efficient climate policy has also to consider trade releated effects. We show with a simple analytical model of non-cooperative optimal climate policy and international trade at hand that unilateral emission abatement in one region has to cope with leakage and that border carbon measures might reduces this problem.

But depending on trade patterns such a distorition of free trade has costs for the imposing country. Using a modified version of the multiregional RICE model, which especially captures international trade in goods and allows to choose unilateral optimal climate policies, we are able to show that for realistic parameter assumptions levying border carbon adjustment in Annex B countries on Non-Annex B carbon-intensive imports worsens welfare in Annex B countries.

Nevertheless, the analyis shows that for some parameter values, e.g. an explicit low elasticity of substitution between domestic and foreign carbon-intensive goods, a BCA introduction can be welfare improving, since it may allow Annex B region to exploit market imperfections and generate rents.

Obviously the answer to the question if BCA is welfare improving depends on the chosen baseline. If one assumes that the environmental policy regulator first decides about the mitigation target and then is looking for instruments to enforce that target, BCA is welfare improving with high certainty, since it is effective in reducing the leakage problem and hence increases the effectivness of the own unilateral climate policy. If on the other hand a region choses the optimal unilateral climate policy and takes leakage and terms of trade effects already into account, then the welfare success of the additional instrument depends not on its environmental policy efficency but rather on the power of the tariff to exploit market imperfections.

Our paper shows that the implementation of border carbon measures had to be chosen very carefully and has to consider all attendant circumstances, such as baseline policy design and trade paterns.

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A Appendix

A.1 Proof of Proposition 1

Proof: The production possibility frontier is a concave function. The slope of the PPF can be written as $\frac{\frac{\partial C_i}{\partial E}\frac{\partial E}{\partial e_i}}{\frac{\partial D_i}{\partial e_i}}$.

This is called the marginal rate of transformation (MRT). For the boundary point $D_i = 0$, the MRT is:

$$\lim_{e_i \to 0} \frac{\frac{\partial C_i}{\partial E}\frac{\partial E}{\partial e_i}}{\frac{\partial D_i}{\partial e_i}} = 0.$$

For the boundary point $C_i = 0$, the MRT is:

$$\lim_{e_i \to \infty} \frac{\frac{\partial C_i}{\partial E}\frac{\partial E}{\partial e_i}}{\frac{\partial D_i}{\partial e_i}} = \infty.$$

Since $D_i(e_i)$ and $C_i(E(e_i, e_j))$ are continuous and differentiable functions, the PPT, which is a graph between the two boundary points, is a concave function. Therefore, the production set is convex. □

A.2 Derivation of the Price Dependency of Emissions

The market clearing condition for the carbon-intensive good sector can be written as follows:

$$H_A(p, G_D(p, e_A, e_N)) + H_N(p, G_N(p, e_A, e_N)) - D_A(p, e_A) - D_N(p, e_N) = 0.$$

With the derivation rule of the implicit function theorem, we find that:

$$\frac{\partial p}{\partial e_A} = \frac{-\left(\frac{\partial H_A}{\partial G_A}\frac{\partial G_A}{\partial e_A} + \frac{\partial H_N}{\partial G_N}\frac{\partial G_N}{\partial e_N} - \frac{\partial D_A}{\partial e_A}\right)}{\frac{\partial H_A}{\partial p} + \frac{\partial H_N}{\partial p} - \frac{\partial D_A}{\partial p} - \frac{\partial D_N}{\partial p}}.$$

Now, we introduce the income elasticity of demand τ_A, the price elasticity of demand ε_A and the price elasticity of supply η_A of the Annex B as follows:

$$\begin{aligned} \sigma_A &= \frac{\partial H_A}{\partial G_A}\frac{G_A}{H_A} \\ \varepsilon_A &= \frac{\partial H_A}{\partial p}\frac{p}{H_A} \\ \eta_A &= \frac{\partial D_A}{\partial p}\frac{p}{D_A}. \end{aligned}$$

Using this elasticities and assuming that $\sigma_A = \sigma_N = \sigma$, $\varepsilon_A = \varepsilon_N = \varepsilon$ and $\eta_A = \eta_N = \eta$, we get:

$$\frac{\partial p}{\partial e_A} = \frac{\frac{\partial D_A}{\partial e_A} - \sigma\left(\frac{\partial G_A}{\partial e_A}\frac{H_A}{G_A} + \frac{\partial G_N}{\partial e_A}\frac{H_N}{G_N}\right)}{(\varepsilon - \eta)(H_A + H_N)}.$$

The terms $\frac{H_A}{G_A}$ and $\frac{H_N}{G_N}$ denote the value share in the utility function of the carbon-intensive good in the A and N, respective. Again, we assume that $\frac{H_A}{G_A} = \frac{H_N}{G_N} = \theta$. The sum of demand $H_A + H_N$ is equal to the sum of supply $D_A + D_N$ and is equal to the market size of the carbon-intensive good. We refer to the market size as Z and can write:

$$\frac{\partial p}{\partial e_A} = \frac{\frac{\partial D_A}{\partial e_A} - \sigma\theta\left(\frac{\partial G_A}{\partial e_A} + \frac{\partial G_N}{\partial e_A}\right)}{(\varepsilon - \eta)Z}.$$

A.3 Damage Parameter in the RICE Model

Region	α_1	α_2
United States	-0.0026	0.0017
China	-0.0041	0.0020
Japan	-0.0042	0.0025
OECD Europe	-0.0010	0.0049
Russia	-0.0108	0.0033
India	-0.0074	0.0049
Other High Income	-0.0108	0.0037
High Income OPEC	0.0041	0.0015
Eastern Europe	-0.0052	0.0019
Middle Income	0.0039	0.0013
Lower Middle Income	0.0022	0.0026
Africa	0.0157	0.0010
Low Income	0.0063	0.0025

Table 1: The 13 world regions in the RICE model and the corresponding damage parameter.

A.4 Damage Representation in the Numerical Model

In the analytical model in section 2, climate damages only affect the vulnerable goods in the numerical representation. This assumption changes in the numerical model, climate damages affect the GDP. We adopt the RICE damage approach by Nordhaus and Boyer (2000). Nordhaus and Boyer use a quadratic damage function, which can be written as follows:

$$D_t = \alpha_1 \cdot T(t) + \alpha_2 \cdot T(t)^2. \tag{18}$$

$D(t)$ denotes the damage factor, $T(t)$ is the temperature increase and α_1 and α_2 are damage parameters. For the 13 world regions in the RICE model, Nordhaus and Boyer calibrate the values of α_1 and α_2, accounting for agricultural damages, Sea-level rise, other vulnerable sectors, health concerns, non-market amenity impacts, human settlements and ecosystem impacts and catastrophic events.[17] Table 1 in the appendix provides an overview of the 13 world regions in the RICE model and the corresponding damage parameter.

For the IAM model used in this paper, we need to aggregate climate damages for the two world regions Annex B and Non-Annex B. From the regions of the RICE model,

[17] Other vulnerable sectors in the RICE damage representation are the sectors forestry, energy, water systems, construction, fisheries and outdoor recreation.

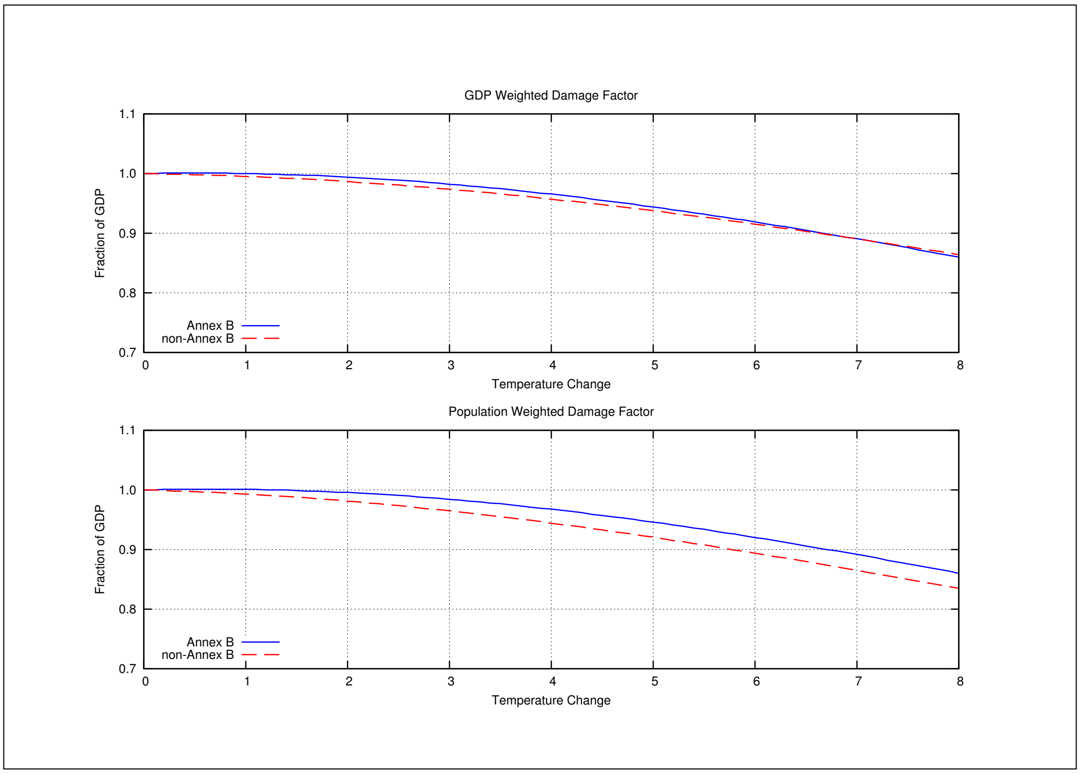

Figure 9: Damage factor of the two regions Annex B and Non-Annex B in the numerical model with a GDP weighted and a population weighted scheme.

the United States, Japan, OECD Europe, the Other High Income States, Russia and Eastern Europe are in the Annex B group.[18] China, India, Africa, the High Income OPEC countries and the Middle, Low Middle and Low Income countries constitute the Non-Annex B region of the model. We aggregate the impact functions in table 1, using the two different weighting schemes motivated by Nordhaus and Boyer (2000): GDP weights and population weights. The corresponding damage factor is illustrated on the top (GDP weighted) and on the bottom of figure 9 (population weighted). In the GDP weighted scheme, the damage parameter of the Annex B and Non-Annex B region looks almost the same. But in the population weighted scheme, the Non-Annex B region is more vulnerable than the Annex B region.

In order to receive a regional damage function which can be used as an input in the model, we approximate the damage curves in figure 9 with a polynomial function of factor 2. This way, we get a damage representation similar to the one of Nordhaus and Boyer (2000), but for the two regions Annex B and Non-Annex B of the numerical model. The damage function for the two regions Annex B and Non-Annex be can be written as follows:

[18] Note that the United States are in the Annex B group in our model, simply because the relatively low damages in the US combined with the large economic output distort the impact factor in the Non-Annex B region.

$$D_{r,t} = a_r \cdot T(t)^2 + b_r \cdot T(t) + 1, \tag{19}$$

where a_r and b_r are the damage parameter for the two regions of the model, estimated with a polynomial approximation of factor 2. The outcome of this approximation can be seen in table 2. Note that we use the population weighted damage representation for the results in section 4.

Weighting Scheme	Annex B		Non-Annex B	
	a_r	b_r	a_r	b_r
GDP weighted	-0.0022	-0.0003	-0.0016	-0.0048
Population weighted	-0.0023	0.0006	-0.0017	-0.0078

Table 2: Damage Parameter for the Annex B and Non-Annex B region in the numerical model.

A.5 Regional Aggregation in the Numerical Model

Model region	Included database regions
Annex B	Australia, Austria, Belgium, Bulgaria, Canada, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, New Zealand, Netherlands, Poland, Portugal, Romania, Russian Federation, United Kingdom, United States, Slovakia, Slovenia, Spain, Sweden, Switzerland, Rest of North America, Rest of EFTA, Rest of Europe.
Non-Annex B	Albania, Argentina, Bangladesh, Brazil, Chile, China, Central America, Colombia, Hong Kong, India, Indonesia, Korea, Madagascar, Malawi, Malaysia, Mexico, Morocco, Mozambique, Peru, Philippines, Singapore, South Africa, Sri Lanka, Taiwan, Tanzania, Thailand, Turkey, Tunisia, Uganda, Uruguay, Venezuela, Vietnam, Zambia, Zimbabwe, Rest of Andean Pact, Rest of Caribbean, Rest of East Asia, Rest of Former Soviet Union, Rest of Middle East, Rest of North Africa, Rest of Oceania, Rest of South Africa CU, Rest of SADC, Rest of Sub-Saharan Africa, Rest of South America, Rest of FTAA, Rest of South and South East Asia.

Table 3: Regional aggregation in the numerical model.

A.6 Sectoral Aggregation in the Numerical Model

Model sector	Included database sectors
Carbon-Intensive Goods	Coal, Oil, Gas, Paper products, Publishing, Petroleum, Coal Products, Chemical, Rubber, Plastic prods, Mineral products, Motor vehicles, Transport equipment, Machinery, Manufactures, Minerals, Electricity, Gas manufacture, distribution, Air Transport.
Affected, Clean Goods	Paddy Rice, Wheat, Cereal grains, Vegetables, Fruit, Nuts, Oil Seeds, Sugar Cane, Plant-based fibers, 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, Textiles, Wearings apparel, Leather products, Wood products,Electronic equipment, Water, Construction, Trade, Communication, Financial Services, Business Services, Public Administration, Defence, Health, Education, Dwellings.

Table 4: Sectoral aggregation in the numerical model.

A.7 Climate Sub-Model

The geophysical constraints and the climate sub model are identical to DICE (Nordhaus 1991). Emission accumulation and transportation is defined as:

$$M_t = 590 + \beta \sum_r E_{r,t} + (1 - \delta_M)(M_{t-1} - 590), \tag{20}$$

where M_t denotes atmospheric concentration of CO_2, β is the marginal atmospheric retention rate and δ_M is the carbon transfer rate to deep ocean.

Radiative forcing F_t (the increase of surface warming in Watts per m^2) is a function of CO_2 and other greenhouse gases in the atmosphere:

$$F_t = 4.1 \left(\frac{\log(M_t/590)}{\log(2)} \right) + O_t, \tag{21}$$

where O_t represents other greenhouse gases, which are taken as exogenous.

The links between radiative forcing and temperature changes in the atmosphere and the deeper ocean are given as:

$$T_t^E = T_{t-1}^E + c_1[F_{t-1} - c_2 T_{t-1}^E - c_3(T_{t-1}^E - T_{t-1}^L], \tag{22}$$

$$T_t^L = T_{t-1}^L + c4(T_{t-1}^E - T_{t-1}^L), \tag{23}$$

where T_t^E is atmospheric temperature, T_t^L is the atmosphere in the lower oceans, and c_1, c_2, c_3, c_4 are geophysical parameters of climate dynamics. Table 5 shows the parameter values of the climate model.

Marginal atmospheric retention rate β	.64
Carbon transfer rate to deep ocean δ_M	.00803
Climate coefficient for upper level c_1	.02059
Climate feedback coefficient c_2	.0914974
Climate coefficient transfer c_3	.03713
Climate coefficient transfer c_4	.00198

Table 5: List of the climate parameters in the numerical model.

As in the paper of Böhringer, Löschel, and Rutherford (2007) the relationship between T_t^E and the climate state, which is a function of previous climate states and emissions, is merged into a single equivalent equation Γ_t:

$$T_t^E = \Gamma_t(S_0, \sum_r E_{r,0}, \sum_r E_{r,1}, ..., \sum_r E_{r,t-1}). \tag{24}$$

The climate sensitivity, i.e. the gradient of temperature in period t to emissions in period $\tau < t$ is:

$$\nu_{t,\tau} = \frac{\partial \Gamma_t(S_0, \overline{E}_t)}{\partial \overline{E}_\tau}, \tag{25}$$

where $\overline{E}_t = \sum_r E_{r,t}$.

Since the climate and the economic model are decomposed and have different time horizons, we can express the atmospheric temperature as:

$$T_t^E \approx \bar{T}_t^E + \sum_{\tau=0}^{t} \nu_{t,\tau}(E_\tau - \bar{E}_t), \tag{26}$$

where $\bar{T}_t^E$ is the reference value of temperature in period t, $\bar{E}_t$ is the reference emissions in period τ.

For an extensive discussion of the climate model and the decomposition between that and the economic model refer to the paper of Böhringer, Löschel, and Rutherford (2007).

A.8 Economic Parameters in the Numerical Model

Parameter	Between	Value
σ^Q	Aggregate commodities to gross GDP	0.2
σ_D^K	Capital and labor in carbon-intensive goods	0.4
σ_V^K	Capital - Labor in carbon-intensive Goods	0.6
σ_V^O	KL - Intermediates in vulnerable Goods	0.7
σ_D^O	KL - Intermediates in carbon-intensive Goods	0.2
σ_V^A	Foreign - Domestic vulnerable Goods	4.66
σ_D^A	Foreign - Domestic carbon-intensive Goods 4.27	
σ	Intertemporal Elasticity of Substitution	5

Table 6: List of the elasticity parameters in the numerical model.

Depreciation rate	5
Discount rate	2.5
Exogenous economic growth rates:	
Annex B	1.5
Non-Annex B	2.5

Table 7: List of the fundamental parameters in the numerical model.

A.9 Emission Technology Parameters in the Numerical Model

The technological change regarding energy efficiency is exogenously given. The cumulative improvement of energy efficiency is identical in both regions and defined as:

$$\phi_t^C = \frac{\phi^G}{\delta_T}(1 - \exp^{-\delta_T(t-1)}), \tag{27}$$

where ϕ^G denotes the annual growth rate of energy efficiency and δ_T the decline in the growth rate. The emission-output ratio $\phi_{r,t}$ is the defined as:

$$\phi_{r,t} = \phi_{0,r} \ \exp^{\phi_t^C}, \tag{28}$$

with $\phi_{0,r}$ as the regional CO_2-output ratio in 2010.

Parameter	Description	Value
$\phi_{0,r}$	Base year CO_2-output ratio	
	Annex B	.49
	Non Annex B	1.34
ϕ^G	Annual growth of $\phi_{t,r}$	-.01234
δ_T	Annual decline rate of technology	.01049
ϕ_t^C	Cumulative improvement of energy efficiency	
γ_1	Intercept of the emission control function	.0686
γ_2	Exponent of emission control function	2.887

Table 8: List of the technology and emission parameter in the numerical model.

A.10 Economic Equations in the Numerical Model

Most equations are identical to the equations of the model in Schenker (2009).

A.10.1 Variables and Prices

$Y_{r,t}$	Net output (consumption good)
$Q_{r,t}$	Gross output
$O_{i,r,t}$	Output of commodity i
$A_{i,r,t}$	Armington good out of sector i
$INV_{r,t}$	Investment in region r
$K_{r,t}$	Capital stock in region r at time t
HH_r	Regional household r
$E_{r,t}$	CO_2-equivalent emissions in billion tons
$D_{r,t}$	Climate damages
$\Upsilon_{r,t}$	Emission control rate
$AB_{r,t}$	Abatement costs

Table 9: List of the activity levels in the numerical model.

$p_{r,t}$	Price Consumption Good (Net Output)
$p^q_{r,t}$	Price Gross Output
$p^o_{i,r,t}$	Price commodity i
$p^a_{i,r,t}$	Price Armington i
$p^k_{r,t}$	Purchase Price of Capital
$rk_{r,t}$	Rental Rate of Capital
$w_{r,t}$	Wage rate
$p^{ab}_{r,t}$	Shadow price on abatement cost coefficient
$p^d_{r,t}$	Shadow price on damage coefficient
$p^e_{r,t}$	Shadow price of emissions

Table 10: List of the price levels in the numerical model.

Note that $\Pi_{i,r,t}$ denotes the profit function of sector i in region r at time t. Differentiating the profit function with respect to input and output prices provides compensated demand and supply (Shepard's lemma) which appears subsequently in the market clearance condition.

A.10.2 Zero Profit Conditions

Zero profit condition for the consumption good:

$$\Pi^{GDP}_{r,t} = p^q_{r,t} \frac{Q_{r,t}}{1 + D_{r,t}} - p_{r,t} Y_{r,t} = 0. \tag{29}$$

Zero profit condition for gross GDP:

$$\Pi^{Q}_{r,t} = p^{q}_{r,t} - (\sum_{i} \theta_{i,r} p^{A(1-\sigma_q)}_{r,t})^{\frac{1}{1-\sigma_q}} - p^{e}_{r,t}\phi_t(1-\Upsilon_{r,t}) - p^{q}_{r,t}AB_{r,t} = 0. \tag{30}$$

Zero profit condition for commodities:

$$\Pi^{O}_{i,r,t} = p^{O}_{i,r,t} - \left(\theta^{O}_{i,r} p^{(1-\sigma^{O}_{i})}_{r,t} + (1-\theta^{O}_{i,r}) \left[\theta^{KL}_{i,r} rk^{(1-\sigma^{K}_{i})}_{r,t} + (1-\theta^{KL}_{i,r}) w^{1-\sigma^{K}_{i}}_{r,t} \right]^{\frac{1-\sigma^{O}_{i}}{1-\sigma^{K}_{i}}} \right)^{\frac{1}{1-\sigma^{O}_{i}}} = 0. \tag{31}$$

Zero profit condition for the Armington production of commodity i:

$$\Pi^{A}_{i,r,t} = p^{A}_{i,r,t} - \left(\theta^{A}_{i,r} p^{O(1-\sigma^{A}_{i})}_{i,r,t} + \sum_{s} \theta^{AM}_{i,r,s} p^{O(1-\sigma^{A}_{i})}_{i,s,t} \right)^{\frac{1}{1-\sigma^{A}_{i}}} = 0. \tag{32}$$

Zero profit condition for the capital accumulation:

$$\Pi^{K}_{r,t} = p^{K}_{r,t} - p^{K}_{r,t+1}(1-\delta) - rk_{r,t} = 0. \tag{33}$$

Zero profit condition for investment:

$$\Pi^{I}_{r,t} = p_{r,t} - p^{K}_{r,t+1} = 0. \tag{34}$$

Zero profit condition for abatement:

$$\Pi^{AB}_{r,t} = p^{ab}_{r,t} + p^{q}_{r,t}Q_{r,t} = 0. \tag{35}$$

Zero profit condition for the emission control rate $\Upsilon_{r,t}$:

$$\Pi^{\Upsilon}_{r,t} = p^{e}_{r,t}\phi_t - p^{ab}_{r,t}\gamma^{1}_{r}\gamma^{2}_{r}\Upsilon^{\gamma^{2}_{r}-1} = 0. \tag{36}$$

Zero profit condition for emissions:

$$-p^{e}_{r,t} = \sum_{t} p^{d}_{r,t}(2\alpha^{1}_{r}T^{E}_{t} + \alpha^{2}_{r}) + \sum_{t>T} p^{d}_{r,t}\chi_{r,t}, \tag{37}$$

where $\chi_{r,t}$ denotes the climate impacts beyond the horizon of the economic model.

A.10.3 Market Clearance Conditions

Market clearance condition for the consumption good:

$$Y_{r,t} = DI_{r,t} + C_{r,t} + INV_{r,t}. \tag{38}$$

Market clearance condition for the gross output:

$$\frac{Q_{r,t}(1-AB_{r,t})}{1+D_{r,t}} = Y_{r,t}. \tag{39}$$

Market clearance condition for the output commodity i:

$$\frac{\partial \Pi^A_{i,r,t}}{\partial p^O_{i,r,t}} + \sum_s \frac{\partial \Pi^A_{i,s,t}}{\partial p^O_{i,r,t}} = O_{i,r,t}, \tag{40}$$

with $\frac{\partial \Pi^A_{i,r,t}}{\partial p^O_{i,r,t}}$ and $\frac{\partial \Pi^A_{i,s,t}}{\partial p^O_{i,r,t}}$ as domestic demand for commodity i and foreign demand in region s for commodity i.

Market clearance condition for the Armington good i:

$$\frac{\partial \Pi^Q_{i,r,t}}{\partial p^A_{i,r,t}} = \frac{\partial \Pi^A_{i,r,t}}{\partial p^A_{i,r,t}}, \tag{41}$$

with $\frac{\partial \Pi^Q_{i,r,t}}{\partial p^A_{i,r,t}}$ as demand in gross output for Armington good i.

Market clearance condition for labor supply:

$$\bar{L}_{r,t} = \sum_i \frac{\partial \Pi_{i,r,t}}{\partial w_{r,t}}, \tag{42}$$

with $\frac{\partial \Pi_{i,r,t}}{\partial w_{r,t}}$ as demand for labor in sector i

Market clearance condition for investments and capital:

$$K_{r,t-1}(1-\delta) + INV_{r,t-1} = K_{r,t} \tag{43}$$

Market clearance condition for abatement costs $AB_{r,t}$:

$$AB_{r,t} = \gamma^1_r \Upsilon^{\gamma^2_r}_{r,t}, \tag{44}$$

where γ^1_r and γ^2_r are the parameters in the abatement cost function (see table 8 for values).

Market clearance condition for emissions:

$$E_{r,t} = \phi_{r,t}(1-\Upsilon_{r,t})O_{D,r,t}. \tag{45}$$

Emissions $E_{r,t}$ are a function of the exogenous emission-output ratio $\phi_{r,t}$, the emissions control rate $\Upsilon_{r,t}$, and the production of emission intensive goods $O_{D,r,t}$.

A.10.4 Economic Impacts

The economic impact of climate change on the regional economies $D_{r,t}$ is given by:

$$D_{r,t} = \alpha^1_r (T^E_t)^2 + \alpha^2_r T^E_t, \tag{46}$$

where α^1_r and α^2_r are regional damage parameters (see table XX in the text) and T_t describes the temperature at time t.

A.10.5 Household Income

$$HH_r = \sum_t w_{r,t}\bar{L}_{r,t} + p^k_{r,t=0}K_{r,t=0} \tag{47}$$

A.10.6 Terminal Capital Constraint

$$\sum_{t} \frac{INV_{r,t}}{INV_{r,t-1}} - \frac{Q_{r,t}}{Q_{r,t-1}} = 0 \ \forall t > T \tag{48}$$