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Abstract

Principles of fairness suggest that the envisaged successor agreement to the Kyoto Protocol should be based on the polluter pays principle. It should also take into account that emerging economies and developing countries will, in the next few decades, put greater emphasis on economic growth than on investing in emissions cuts. To analyse the implications of these two requirements, we estimate regional carbon prices that are based on regional cost-benefit analysis and strict liability of countries for damages caused by their emissions. Our estimates indicate a big gap between the carbon prices chosen by OECD countries and those of other countries. Because regional carbon pricing is probably neither feasible nor desirable we introduce transfer payments to make a globally uniform carbon price more acceptable. We estimate that OECD countries would currently have to transfer US$27 billion per year to compensate the rest of the world for implementing a global carbon price of $35/t$CO_2$.

The 2009 and 2010 Conferences of the Parties (COP) to the UN Framework Convention on Climate Change (UNFCCC) have demonstrated, once more, that there is fundamental disagreement in the international community about which countries should contribute how much to the global effort to reduce emissions of greenhouse gases (GHG). The United States, which accounts for around a quarter of global GHG emissions (IEA, 2010), refuses to join the Kyoto Protocol as well as follow-up agreements as long as large emerging economies, such as China and India, do not formally commit to substantive emissions cuts as well. Emerging economies object. They point to the greater historical responsibility of richer countries for the climate change problem and argue that GHG cuts could imperil their economic growth, which they expect to lift millions out of poverty.

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In this paper we are interested in how the international community could cope with the challenge of integrating emerging economies and developing countries into a follow-up agreement to the Kyoto Protocol. This challenge emanates from the fact that these countries have less capacity for GHG mitigation, but also from the fact that, given their economic growth perspectives, they have a different view on the intertemporal problem of climate change as well. If the international community wishes current non-Annex I countries to participate in collective action against climate change, it should consider not only differences in 'ability to pay' for abatement efforts (Lange et al., 2007), but also differences in what countries consider the optimal reaction to the threats posed by climatic change.

Assuming that states accept liability for climate change damages (Tol and Verheyen, 2004) caused by their respective GHG emissions and thus accept, in principle, to internalise the losses they inflict on the world, we compare carbon prices that would result from regional cost-benefit analyses. We focus on regions, which are groups of countries, because this makes the analysis more tractable. These regional cost-benefit analyses weigh the benefits from current emissions against liabilities for these emissions in future periods. Regional carbon prices, which reflect countries' efforts to internalise the losses they impose on the world, are bound to differ because regions hold different expectations concerning their future economic growth. Assuming that the marginal utility of consumption decreases with rising wealth implies that countries expecting rapid economic growth will discount future liabilities more than countries that, ceteris paribus, expect slower economic growth (Dasgupta, 2008).

The uncertainty inherent in predictions of climatic change and associated economic losses is considerable and makes calculating the social cost of carbon difficult (Yohe et al., 2008). However, while such uncertainties make it hard to identify the *absolute* value of appropriate carbon prices, we find that the *ratios* between concurrent carbon prices of different regions remain within reasonable bounds when we cycle through different assumptions about climate change and associated damages.

We then use our estimates of ratios between concurrent regional carbon prices to address the issue of how emerging economies and developing countries could be integrated into a new global climate change treaty. Specifically, we argue that liability for climate change damages will be very hard to enforce. Moreover, regional carbon prices would lack the efficiency of abatement allocation that a global carbon price exhibits. These problems could be circumvented by compensating emerging economies and developing countries for the difference between a global carbon price and their respective regional carbon price. Our results suggest that OECD countries would currently have to transfer around US$27 billion per year to compensate the rest of the world for abating according to a global carbon price of $35/t$CO_2$.

1 Liability and Fairness

Some economists and political scientists have argued that the basic architecture of the Kyoto Protocol, which explicitly defines emission reduction goals and then distributes the burden among countries through international bargaining, is flawed (Barrett, 2006; Nordhaus, 2007; Victor, 2004). Many economists in fact argue that negotiations should focus on setting a global carbon price rather than specific reduction targets for individual countries (Nordhaus, 2007). Their rationale is that an optimally set carbon price will make CO_2 emitters equate the marginal profit from releasing one unit (usually expressed in tons) of carbon into the atmosphere to the present value of marginal damages caused by that emission in the future. It is this condition that policy-optimising integrated assessment models (IAMs) strive to attain.

If we follow the advice of some such IAMs, we should allow for GHG emissions that could lead to global warming exceeding 2 °C, for instance by letting CO_2 concentrations raise to 600 ppm (Nordhaus, 2010). Most climate scientists believe that the 2 °C goal cannot be achieved at such high GHG concentration levels (den Elzen et al., 2007; Meinshausen et al., 2009). They expect global warming exceeding 2 °C to have strong and potentially irreversible impacts on the environment and humanity (Solomon et al., 2009). Moreover, it appears likely that those countries that will suffer most from climatic changes tend to be those that are least responsible for the problem (Füssel, 2010a). From a fairness perspective, any policy that does not achieve the lowest possible temperature change should therefore include mechanisms for compensating countries that experience climate change damages.

The obvious solution could be that, each year, emitting countries compensate countries experiencing climate change damages according to their share of responsibility for concurrent climate change. In its most rigorous form, which corresponds to the polluter pays principle, this solution means that emitting countries are fully liable for damages their emissions are causing outside their territory. The economics literature offers some analysis of the feasibility of such a liability system and the size of damages that different world regions would have to be held liable for (Tol and Verheyen, 2004). Interestingly, even though a general 'no harm' rule is included both in the 1992 UNFCCC and the 1997 Kyoto Protocol, several countries have explicitly rejected the idea that the Kyoto Protocol should include any specific provisions on state responsibility (Tol and Verheyen, 2004).

If, nonetheless, full liability for climate change damages could be established and enforced, countries would have a strong incentive to internalise the damages their emissions are inflicting on others. At the same time, under such a system, countries could also, individually, trade off costs and benefits between emitting today and facing the consequences (liability) in the future. With a view to contemporary controversies about how to share

the global mitigation burden it appears quite reasonable to assume that countries *should* value future payments for liabilities differently because of their different economic growth prospects. The faster a country expects its economy to grow over the coming years, the higher its willingness is likely to be to trade liabilities in the future against emission rights at present. The simple reason is that paying off a liability in the future becomes less painful the richer the country will be at the time of payment.[1]

Under the conditions just discussed, any post-Kyoto agreement that is based on a globally uniform price of emission permits will not be able to take into account obvious differences in the time preferences of countries. If the globally uniform carbon price reflected the time preference of advanced industrialised countries, emerging economies would regard this price as unfair because they prefer a lower price of emitting on their territory and compensating damaged countries at a later point. If the global carbon price reflected the time preferences of emerging economies, those countries would probably conclude that advanced industrialised countries are failing to fully internalise the damages their emissions are causing.

2 Regional Carbon Prices

To arrive at an estimate of compensation payments that would be required to get emerging economies and developing countries to fully participate in a new post-Kyoto agreement, we first need to estimate regional carbon prices under the assumption that countries accept liability. Figure 1 summarises our estimates of relative regional carbon prices for the regions Africa and Latin America (ALM), Asia (ASIA), and transition economies (REF) relative to the OECD countries as of 1990 (OECD90). Regions follow the convention of the IPCC special report on emission scenarios (SRES) (Nakicenovic and Swart, 2000). Panel **a** in Figure 1 indicates relative carbon prices in the year 2010. Price estimates for world regions relative to OECD90 prices are distinguished according to (i) economic scenario, (ii) climate model, and (iii) damage function used for the estimate. As expected, the most obvious difference in estimated prices stems from different economic scenarios. Differences in projected economic growth—and the associated discounting—in fact influence relative carbon prices much more than differences in modelling climate and climate change-related damages.

The estimates based on the B2 scenario are particularly interesting. If

[1]Such differences in time preferences are at odds with the assumption of perfect international capital markets, an assumption that is usually made in IAMs. In the context of perfect capital mobility, if investors of an emerging economy decide not to invest because they prefer consumption today over collecting the expected rents later, investors from more slowly growing countries can fill in for them. However, macroeconomic studies do not offer a conclusive answer to the question of whether frictions in international capital markets do or do not matter (Acemoglu, 2008).

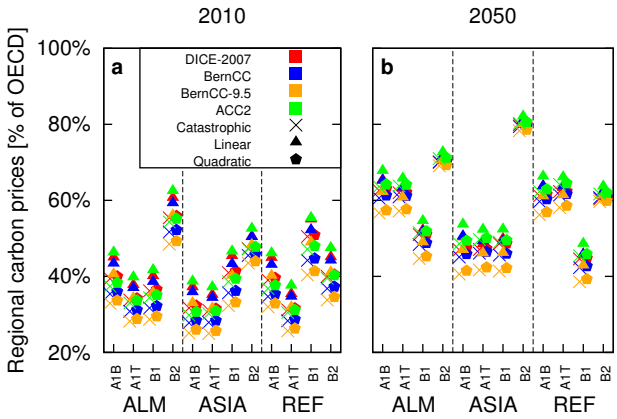

Figure 1: **Sensitivity of price ratios to scenarios.** Carbon prices relative to the OECD90's carbon price for SRES regions *Africa and Latin America* (ALM), *Asia* (ASIA), and *countries undergoing economic reform* (REF). Panel **a** shows price ratios for the year 2010, panel **b** shows price ratios for the year 2050 (based on projections of SRES data beyond 2100; see Appendix). Results based on the four climate models are in different colours. Different marker types denote the results based on the three damage functions. Relative carbon prices vary considerably with economic scenarios, but less so with climate and damage modelling.

we rely on this scenario, the region 'Africa and Latin America' is likely to discount future damages almost as little as the OECD90 region. The reason is that the B2 scenario predicts relatively (relative to other economically less developed regions) low economic but high population growth for this region; that is, per capita GDP in this region hardly grows at all for the first few decades in that scenario. With small per capita growth the social rate of time preference is relatively low and the ALM region does not discount future climate damages much.

Panel **b** of Figure 1 indicates strong consistency of carbon price predictions for the year 2050 as well, except that for the A1B scenario (the one with the biggest global emissions; see Appendix) the 'hockey stick' damage assumption produces very different results than the other damage functions. However, we regard the 'hockey stick' damage factor as highly pessimistic and think that it will eventually be easier to identify relative prices in 2050 than is suggested by the results shown in Figure 1.

Figure 2 shows how using different parameterisations for estimating social rates of time preference influences the results. Cycling through the different sets of parameter choices produces similar variation in price ratios, as is the case for using different climate models and different damage functions.

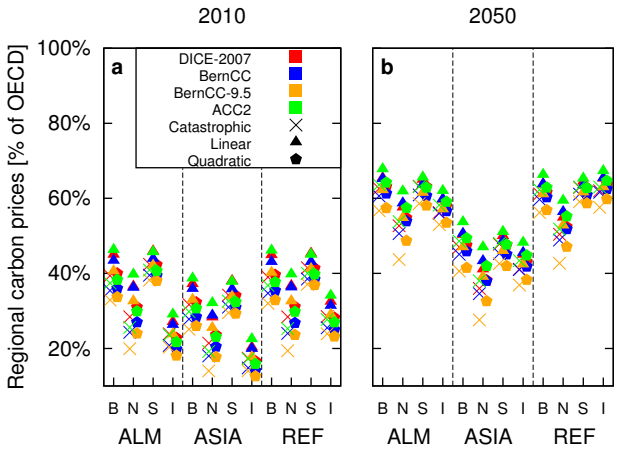

Figure 2: **Sensitivity of price ratios to discounting parameters.** Carbon prices for regions ALM, ASIA, and REF, relative to the OECD90's carbon price, based on the A1B scenario. Panel **a** shows price ratios for the year 2010, panel **b** projected price ratios for the year 2050. Results based on the four climate models are in different colours. Marker types distinguish the results obtained from different damage functions. The different choices of parameters for determining the social rate of time preference are referred to as 'Base case' (B), 'Nordhaus' (Nordhaus, 2007) (N), 'Stern' (Stern, 2007) (S), and 'Increasing EIS' (I) in the methodology section.

We conclude that the ratios between regional carbon prices are surprisingly robust against changes in climate change and damage assumptions as well parameter choices for discounting, but crucially depend on growth perspectives of the different regions. These results offer the foundation for proceeding to the next step of the analysis, namely estimating compensation payments required to obtain the participation of emerging economies and developing countries.

3 Compensation Payments

A new global climate change agreement based solely on regional carbon pricing and strict liability is probably not feasible because it would require an unprecedented global enforcement mechanism that remains robust over many decades. Nor may such an approach be desirable if economically less developed countries postponed emission cuts or compensation for their liabilities long into the future and, as a consequence, risked climate change-related damages that cross thresholds that climate scientists regard as critical in terms of irreversible damages. A practical solution to this problem could be to set a global carbon price that motivates economically efficient

mitigation efforts aimed at the 2 °C goal, and to compensate economically less developed countries for the difference between their preferred regional carbon price and the global carbon price.

How much compensation would be required to that end? In principle, transfer payments should compensate emerging economies and developing countries for accepting a (global) carbon price that is higher than the price they would otherwise choose, assuming liability for climate change damages. Advanced industrialised countries, in turn, should be willing to foot the bill for those transfers because the global carbon price is lower than the price they would be willing to pay, also assuming liability. Such a solution in fact approximates what emerging economies asked for at the UNFCCC COPs in Copenhagen and Cancun. It could even rely on a global "cap and trade" system under which a global carbon price (the equivalent of a carbon tax) would emerge.

To estimate the amount of compensation that would be required to make such a deal acceptable for all countries, we compare a case in which all countries apply a (global) carbon tax of \$35 per ton of CO_2 (\$/tCO_2) to a case in which world regions set their own carbon prices in line with our analysis above, but reach the same global abatement cost. The global carbon price assumed here comes close to the common €25/tCO_2 prediction for the European emissions trading system (EU ETS) over the next few years[2], and is about one standard deviation higher than the mean value for the social cost of carbon estimated in the academic literature (Yohe et al., 2008, p.813). In the case of regional carbon pricing we assume that the ALM region's carbon price is 40% of the OECD90's and that the carbon prices in regions REF and ASIA are 30% and 40% of the OECD90's (compare to panel a of Figure 1). With this approach we can calculate how much the regions should pay each other to switch from one scenario to the other.

To estimate marginal abatement cost (MAC) we used a general equilibrium model of the world economy (Böhringer et al., 2006) (see Appendix). The first column in Table 1 shows regional costs of abatement when all regions apply a carbon tax of \$35/tCO_2. In the regional pricing case , the carbon prices are $p_{\text{OECD90}} = \$58/\text{tCO}_2$, $p_{\text{ALM}} = \$23/\text{tCO}_2$, $p_{\text{ASIA}} = \$17/\text{tCO}_2$, and $p_{\text{REF}} = \$23/\text{tCO}_2$. This results in global abatement costs that equal the costs in the uniform pricing case, which in turn ascertains that the costs the OECD90 region avoids when it is allowed to apply carbon prices as in the uniform pricing case rather than the regional pricing case equal the cost the other regions incur in addition from this change of pricing.

The results shown in Table 1 suggest that the OECD90 region would currently have to pay around US\$27 billion per year to compensate the rest of the world for reducing emissions according to the global carbon price of \$35/tCO_2, rather that internalising the damage according to regional pref-

[2] http://www.icfi.com/Publications/Perspectives-2005/price-carbon.asp

	Region	*Uniform Pricing* Cost [billion \$]	*Regional Pricing* 'base case' Price [\$/tCO_2]	'base case' Cost [billion \$]	'increasing EIS' Price [\$/tCO_2]	'increasing EIS' Cost [billion \$]
A1B	ALM	10.4	20 - 26	4.4 - 6.3	12 - 19	1.9 - 3.7
	ASIA	29.8	15 - 21	10 - 16	8.7 - 15	4.1 - 9.4
	OECD90	25.7	54 - 62	47 - 57	62 - 70	58 - 67
	REF	10.3	19 - 25	4.3 - 6.3	16 - 22	3.1 - 4.9
A1T	ALM	10.4	17 - 23	3.5 - 5.2	10 - 16	1.3 - 2.8
	ASIA	29.8	15 - 21	10 - 16	8.8 - 14	4.2 - 9.1
	OECD90	25.7	56 - 63	50 - 59	64 - 71	61 - 69
	REF	10.3	16 - 22	3.1 - 4.9	11 - 17	1.8 - 3.3
B1	ALM	10.4	16 - 22	3.2 -4.9	10 - 16	1.5 - 2.9
	ASIA	29.8	18 - 25	14 - 19	11 - 18	6.7 - 13
	OECD90	25.7	51 - 59	44 - 53	59 - 67	55 - 64
	REF	10.3	23 - 29	5.7 - 7.7	18 - 25	3.9 - 5.9
B2	ALM	10.4	26 - 31	6.6 - 8.5	17 - 24	3.6 - 5.5
	ASIA	29.8	23 - 26	18 - 21	16 - 19	11 - 21
	OECD90	25.7	48 - 54	41 - 48	52 - 63	45 - 59
	REF	10.3	18 - 24	3.8 - 5.6	15 - 20	2.8 - 4.2

Table 1: **Regional abatement costs at a globally uniform carbon price of \$35/tCO_2 and at regionally differing carbon prices.** In the 'base case', $\sigma = 1.3$, and in the 'increasing EIS' case, an income dependent $\sigma(i_t)$ was chosen. Remaining variance of results for any combination of scenario and region comes from different assumptions about climate change and damages.

erences. Interestingly, this amount corresponds by-and-large to the US$30 billion that, according to a non-legally binding agreement reached in Copenhagen and Cancun, is supposed to flow from Annex I to non-Annex I countries in the time-period 2010 to 2012. While the figures advanced in Copenhagen and Cancun are based primarily on political considerations, our estimates are, to our knowledge, the first that are based on a scientific modelling approach. Our findings suggest that financial support of this order of magnitude should be sufficient to motivate countries that are willing to internalise the damages their carbon emissions are causing to join a global agreement at a carbon price level that is comparable to the one anticipated for the EU ETS.

4 Conclusion

We believe that a new global climate change agreement that is acceptable to advanced industrialised countries as well as emerging economies and developing countries will have to combine at least two elements. First, it will have to take into account that, due to different preferences and prospects for economic growth, emerging economies and developing countries will, over the next few decades, prioritise economic growth over investments in climate change mitigation. Second, in view of potentially enormous mitigation costs efficiency considerations are key. Hence our approach seeks to combine these two considerations.

Our results for responsibility allocations and regional carbon pricing (which reflect regional priorities and trade-offs) indicate that such an agreement is feasible. While estimates of regional carbon prices are very useful for identifying regional preferences concerning the size and timing of mitigation efforts, a global climate change agreement based on regional carbon prices is probably neither practicable nor desirable. The problem of practicability emanates from the fact that a regional carbon pricing system within a system of strict responsibility would require a strong enforcement mechanism that remains effective over many decades. It is highly doubtful that the international community will be able to establish and maintain such a mechanism. The desirability problem emanates from the fact that a uniform global carbon price is likely to be more efficient and involve lower transactions costs. Consequently, we propose resorting to a global carbon price, but implementing transfer payments by advanced industrialised countries to emerging economies and developing countries. Estimates of such transfer payments should be based on estimates of regional carbon prices.

We estimate that OECD countries would currently have to transfer around US$27 billion per year to compensate the rest of the world for implementing a global carbon price of $35/tCO_2$. This estimate focuses exclusively on offsetting regionally different time preferences. Additional transfer

payments may be appropriate, e.g. for humanitarian reasons, but are outside our modelling framework. The estimated compensation required to bring economically less developed countries on board, and also the assumed global carbon price of \$35/tCO_2, line up quite well with the financial transfers from Annex I to non-Annex I countries agreed to in Copenhagen and Cancun. It is also compatible with the anticipated carbon price in the EU Emissions Trading System over the next few years. Hence our results, and the assumptions on which they are based, suggest that a global deal of this kind is possible.

5 Methodology

Using climate models, we can analyse how small differences in annual emissions change future temperature and keep track of which year's emissions affect climate change by how much. In this section we discuss how economic scenarios, climate models, and assumptions about climate damages can be combined to estimate regional carbon prices motivated by strict liability for climate change related damages.

5.1 Estimating Responsibility

The allocation of responsibility for climate change to the emissions of different years is well understood and regional shares of responsibility can be established (den Elzen et al., 2005). Based on scenarios for GHG emissions, we can determine the *share of responsibility* for global temperature change ΔT_{t_d} at time t_d caused by emissions E_{r,t_e} of region r in preceding periods t_e:

$$S_{\mathsf{r},t_d} := \frac{\sum_{t_e=t_0}^{t_d} E_{\mathsf{r},t_e} \frac{\mathrm{d}T_{t_d}}{\mathrm{d}E_{t_e}}}{\sum_{t_e=t_0}^{t_d} E_{t_e} \frac{\mathrm{d}T_{t_d}}{\mathrm{d}E_{t_e}}}. \tag{1}$$

We assume that a small country will only pays attention to the change in this responsibility share when it determines by how much its liability will increase with an additional unit of emissions in year t_e. In other words, this country will ignore the marginal effect of its additional emissions on temperature change ΔT_{t_d} and thus on global damages $D(\Delta T_{t_d})$. This country will then put a price on CO_2 emissions that equals the sum of discounted (with a social rate of time preference r_{r}) future marginal increases in liability:

$$P_{\mathsf{r}}(t_e) := \sum_{t_d=t_e}^{t_e+\Delta t_{\mathrm{liab}}} \left[\prod_{t=t_e}^{t_d} \frac{1}{1+r_{\mathsf{r}}(t)} \right] \frac{D_{t_d}(\Delta T_{t_d}) \frac{\mathrm{d}T_{t_d}}{\mathrm{d}E_{t_e}}}{\sum_{t=t_0}^{t_d} E_t \frac{\mathrm{d}T_{t_d}}{\mathrm{d}E_{t_e}}}. \tag{2}$$

We assume that countries will only be held liable for damages that materialise within $\Delta t_{\mathrm{liab}} = 100$ years after the respective emissions took place (see Appendix for further comments on this).

5.2 Economic Scenarios and Social Rates of Time Preference

To obtain estimates of regional rates of social time preference, we assume that regions have a social welfare function of the form

$$W(\{c_t\}) \quad = \quad \sum_{t \geq t_0} \left(\frac{1}{1+\rho} \right)^{t-t_0} \frac{c_t^{1-\sigma}}{1-\sigma},$$

with c_t denoting the regional per capita consumption. ρ is the pure rate of time preference, and σ the inverse of the elasticity of intertemporal substitution. A high value of σ indicates a high willingness to shift consumption from years of high per capita consumption to years of low per capita consumption. This high willingness results in high levels of savings in periods of abundance if periods of scarcity are expected in the future, or in low levels of saving or even going into debt in times of poverty if times of prosperity are anticipated.

In estimating the social rate of time preference, we compare the compensation a region would request in period $t+1$ in exchange for having to give up consumption in period t without decreasing $W(\{c_t\})$. A rate of social time preference of r_s indicates that, in exchange for having to give up one (small) unit of c_t, the representative consumer will demand at least $1 + r_s$ units of c_{t+1} in the following period. In the context of the intertemporal welfare function shown above, this solves to

$$r_s = (1+\rho) \left(\frac{c_{t+1}}{c_t} \right)^{\sigma} - 1. \tag{3}$$

Assumptions about the social rate of time preference have been found to influence the results of integrated assessment of climate change considerably (Dasgupta, 2008). Some exemplary choices of the parameters σ and ρ from the integrated assessment literature are: $\rho = 0, \sigma = 1.5$ (Cline, 1992), $\rho = 1.5\%$ per year, $\sigma = 2$ (Nordhaus, 2007), $\rho = 3.0\%$ per year, $\sigma = 1$ (Nordhaus, 1994), and $\rho = 0.1\%$ per year, $\sigma = 1$ (Stern, 2007). In our analysis, we use

$$\rho = 1.5\% \text{ and } \sigma = 1.3 \qquad \text{(Base case)} \tag{4}$$

as the base case which is in the range of what has been estimated for OECD countries (Evans and Sezer, 2004). To assess how sensitive our results are to alternative values of these parameters, we repeat some of our calculations with alternative parameter choices (Stern, 2007; Nordhaus, 2007):

$$\rho = 0.1\% \text{ and } \sigma = 1 \qquad \text{(Stern)}, \tag{5}$$

$$\rho = 1.5\% \text{ and } \sigma = 2 \qquad \text{(Nordhaus), and} \tag{6}$$

$$\rho = 1.5\% \text{ and } \sigma(i_t) = 1 + \exp\left(\frac{i_t - i_a}{i_o - i_a} \ln 0.3 \right) \quad \text{(Increasing EIS)}. \tag{7}$$

$\sigma(i_t)$ in equation (7) accounts for the fact that, according to several studies (Guvenen, 2006; Ogaki et al., 1996), the elasticity of intertemporal substitution $1/\sigma$ grows with per capita income levels i_t. With our parametrisation, in the year 2000, the OECD90 countries with a per capita income of $i_o =$ US\$29 383 are at $\sigma(i_o) = 1.3$ and ASIA with p.c. income $i_a =$ US\$3 858 is at $\sigma(i_a) = 2$. Additionally, $\sigma(i_t)$ converges to 1 as i_t goes to infinity.

We base our analysis on the IPCC's Special Report on Emissions Scenarios SRES (Nakicenovic and Swart, 2000). The report's scenarios are divided into A1,A2,B1, and B2 type scenarios. The 'A.' scenarios are scenarios assuming rapid economic growth, while the 'B.' scenarios assume economic development that is more compatible with principles of environmental sustainability. '.1' scenarios assume a collaborating world where national growth rates converge on a common rate over time, whereas '.2' scenarios assume that countries respond in a less coordinated way to the challenges of climate change (Nakicenovic and Swart, 2000).

For our estimates we considered two A1 scenarios, A1B (balanced emphasis on all energy sources), A1T (emphasis on non-fossil energy sources), and the B1 and B2 scenarios. We assume that these scenarios cover an appropriately wide range of possible futures in which at least *some* mitigation measures are implemented (the A2 scenario is the most pessimistic scenario and does not assume any coordinated mitigation policies, see Appendix), and that the resulting range of carbon prices thus accounts for uncertainty about the economic future of the world.

The SRES scenarios cover four world regions: Africa and Latin America (ALM), Asia (ASIA), the OECD countries as of 1990 (OECD90), and transition economies (REF). The REF region includes 'Central and Eastern Europe' and 'newly independent states of the former Soviet Union' (Nakicenovic and Swart, 2000).

5.3 Climate Models

To account for uncertainties that affect climate modelling and the resulting projections, we use three different climate models. First, we use the climate module from the DICE-2007 model, by William Nordhaus (Nordhaus, 2008). It is a simplistic representation (Joos et al., 1999) of the earth's climate in 7 equations that runs on the time scale of decades.

Second, we use a simple version of the Bern carbon cycle-climate (BERNCC) model (Joos et al., 2001). Besides a radiative forcing, climate, and carbon cycle module, the BERNCC model also includes a model of atmospheric chemistry. The carbon cycle module couples the atmosphere to the two carbon sinks, namely the ocean and the land-biosphere.

Third, we use the Aggregated Carbon Cycle, Atmospheric Chemistry, and Climate Model (ACC2) of the Max Planck Institute for Meteorology in Hamburg (Tanaka et al., 2007). This model includes the same types of

modules as BERNCC (that is, radiative forcing, climate, carbon cycle, and atmospheric chemistry).

Figure C.1 (see Appendix) shows the implications of a marginal increase in emissions in the decade around the year 2000 for temperatures in future years, as predicted by the three climate models. To obtain the marginal effect of emissions in the decade around 2000, we let the yearly emissions in the SRES scenario A1B increase by 10 MtC from 1996 to 2005. The comparison of the three climate models reveals remarkable differences in how fast the effects of a marginal emissions increase are predicted to fade (see Appendix).

5.4 Damage Functions

Another important yet controversial issue in integrated assessment modelling (IAM) is the description of damages to be expected from climatic change. Estimates of how temperature increases will affect the world economy are based on expert assessments and 'guesstimates of the modellers' (Füssel, 2010b). These estimates vary considerably across models and affect estimates of optimal taxes on carbon emissions (Roughgarden and Schneider, 1999).

A simple approach that is often used in modelling of global damages is to assume that damages at time t are proportional to world GDP at time t, and that the proportionality factor depends on temperature increase $\Delta T(t)$ alone (Tol and Fankhauser, 1998; Füssel, 2010b):

$$D(t) = \mathrm{GDP}(t) \cdot \delta(\Delta T(t)). \tag{8}$$

Some exemplary damage factors $\delta(\Delta T)$ from the literature are (Nordhaus, 1994, 2008; Roughgarden and Schneider, 1999; Manne and Richels, 2005)

$$\begin{aligned} \delta(\Delta T) &= 1 - \left(1 + \alpha \Delta T^2\right)^{-1} && (\textit{Catastrophic}), \\ \delta(\Delta T) &= \beta \Delta T^2 && (\textit{Quadratic}), \quad \text{and} \\ \delta(\Delta T) &= \gamma \Delta T && (\textit{Linear}). \end{aligned}$$

When we compute carbon prices according to equation (10) it turns out that the ratios between such prices do not depend on the scale of the damage function: different values of β and γ leave carbon price ratios approximately invariant (see Appendix for a more detailed discussion). We therefore consider the different calibrations of linear and quadratic damage functions as equivalent. We set $\alpha = 0.085164$ to model extreme catastrophic climate damages. Figure D.1 (see Appendix) displays the above damage factors.

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Appendices

A Estimating Responsibility

The allocation of responsibility for climate change to the emissions of different years is well understood and regional shares of responsibility can be established (den Elzen et al., 2005). Based on scenarios for GHG emissions, we can determine the *share of responsibility* for global temperature change ΔT_{t_d} at time t_d caused by emissions E_{r,t_e} of region r in preceding periods t_e:

$$S_{\mathsf{r},t_d} := \frac{\sum_{t_e=t_0}^{t_d} E_{\mathsf{r},t_e} \frac{\mathrm{d}T_{t_d}}{\mathrm{d}E_{t_e}}}{\sum_{t_e=t_0}^{t_d} E_{t_e} \frac{\mathrm{d}T_{t_d}}{\mathrm{d}E_{t_e}}}. \tag{9}$$

We assume that a small country will only pay attention to the change in this responsibility share when it determines by how much its liability will increase with an additional unit of emissions in year t_e. In other words, this country will ignore the marginal effect of its additional emissions on temperature change ΔT_{t_d} and thus on global damages $D(\Delta T_{t_d})$. This country will then put a price on CO_2 emissions that equals the sum of discounted (with a social rate of time preference r_{r}) future marginal increases in liability:

$$P_{\mathsf{r}}(t_e) := \sum_{t_d=t_e}^{t_e+\Delta t_{\mathrm{liab}}} \left[\prod_{t=t_e}^{t_d} \frac{1}{1+r_{\mathsf{r}}(t)} \right] \frac{D_{t_d}(\Delta T_{t_d}) \frac{\mathrm{d}T_{t_d}}{\mathrm{d}E_{t_e}}}{\sum_{t=t_0}^{t_d} E_t \frac{\mathrm{d}T_{t_d}}{\mathrm{d}E_{t_e}}}. \tag{10}$$

We assume that countries will only be held liable for damages that materialise within $\Delta t_{\mathrm{liab}} = 100$ years after the respective emissions took place.

A.1 Time Limit for Liability

We assume that countries can only be held liable for damages that materialise within $\Delta t_{\mathrm{liab}} = 100$ years after the respective emissions took place. Discounting implies that liabilities in the far future become irrelevant for current carbon prices. We find that the carbon price would continue to grow only in industrialised countries (low discount rates) if we included liability for damages that occur more than a hundred years from now. We ignore such damages to facilitate use of established scenarios of economic development. Note that with longer liability periods Δt, $P_{\mathsf{r}}(t_e)$ for developed countries becomes larger, while it remains almost unchanged for emerging economies.

A.2 Responsibility for Past Emissions

When we analyse historical responsibility and project it into the future, we come to conclusions similar to what has been found in another study (Rive

et al., 2006): We find that when projecting responsibility shares into the future the shares of emerging economies increase quite quickly (see Figure A.1).

To compute the responsibility share in a given year, the effect of all past emissions up to the year in question were taken into account. We restrict the analysis to CO_2 and use the *marginal* attribution method (den Elzen et al., 2005). Our estimates are based on the DICE-2007 climate module. The emissions data by the World Resources Institute[3] was projected into the future using the reference scenario from the International Energy Outlook of the U.S. Energy Information Administration[4]. The results shown in Figure A.1 suggest that, in line with with other published findings (Rive et al., 2006), the historical responsibility of developing countries and emerging economies, and in particular the responsibility of China, will grow quickly.

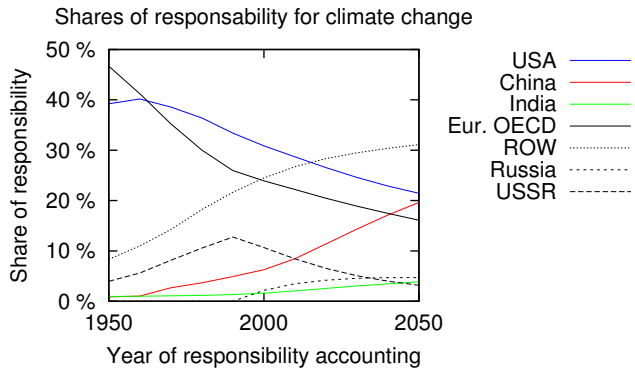

Figure A.1: Shares of responsibility for climate change related damages, as caused by all past emissions

B SRES Scenarios

We base our analysis on the IPCC's Special Report on Emissions Scenarios SRES (Nakicenovic and Swart, 2000). The report's scenarios are divided into A1,A2,B1, and B2 type scenarios. The 'A.' scenarios are scenarios assuming rapid economic growth, while the 'B.' scenarios assume economic development that is more compatible with principles of environmental sustainability. '.1' scenarios assume a collaborating world where national growth rates converge on a common rate over time, whereas '.2' scenarios assume that countries respond in a less coordinated way to the challenges of climate change (Nakicenovic and Swart, 2000).

[3] http://cait.wri.org/

[4] http://www.eia.doe.gov/oiaf/ieo/index.html

For our estimates we considered two A1 scenarios, A1B (balanced emphasis on all energy sources), A1T (emphasis on non-fossil energy sources), and the B1 and B2 scenarios. We assume that these scenarios cover an appropriately wide range of possible futures in which at least *some* mitigation measures are implemented (the A2 scenario is the most pessimistic scenario and does not assume any coordinated mitigation policies, see Appendix), and that the resulting range of carbon prices thus accounts for uncertainty about the economic future of the world.

The SRES scenarios cover four world regions: Africa and Latin America (ALM), Asia (ASIA), the OECD countries as of 1990 (OECD90), and transition economies (REF). The REF region includes 'Central and Eastern Europe' and 'newly independent states of the former Soviet Union' (Nakicenovic and Swart, 2000).

Figure B.1 shows global emissions under the different SRES scenarios, Figure B.2 shows regional GDP predictions of the different scenarios.

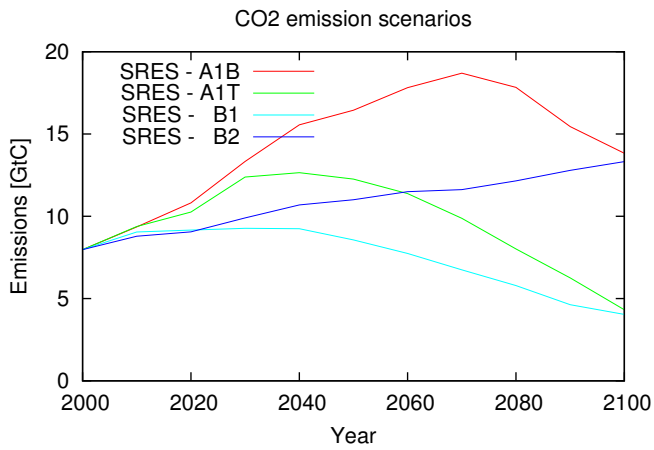

Figure B.1: Global CO_2 emissions in giga tons carbon (GtC) according to the SRES scenarios of the IPCC

C Climate Models

To account for uncertainties that affect climate modelling and the resulting projections, we use three different climate models. First, we use the climate module from the DICE-2007 model, by William Nordhaus (Nordhaus, 2008). Nordhaus' work has been very influential in integrated assessment modelling, but has also been criticised. The climate module of the DICE model has attracted criticism because it is said to remove carbon from the atmosphere at too high a rate (Joos et al., 1999). We ran this model using its standard setting for climate sensitivity of 3.0. The magnitude of climate sensitivity

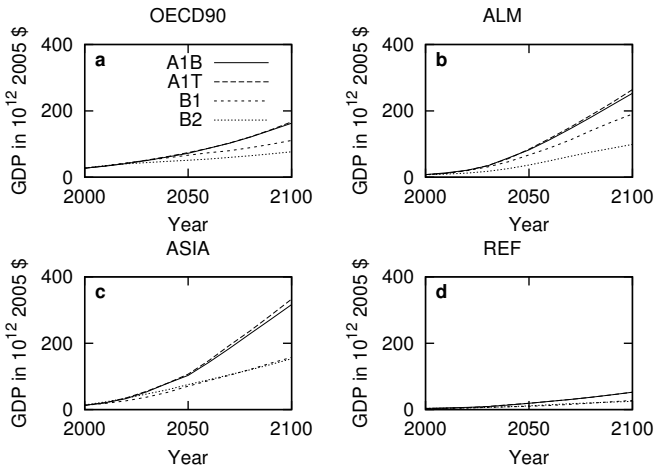

Figure B.2: GDP predictions for the four SRES regions according to different scenarios in trillion 2005 dollars.

describes long run equilibrium temperature increase (in °C), if atmospheric CO_2 concentration were kept at twice the preindustrial level.

Second, we use a customised version of the Bern carbon cycle-climate (BERNCC) model (Joos et al., 2001). Besides a radiative forcing, climate, and carbon cycle module, the BERNCC model also includes a model of atmospheric chemistry. The carbon cycle module couples the atmosphere to the two carbon sinks, namely the ocean and the land-biosphere. The models of both sinks are calibrated to reproduce with very high accuracy the results from detailed high resolution climate models. We used the BERNCC with a setting of the climate sensitivity parameter of 3.2 and conducted sensitivity analysis with a climate sensitivity parameter of 9.5.

Third, we use the Aggregated Carbon Cycle, Atmospheric Chemistry, and Climate Model (ACC2) of the Max Planck Institute for Meteorology in Hamburg (Tanaka et al., 2007). This model includes the same types of modules as BERNCC (that is, radiative forcing, climate, carbon cycle, and atmospheric chemistry). It uses maximum likelihood estimation with historical data to determine climate sensitivity internally and uses a value of 4.0.

Figure C.1 shows the implications of a marginal increase in emissions in the decade around the year 2000 for temperatures in future years, as predicted by the three climate models. To obtain the marginal effect of emissions in the decade around 2000, we let the yearly emissions in the SRES scenario A1B increase by 10 MtC from 1996 to 2005. This increase produces a total emissions increase of 100 MtC, parts of which already affect the temperature of the year 2000. This immediate effect is not observed in the DICE-2007 model, which operates on the time scale of decades.

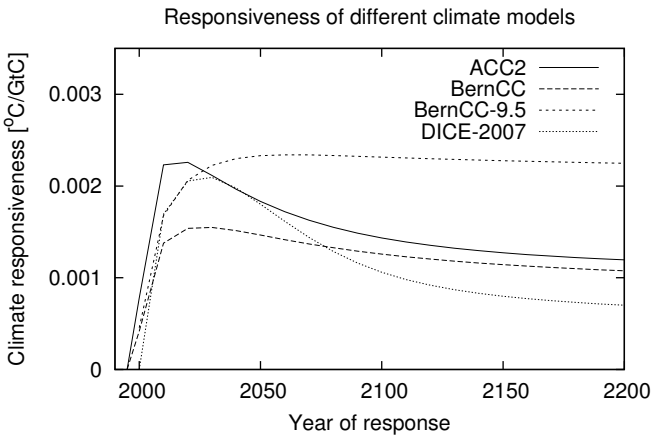

Figure C.1: **Responsiveness of Temperature at time t to a marginal emissions increase in the decade around 2000** Temperature responses according to three climate models ACC2, BernCC, and DICE-2007 and the SRES scenario A1B are shown. The BernCC model is represented twice, once with climate sensitivity 3.2 and once with 9.5.

The comparison of the three climate models reveals remarkable differences in how fast the effects of a marginal emissions increase are predicted to fade. The climate module of DICE-2007 predicts large effects of emissions on temperatures up to 50 years after the respective emissions took place, but then predicts the temperature effect to decrease rapidly within the following 150 years. The ACC2 model also predicts a strong short term effect of emissions that fades rather fast in the first 100 years, but then remains at much higher levels than predicted by DICE-2007. BERNCC's predictions look very similar to those of ACC2 100 years after the emission, but do not produce the high peak of the temperature effect in the short term.

D Damage Functions

In our work, we use the simple approach that damages at time t are proportional to world GDP at time t, and that the proportionality factor depends on temperature increase $\Delta T(t)$ alone:

$$D(t) = \mathrm{GDP}(t) \cdot \delta(\Delta T(t)). \tag{11}$$

We carry out our calculations using the damage factors

$$\delta(\Delta T) = 1 - \left(1 + \alpha \Delta T^2\right)^{-1}, \tag{12}$$

$$\delta(\Delta T) = \beta \Delta T^2, \quad \text{and} \tag{13}$$

$$\delta(\Delta T) = \gamma \Delta T. \tag{14}$$

In the paper we argue that different realistic choices of γ (we have found $\gamma = 0.001$ (Manne and Richels, 2005) and $\gamma = 0.0218$ (Roughgarden and Schneider, 1999) in the literature) produce virtually the same results. This is because according to equation (10), the ratios between regional carbon prices does not depend much on the scale of the damage function: using different values γ for $D(t, \Delta T) = \gamma GDP(t)\Delta T$ in (10) leaves *ratios* of regional carbon prices invariant, as both the numerator and denominator price are proportional to γ. However, damages $D(t, \Delta T)$ reduce future consumption levels and thus influence the discount rates r_{r}. The effects of this on price ratios was found to be very small. If for $\gamma = 0.0218$, we compare the results with and without damage-adjusted consumption, the resulting price ratios never deviate by more than 2.9%. Analogous observations can be made about the effect of any realistic choice of β on r_{r} and thus on price ratios. When we compared results with and without damage-adjusted consumption for $\beta = 0.0032$ (Manne and Richels, 2005), maximum deviation was 2.5%.

For the purpose of our analysis, we therefore consider the different calibrations of linear and quadratic damage functions as equivalent.

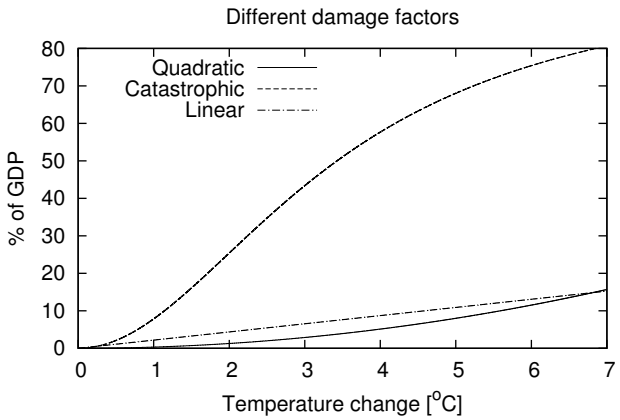

Figure D.1: **Damage factors used for estimating regional carbon prices** The *Quadratic* and the *Linear* damage factors have been used with $\beta = 0.0032$ (Manne and Richels, 2005) and $\gamma = 0.0218$ (Roughgarden and Schneider, 1999). *Catastrophic* damage factor has been used with $\alpha = 0.085164$, which is 30 times as high as the value used in the DICE-2007 model (Nordhaus, 2008).

E Marginal Abatement Cost Curves

In order to find marginal abatement cost curves, a general equilibrium model calibrated to data of the year 2004 from the GTAP data base (Badri and

Walmsley, 2008; Böhringer et al., 2006) was used. When carbon taxes for all sectors are applied in the different regions, the corresponding emission reduction is found by the model. If the carbon taxes are changed in steps of $\$1/\text{tCO}_2$, this gives the correspondence of different emission reduction levels to marginal abatement cost. By fitting polynomials of degree 3 to these correspondences, simple but accurate approximations for the marginal abatement cost of the different sectors can be found. Table E.1 lists the coefficients of the polynomials $a_0 + a_1(e_0 - e) + a_2(e_0 - e)^2 + a_3(e_0 - e)^3$ that we used to approximate the marginal abatement cost curves for the different countries. Abatement $(e_0 - e)$ is measured in million tons of CO_2 (MtCO_2) and marginal abatement cost in dollars per ton of CO_2 ($\$/\text{tCO}_2$).

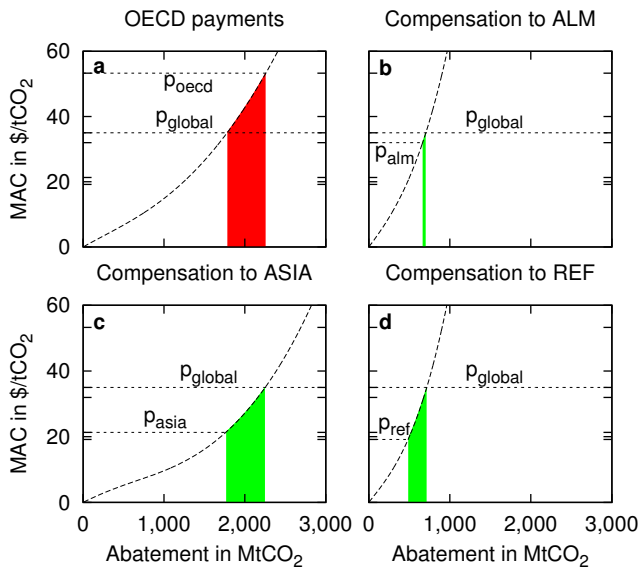

Figure E.1: Marginal abatement cost curves for the SRES regions. The red area in panel **a** corresponds to abatement costs the OECD90 region saves if it implements the global carbon price $p_{\text{global}} = \$35/\text{tCO}_2$ rather than the regional $p_{\text{oecd}} = \$59/\text{tCO}_2$. Regional prices for the other regions are $p_{\text{alm}} = \$32/\text{tCO}_2$, $p_{\text{asia}} = \$21/\text{tCO}_2$, and $p_{\text{ref}} = \$19/\text{tCO}_2$. The green areas in panels **b** to **d** indicate abatement costs the other three world regions would additionally incur if they implemented the global carbon price of $\$35/\text{tCO}_2$ instead of their preferred regional carbon prices.

Sector	Coeff.	Brazil	Rest of ALM	China	India	Indonesia	Rest of ASIA	OECD90	Russia	Rest of REF
ELE	a_1	4.824	0.151	0.029	0.139	0.778	0.155	0.019	0.074	0.067
	a_2	0.058	1.98E-4	-3.43E-5	-9.84E-4	-0.020	-1.89E-5	-7.73E-6	4.61E-5	-1.38E-4
	a_3	0.061	9.64E-7	4.14E-8	3.59E-6	0.001	4.60E-6	1.26E-8	4.90E-7	7.12E-7
EIS	a_1	1.837	0.118	0.074	0.418	0.642	0.241	0.081	0.451	0.187
	a_2	0.031	-5.09E-5	-2.45E-4	-0.007	-0.005	2.29E-4	6.48E-5	-4.90E-4	5.14E-4
	a_3	0.001	6.90E-7	5.91E-7	1.77E-4	2.77E-4	1.45E-5	6.90E-8	3.49E-5	1.15E-5
OTP	a_1	6.205	0.724	0.972	7.330	11.480	1.663	0.312	1.025	1.835
	a_2	0.220	0.003	0.054	0.235	0.714	0.020	3.73E-4	0.008	0.020
	a_3	0.007	2.33E-5	4.28E-4	0.004	0.073	1.61E-4	5.88E-7	1.28E-4	1.61E-4
WTP	a_1	7.060	1.148	1.417	26.035	20.591	1.609	1.029	15.940	11.375
	a_2	-1.708	-0.033	0.014	1.910	2.258	-0.028	0.005	1.914	0.720
	a_3	0.229	0.001	5.42E-4	0.165	0.473	0.002	7.26E-5	0.346	0.055
ROI	a_1	6.679	0.849	0.229	6.049	3.087	0.804	0.246	3.071	0.540
	a_2	0.438	0.005	-1.13E-4	1.483	0.107	0.018	3.86E-4	0.071	0.004
	a_3	0.036	1.01E-4	3.36E-5	-0.047	0.013	3.56E-4	1.70E-6	0.001	9.42E-5

Table E.1: Coefficients of the marginal abatement cost curves. The sectors are: electricity production ELE, energy intensive industries EIS, other transport OTP, water transport WTP, and rest of industry ROI.