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The Uncertainty about the Social Cost of Carbon: A Decomposition Analysis Using FUND

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Abstract: We report the results of an uncertainty decomposition analysis of the social cost of carbon as estimated by FUND, a model that has a more detailed representation of the economic impact of climate change than any other model. Some of the parameters particularly influence impacts in the short run whereas other parameters are important in the long run. Some parameters are influential in some regions only. Some parameters are known reasonably well, but others are not. Ethical values, such as the pure rate of time preference and the rate of risk aversion, therefore affect not only the social cost of carbon, but also the importance of the parameters that determine its value. Some parameters, however, are consistently important: cooling energy demand, migration, climate sensitivity, and agriculture. The last two are subject to a large research effort, but the first two are not.

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1. Introduction

The social cost of carbon is a measure of the seriousness of climate change. It is the carbon tax that would be imposed by a benevolent social planner. Like everything with climate change, there is a large uncertainty about the social cost of carbon (Tol 2009). In this paper, we analyze the structure of that uncertainty – that is, we identify those parameters that contribute most to the variation in the social cost of carbon. Some parameters are relatively unimportant, and further research would therefore probably not teach us much about the "true" value of the social cost of carbon. Other parameters are more important. Further research could therefore change the uncertainty about the social cost of carbon, although some uncertainties are irreducible.

We are not the first to do this. Other studies have decomposed the uncertainty about the marginal impact of climate change (Hope 2006). Any decomposition is model-dependent. We here use FUND3.7, a model that is considerably more complex than other integrated assessment models. We are therefore able to assess the relative importance of parameters that are not included in other models.

We estimate the relative contribution of parameter uncertainty to the uncertainty about the social cost of carbon. Other studies estimate the value of reduced uncertainty (Nordhaus and Popp 1997;Peck and Teisberg 1993). Such estimates are particularly useful if coupled to estimates of the costs and efficacy of research – unfortunately unavailable. Studies typically estimate the value of a complete resolution of the uncertainty, even though the value of a partial resolution may be very different (Baker 2005).

The paper proceeds as follows. Section 2 presents the model used. Section 3 discusses the scenarios and methods. Section 4 analyzes the results. Section 5 concludes.

2. The model

This paper uses version 3.7 of the *Climate Framework for Uncertainty, Negotiation and Distribution* (*FUND*). FUND is an integrated assessment model of projections of populations, economic activity and emissions, carbon cycle and climate model responses, and estimates of the monetized welfare impacts of climate change (Link and Tol 2011;Tol 1997).[1] Climate change impacts are monetized in 1995 dollars and are modelled over 16 regions. Modelled impacts include agriculture, forestry, sea level rise, cardiovascular and respiratory disorders influenced by cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy

[1] FUND is one of the few integrated assessment models that produce SCC estimates. Other models include DICE (Nordhaus 2008) and PAGE (Hope 2008).

consumption, water resources, unmanaged ecosystems and tropical and extratropical storm impacts. The source code, data, and a technical description of the model can be found at http://www.fund-model.org.

The model distinguishes 16 major regions of the world, viz. the United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States. The model runs from 1950 to 3000 in time steps of one year. The prime reason for starting in 1950 is to initialize the climate change impact module. In *FUND*, some of the impacts of climate change are assumed to depend on the impact of the previous year, this way reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical and monetized impacts of climate change tend to be misrepresented in the first few decades of the model runs.[2] The centuries after the 21st are included to assess the long-term implications of climate change. Previous versions of the model stopped at 2300.

2.1. Scenarios and Climate Module

The scenarios are defined by the rates of population growth, economic growth, autonomous energy efficiency improvements as well as the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide. The scenarios of economic and population growth are perturbed by the impact of climatic change. Market impacts are a deadweight loss to the economy. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress, malaria, and storms. Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the reproductive population. Heat stress only affects the urban population. The share of the urban population among the total population is based on the World Resources Databases (http://earthtrends.wri.org). It is extrapolated based on the statistical relationship between urbanization and per capita income, which are estimated from a cross-section of countries in 1995. Climate-induced migration between the regions of the world also causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane, nitrous oxide and sulphur hexafluoride, the global mean temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The

[2] The period of 1950–2000 is used for the calibration of the model, which is based on the *IMAGE* 100-year database (Batjes and Goldewijk 1994). The scenario for the period 2010–2100 is based on the EMF14 Standardized Scenario, which lies in between IS92a and IS92f (Leggett et al. 1992). The 2000–2010 period is interpolated from the immediate past (http://earthtrends.wri.org), and the period 2100–3000 extrapolated.

atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model (Hammitt et al. 1992;Maier-Reimer and Hasselmann 1987). The model also contains sulphur emissions (Tol 2006).

The radiative forcing of carbon dioxide, methane, nitrous oxide, sulphur hexafluoride and sulphur aerosols is as in the IPCC (Ramaswamy et al. 2001). The global mean temperature T is governed by a geometric build-up to its equilibrium (determined by the radiative forcing RF), with an e-folding time of 66 years. In the base case, the global mean temperature rises in equilibrium by 3.0°C for a doubling of carbon dioxide equivalents. Regional temperatures follow from multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 General Circulation Models (Mendelsohn et al. 2000). The dynamics of the global mean sea level are also geometric, with its equilibrium level determined by the temperature and an e-folding time of 500 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario (Kattenberg et al. 1996).

2.2. Impacts and Damages

The climate impact module includes the following categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, energy consumption, water resources, unmanaged ecosystems (Tol 2002a;Tol 2002b), diarrhoea (Link and Tol 2004), and tropical and extra tropical storms (Narita et al. 2009;Narita et al. 2010). Climate change related damages can be attributed to either the rate of change (where damages are calibrated at 0.04°C/yr) or the level of change (with damage functions calibrated at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (Tol 2002b).

People can die prematurely due to climate change, or they can migrate because of sea level rise. Like all impacts of climate change in FUND, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita income. The resulting value of a statistical life lies in the middle of the range of values in the literature (Cline 1992). The value of emigration is set to be 3 times the per capita income (Tol 1995), the value of immigration is 40 per cent of the per capita income in the host region (Cline 1992). Losses of dryland and wetlands due to sea level rise are modeled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 (Fankhauser 1994). Dryland value is assumed to be proportional to GDP per square kilometre. Wetland losses are valued at $2 million per square kilometre on average in the OECD in 1990 (Fankhauser 1994). The wetland value is assumed to have logistic relation to per capita income. The level of coastal protection is based on an internal cost-benefit analysis that includes the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other impact categories, such as agriculture, forestry, energy, water, storm damage, and ecosystems, are directly expressed in monetary values without an first estimating impacts in ‘natural’ units (Tol 2002a). Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (Tol 2002b).

The impacts of climate change on coastal zones, forestry, tropical and extratropical storm damage, unmanaged ecosystems, water resources, diarrhoea, malaria, dengue fever, and schistosomiasis are modelled as power functions. Impacts are either negative or positive with greater climate change, and they do not change sign (Tol 2002b).

Vulnerability to a given climate change is a function of population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable with increases in these factors, such as water resources (with population growth), heat-related disorders (with urbanization), and ecosystems and health (with higher per capita incomes). Other systems such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) are projected to become less vulnerable at least over the long term (Tol 2002b). The income elasticities (Tol 2002b) are estimated from cross-sectional data or taken from the literature.

2.3. The Social Cost of Carbon

We estimated the social cost of carbon, *SCC*, by computing the difference between welfare along a business as usual path and those along a path with an incremental increase in emissions between 2010 and 2019.[3] The differences in welfare are discounted back to the year 2010, and normalised by the difference in emissions. Because the estimate is at the margin, it is also a conceptually appropriate measure for the avoided damages from reducing emissions by one tonne. Ignoring uncertainty, the regional *SCC* is defined as:

$$(1) \quad SCC_r = \frac{1}{\frac{\partial U_{2010,r}}{\partial C_{2010,r}}} \frac{1}{\sum_{t=1950}^{2300} \delta_t} \sum_{t=2010}^{2300} \frac{\left[C_{t,r}\left(E_{2010}+\delta,...,E_t+\delta_t\right) - C_{t,r}\left(E_{2010},...,E_t\right)\right] \frac{\partial U_{t,r}}{\partial C_{t,r}}}{\prod_{i=2010}^{t} 1+\rho}$$

where

- $\delta_t = \begin{cases} \omega & \text{for } 2010 \le t < 2020 \\ 0 & \text{for all other cases} \end{cases}$
- $SCC_{r,s}$ is the regional, sector specific social cost of carbon (in 1995 US dollars per tonne of carbon);

[3] The social cost of carbon of emissions in future or past periods is not the focus of this paper.

- *r* denotes region;
- *s* denotes sector/impact type;
- *t* and *i* denote time (in years);
- *U* is utility;
- *E* are carbon emissions (in metric tonnes of carbon);
- *δ* are incremental emissions (in metric tonnes of carbon);
- ω is the marginal amount of extra emissions; and
- *ρ* is the pure rate of time preference (in fraction per year).

We assume a CRRA utility function

$$(2)\quad U\left(\frac{C}{P}\right)=\begin{cases}\ln c & \text{for } \eta=1\\ c^{1-\eta}\left(1-\eta\right)^{-1} & \text{for } \eta\neq 1\end{cases}$$

where

- *C* is total consumption (in 1995 dollar per person per year);
- *P* is population (in number of people);
- *c* is per capita consumption (in 1995 dollar per person per year); and
- *η* is the rate of risk aversion.

We define the regional *SCC* by using regional consumption and population. We define the global *SCC* by using global consumption and population. We define the equity weighted SCC as

$$(3)\quad SCC_{ew}=\frac{1}{\frac{\partial U_{2010,ref}}{\partial C_{2010,ref}}}\frac{1}{\sum_{t=1950}^{2300}\delta_t}\sum_{r=1}^{16}\sum_{t=2010}^{2300}\frac{\mathrm{d}C_{t,r}\frac{\partial U_{t,r}}{\partial C_{t,r}}}{\prod_{i=2010}^{t}1+\rho}$$

For Pearce equity weights (Fankhauser et al. 1997), marginal reference utility U'_{ref} is evaluated at the global average consumption level. For Anthoff equity weights (Anthoff et al. 2009a), U'_{ref} is any of the 16 regions. Approximately

$$(4)\qquad SCC_{ew}\approx\sum_{r}\left(\frac{c_{2010,ref}}{c_{2010,r}}\right)^{\eta}SCC_r$$

The expected value of the social cost of carbon is defined as

$$(5)\quad \mathrm{E}SCC=\sum_{i}p_iSCC_i$$

3. Experiments and methods

3.1. Experiments

The social cost of carbon is computed as the difference in the net present welfare induced by a small pulse of additional carbon dioxide emissions in the period 2010-2019. This gives a value in utils per tonne of carbon. This is transformed to dollars per tonne of carbon by the marginal value of consumption. This procedure depends on the specification of the welfare function and its parameters. For the pure rate of time preference, we consider 0.1%, 1.0% and 3.0% per year, spanning a range of opinions. We assume that regional welfare is a CRRA function of average per capita consumption, with a rate of risk aversion of 1.0, 1.5 and 2.0, reflecting the range of estimates on the social rate of risk aversion. We show estimates of the regional social cost of carbon, ignoring impacts in the other parts of the world (Anthoff and Tol 2010). We also show global estimates. We first evaluate Equation (1) for global average consumption, assuming away all distributional effects. We then use a utilitarian welfare function, aggregating regional welfare, and converting welfare to consumption using the average per capita consumption in the world – we refer to this as Pearce equity weights (Fankhauser et al. 1997). Finally, we evaluate the social cost of carbon using the average per capita consumption in each of the 16 regions – we refer to this as Anthoff equity weights (Anthoff et al. 2009a).

3.2. Methods

We use two alternative methods to assess the impact of parameter uncertainty on the uncertainty about the social cost of carbon. Both methods rely on Monte Carlo analysis. First, we compute the correlation coefficient between the individual inputs (parameters) and the output (social cost of carbon). Second, we run a regression of the inputs on the outputs and compute the standardized regression coefficients. Both methods thus account for scale and allow for a ranking of the importance of the parameters. Both methods essentially linearize the model and therefore capture local sensitivities only – that is, they estimate the relative effect of a small change in a parameter on the social cost of carbon. However, the correlation coefficient measures the impact of a parameter with all other parameters assuming random values. The standardized regression coefficient measures the impact of a parameter with the impact of all other parameters removed. This is the theoretically preferred method of measuring impact, and we use it as our standard.

4. Results

We present the results in three different ways. First, we assess the "global" importance of parameters, focusing on the central welfare specifications. Second, we discuss the variation in parameter contribution between welfare specifications. Third, we analyze the variation in parameter contribution between regions. However, before we discuss the importance of particular parameters to the social cost of carbon, we first briefly discuss the social cost of carbon itself.

4.1. The social cost of carbon

Table 1 shows the expected value of the social cost of carbon (*SCC*) for three pure rates of time preference (ρ) and three rates of risk aversion (η) assuming away all income differences. For ρ=3% and η=1, *SCC*= $10/tC, well in line with results published earlier. For lower pure rates of time preference, the social cost of carbon rises (Guo et al. 2006). For higher rates of risk aversion, the social cost of carbon falls, because its effect on the discount rate dominates its effect on the certainty equivalent (Anthoff et al. 2009b;Anthoff et al. 2009c).

Table 2 shows the regional results for ρ=1% and η=1.5. In the first column, we show the expected social cost of carbon for each of the 16 regions, ignored the impacts in the 15 other regions. Three regions show a negative cost (i.e., a benefit), implying that if they would not care about the rest of the world, the optimal policy would be a carbon subsidy. The unweighted sum of the regional impacts is positive, however: $1,344/tC. This is shown in the second column. In the next two columns, we add equity weights, Pearce weights in the third column and Anthoff weights in the fourth. With Pearce equity weights, evaluating the distributional impacts from the perspective of a global planner, the social cost of carbon is $9,974/tC. With Anthoff equity weights, evaluating the impacts as a regional planner, the social cost of carbon range from $212/tC in the poorest region to $148,621/tC in the richest.

Both Table 1 and 2 show results for the global social cost of carbon. For ρ=1% and η=1.5, Table 1 shows $69/tC and Table 2 shows $1,344/tC – a difference of two orders of magnitude. One reason is that Table 1 assumes away income differences, while the non-weighted aggregate in Table 2 acknowledges income differences but does not emphasize them. Another reason for the difference between Table 1 and 2 is the correlation between the regional results. In Table 1, the global aggregate is calculated directly. In Table 2, the regional social costs of carbon are calculated and then added. The difference is so large because correlations are so strong: Regions share the same carbon dioxide concentration and global warming, and the same structural parameters (e.g., income elasticities, curvatures of impact functions). This implies that the absolute values in Table 2 are not particularly interesting; the relative vulnerabilities are, however.

4.2. Base results

Table 3 shows the 10 most important parameters according to the standardized regression coefficient and the correlation coefficient. The two measures roughly agree. The rank correlation is 94%. Figure 1 plots both measures. Returning to Table 1, the top 10 parameters according to one measure are in the top 14 according to the other measure; the top 4 are identical; and the top 7 contain the same parameters.

Figure 2 shows the 10 most important parameters according to the standardized regression coefficient. The curvature of the demand for cooling energy is the most important parameter. I the best guess, energy demand increases with warming to the power 1.5. This parameter is poorly constrained because empirical evidence on air conditioning demand is limited. Cooling energy demand is an important impact particularly since the base scenario has rapid economic growth in the tropics and subtropics. The benchmark impact estimate for cooling energy demand in China also features in the top 10 most important parameters. The income elasticity of cooling energy demand is in the top 10 according to the correlation coefficient.

Climate sensitivity is the second most important variable. This is defined as the equilibrium warming of the lower atmosphere due to a doubling of the ambient concentration of carbon dioxide – climate sensitivity thus drives all impacts. There is a wide range of estimates of its value. The scenario uncertainty about methane emissions is the ninth-most important parameter as methane can cause rapid warming in the short term.

The curvature of the agricultural impact function in China is the third most important variable. This parameter determines how rapidly impacts escalate in a large and rapidly growing part of the world economy. The impact of cold stress on cardiovascular mortality of people under 65 years of age in Southeast Asia ranks fourth. Again, the reason is twofold: This parameter affects a large number of people who are rapidly becoming richer; and the parameter is particularly uncertain. The effect of carbon dioxide fertilization in Japan and South Korea ranks sixth, reflecting the high prices (due to market distortions) of food products in this part of the world.

The remaining parameters in the top 10 relate to migration due to sea level rise. This is an important impact in itself, but migration also affects population growth, one of the key inputs to welfare. There is a fourth migration parameter in the top 10 according to the correlation coefficient.

4.3. Variations with welfare

Table 4 shows the 10 most important parameters (according to the standardized regression coefficient) for various pure rates of time preference and rates of risk aversion.

The ranking of parameters varies with time preference. Migration is more important in the long term because of its effect on population growth and because the sea continues to rise for a long time. Carbon dioxide fertilization is more important in the short term because it saturates in the long term and the share of agriculture in economic activity falls over time. The income elasticity of cooling energy demand is more important in the short term because (assumed) energy efficiency improvements take away the concern about this impact in the long run.

The effect of changes in the rate of risk aversion is harder to interpret, because it affects the discount rate, the equity weights, and, of course, the certainty equivalent (Anthoff et al. 2009b;Anthoff et al. 2009c). As the rate of risk aversion increases, uncertainty becomes more important, the impacts on developing countries get a higher weight, and future counts for less. Carbon dioxide fertilization in poorer countries therefore becomes more important for greater risk aversion. This also explains the large drop in importance of impacts in China and the income elasticity of cooling energy demand.

4.4. Regional variations

Table 5 shows the five most important parameters for each of the sixteen regions. The parameters identified in Table 3 return in Table 5: cooling energy, migration, agriculture.

But there are others parameters too that are important for certain regions but not globally. These include the parameters of the carbon cycle model and population aging. These parameters have a net positive effect in some regions, but a net negative effect elsewhere, and thus show up regionally but not globally. More carbon dioxide in the atmosphere means more fertilization (positive) but also more warming (generally negative). An older population means fewer cold-related deaths (positive) but also more heat-related deaths (negative).

In some of the poorer regions, health parameters are important, particularly diarrhea, malaria and cardiovascular diseases but also the value of mortality and morbidity. In Eastern Europe and the former Soviet Union, water resources are found to be important.

5. Discussion and conclusion

In this paper, we decompose the uncertainty about the social cost of carbon as estimated by the FUND model. The impact model in FUND is considerably more complex than in other integrated assessment models. Some parameters are important in the short run but not in the long run; some parameters are important to some regions but not to others; some parameters are more uncertain than others. Therefore, the pure rate of time preference and the rate of risk aversion not only determine the social cost of carbon, but also the parameters that affect its value. That said, some parameters are consistently important: cooling energy demand, climate sensitivity, migration, and agriculture.

This has implications for research priorities. There is a large effort underway to estimate the climate sensitivity, i.e., the equilibrium warming due to a doubling of atmospheric carbon dioxide. The current results help to justify this effort. There is also a large research program, rightly so, on the impacts of climate change on agriculture.

However, the impact of climate change on energy demand has received less attention. Although there are an increasing number of case studies (Bessec and Fouquau 2008;Christenson et al. 2006;Considine 2000;Lee and Chiu;Mansur et al. 2008;Moral-Carcedo and Vicéns-Otero 2005), a synthesis is lacking – this could be forged with a relatively small effort. The impact of climate change on migration is not well-understood either (Barrios et al. 2006;Bates 2002;Kuentzel and Ramaswamy 2005;Reuveny 2007). Relationships are much more complex than in the case of energy demand, but an improved synthesis would increase our confidence in the estimates of the social cost of carbon. It should be noted that climate-change-induced migration implies endogenous population growth. The relevant state of the art in welfare theory (Blackorby et al. 2002;Blackorby and Donaldson 1984) has yet to be operationalized in climate economics.

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Table 1. The social cost of carbon (in dollars per metric tonne of carbon) for various pure rates of time preference and rates of risk aversion.

		Risk aversion		
		1.0	1.5	2.0
Time preference	0.1	771.31	284.88	113.76
	1.0	167.84	68.88	28.84
	3.0	9.69	2.57	-0.79

Table 2. The social cost of carbon (in dollars per metric tonne of carbon) per region, and aggregated in three different ways.

		Equity weights		
Region	Regional	None	Pearce	Anthoff
Australia and New Zealand	63	1344	9974	87907
Central America	33	1344	9974	4047
Canada	1	1344	9974	76177
China, Mongolia and North Korea	-32	1344	9974	928
Eastern Europe	67	1344	9974	4347
Former Soviet Union	732	1344	9974	1936
Japan and South Korea	-1	1344	9974	148621
South America	2	1344	9974	5954
North Africa	334	1344	9974	956
Middle East	29	1344	9974	3144
South Asia	67	1344	9974	235
Southeast Asia	-193	1344	9974	1677
Small Island States	2	1344	9974	913
Sub-Saharan Africa	21	1344	9974	212
United States of America	49	1344	9974	128119
Western Europe	169	1344	9974	94390

Table 3. The top 10 most important parameters according to the standardized regression and correlation coefficients for a 1% pure rate of time preference and a 1.5 rate of risk aversion.

	Rank	
	regression	Correlation
Curvature cooling energy	1	1
Climate sensitivity	2	2
Curvature agriculture, China	3	3
Benchmark cold related cardiovascular under 65, Southeast Asia	4	4
Benchmark migration, Small Island States to Sub-Saharan Africa	5	7
Benchmark CO2 fertilization, Japan and South Korea	6	5
Benchmark migration, Australia and New Zealand to Western Europe	7	5
Benchmark cooling energy, China	8	10
Benchmark migration, North Africa to Eastern Europe	9	14
Methane scenario	9	8
Benchmark migration, Australia and New Zealand to USA	11	8
Income elasticity cooling energy	14	10

Table 4. The top 10 most important parameters according to the standardized regression coefficients for various pure rates of time preference and rates of risk aversion.

Pure rate of time preference (%)	1.0	0.1	3.0	1.0	1.0
Rate of risk aversion	1.5	1.5	1.5	1.0	2.0
Curvature cooling energy	1	1	1	1	1
Climate sensitivity	2	2	3	2	2
Curvature agriculture, China	3	15	4	10	3
Benchmark cold related cardiovascular under 65, Southeast Asia	4	3	32	3	8
Benchmark migration, Small Island States to Sub-Saharan Africa	5	4	47	4	10
Benchmark CO2 fertilization, Japan and South Korea	6	12	7	10	7
Benchmark migration, Australia and New Zealand to Western Europe	7	5	92	5	11
Benchmark cooling energy, China	8	43	6	40	5
Benchmark migration, North Africa to Eastern Europe	9	6	150	6	12
Methane scenario	9	34	9	29	6
Benchmark migration, North Africa to USA	11	7	542	6	16
Benchmark migration, South America to Sub-Saharan Africa	11	8	207	9	14
Benchmark migration, Australia and New Zealand to USA	11	9	124	6	16
Income elasticity cooling energy	14	171	5	180	4
Benchmark migration, South Asia to Japan and South Korea	15	10	444	10	26
Asymptotic value of biodiversity, Southeast Asia	15	10	207	10	26
Benchmark CO2 fertilization, Southeast Asia	145	579	2	825	9
Benchmark CO2 fertilization, Western Europe	351	705	8	779	46
Benchmark CO2 fertilization, China	456	772	10	825	66

Table 5. The five most important parameters affecting the regional social cost of carbon according to the standardized regression coefficient for a 1% pure rate of time preference and a 1.5 rate of risk aversion.

Region	Parameters
Australia and New Zealand	Benchmark migration, Australia and New Zealand to Sub-Saharan Africa Benchmark migration, North Africa to Australia and New Zealand Climate feedback on terrestrial carbon dioxide emissions Curvature agriculture, Australia and New Zealand Speed of population aging
Central America	Curvature agriculture, Central America Benchmark migration, Central America to South America Benchmark malaria, Central America Benchmark cold related cardiovascular under 65, Central America Aging effect on cardiovascular mortality
Canada	Curvature cooling energy Benchmark cooling energy, Canada Climate sensitivity Cost of emigration Methane scenario
China, Mongolia and North Korea	Income elasticity hurricane damage Benchmark value of land Sulfur hexafluoride scenario Income elasticity extratropical storm mortality Benchmark migration, former Soviet Union to China
Eastern Europe	Curvature agriculture, Eastern Europe Benchmark migration, Southeast Asia to Eastern Europe Curvature water resources Benchmark value of morbidity Benchmark schistosomiasis, Eastern Europe
Former Soviet Union	Climate sensitivity Curvature water resources Curvature agriculture, former Soviet Union Benchmark value of wetland Energy efficiency scenario, former Soviet Union
Japan and South Korea	Curvature agriculture, Japan and South Korea Benchmark CO2 fertilization, Japan and South Korea Climate sensitivity Methane scenario Speed of population aging
South America	Curvature cooling energy Benchmark cooling energy, South America Benchmark migration, South America to former Soviet Union Benchmark migration, South America to South Asia Curvature heat related cardiovascular over 65, South America
North Africa	Benchmark migration, Japan and South Korea to North Africa Curvature agriculture, North Africa Income elasticity, wetland value Benchmark migration, Canada to North Africa Income elasticity diarrhea mortality
Middle East	Curvature agriculture, Middle East Speed of population aging Climate sensitivity Economic growth scenario, Middle East Income elasticity value of mortality
South Asia	Speed of population aging Climate sensitivity Curvature agriculture, South Asia Atmospheric life time carbon dioxide (shortest) Benchmark migration, South Asia to China
Southeast Asia	Curvature cold related cardiovascular under 65, Southeast Asia Asymptotic value of biodiversity, Southeast Asia Benchmark migration, South Asia to Southeast Asia

	Benchmark value of morbidity Aging effect on cardiovascular mortality
Small Island States	Curvature agriculture, Small Island States Benchmark migration, Middle East to Small Island States Income elasticity diarrhea mortality Income elasticity diarrhea morbidity Speed of population aging
Sub-Saharan Africa	Curvature agriculture, Sub-Saharan Africa Climate sensitivity Curvature cooling energy Benchmark cooling energy, Sub-Saharan Africa Curvature diarrhea mortality
United States of America	Curvature cooling energy Benchmark cold related cardiovascular under 65, USA Rate of heat uptake in the ocean Atmospheric life time carbon dioxide (shortest) Benchmark migration, South Asia to USA
Western Europe	Curvature cooling energy Climate sensitivity Methane scenario Nitrous oxide scenario Curvature diarrhea morbidity

Figure 1. The relationship between the standardised regression coefficient and the correlation coefficient between the input parameter and the social cost of carbon for a 1% pure rate of time preference and a 1.5 rate of risk aversion.

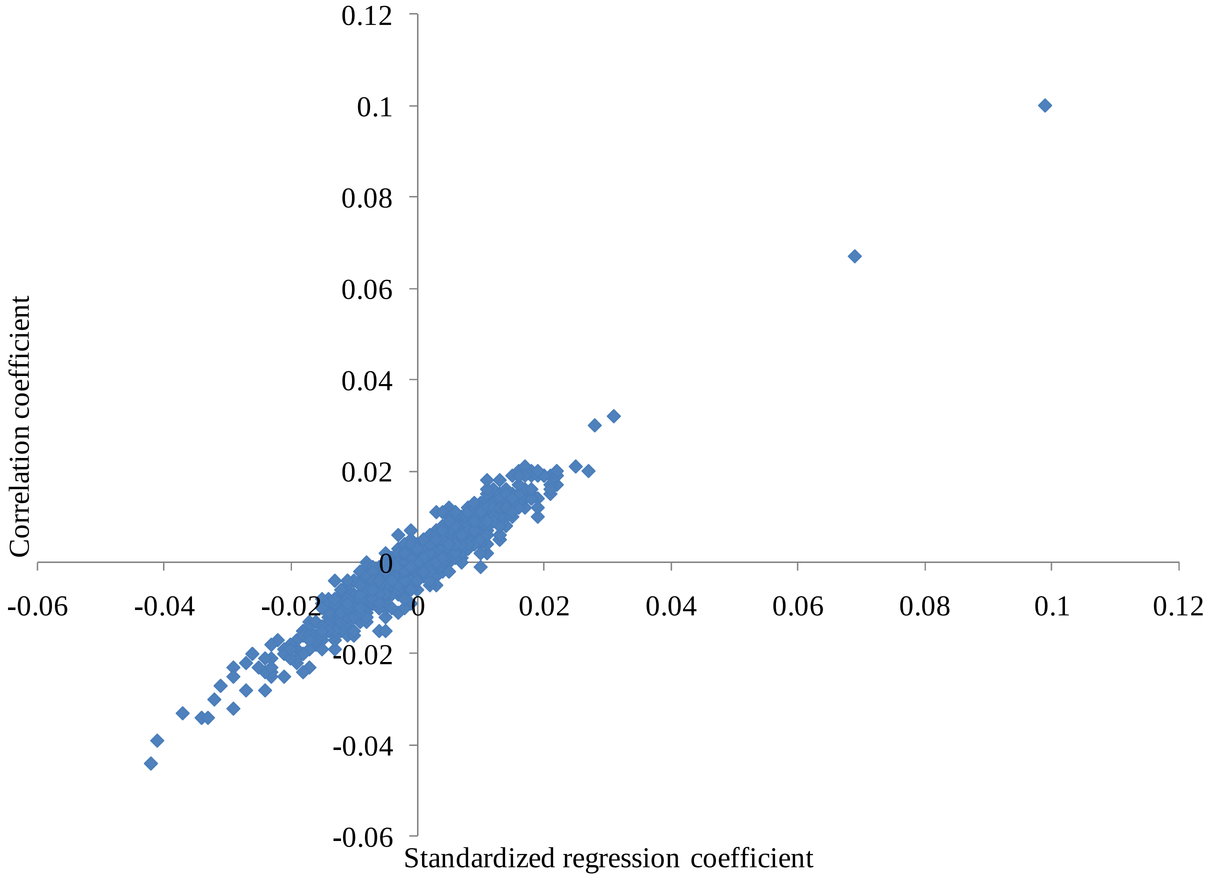
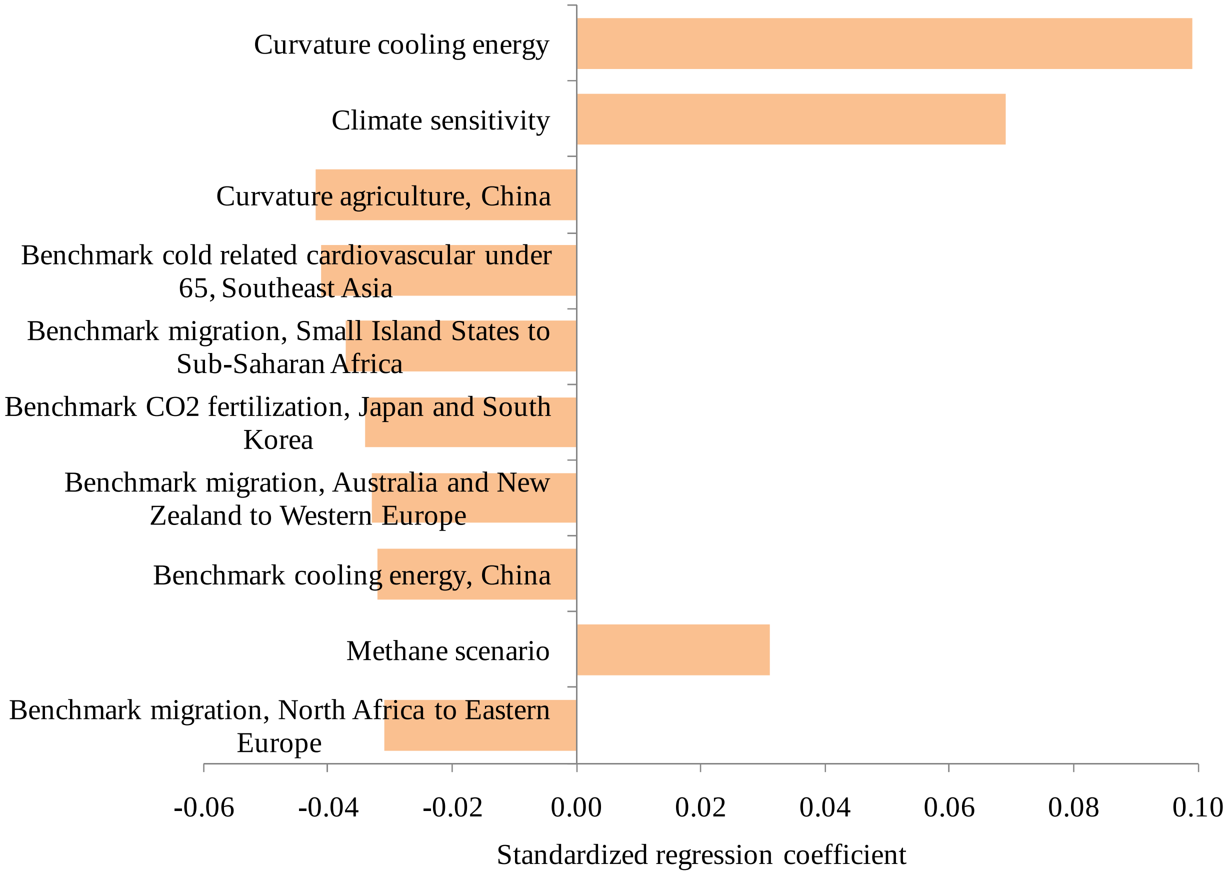


Figure 2. The ten most important parameters that determine the social cost of carbon and their standardised regression coefficient for a 1% pure rate of time preference and a 1.5 rate of risk aversion.



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