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A social cost of carbon for (almost) every country

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JEL classification: Q54

Key words: climate change, Pigou tax, climate policy, non-cooperation

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Abstract

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1. Introduction

The social cost of carbon is the incremental impact of emitting an additional tonne of carbon dioxide, or the benefit of slightly reducing emissions. When evaluated along an optimal emissions trajectory, it is the Pigou tax (Pigou, 1920)—the carbon tax needed to restore efficiency. Greenhouse gases mix uniformly in the atmosphere. Emissions are *global* externalities. The social cost of carbon is the tax a global planner would impose. National planners may disagree. This paper therefore presents estimates of the social cost of carbon *for every nation*.

There have been a number of reviews of the social cost of carbon (Pizer et al., 2014, Guivarch et al., 2016, Metcalf and Stock, 2017, Pindyck, 2017a,b, Revesz et al., 2017) and its application (Rose, 2012, Greenstone et al., 2013, Heyes et al., 2013, Sunstein, 2014, Hahn

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and Ritz, 2015), as well as meta-analyses (Tol, 2005, 2009, 2011, 2013, 2018, Havranek et al., 2015, Wang et al., 2018). These papers focus on the global social cost of carbon, and largely ignore the regional composition. That is exactly what this paper is about.

The models used to estimate the global social cost of carbon, and the studies on which they are calibrated, often have regional or even national estimates. The national social costs of carbon are rarely spelled out, and hardly ever discussed. That is perhaps as it should be, carbon dioxide is a global externality after all (Gayer and Viscusi, 2016). However, besides the academic interest in knowing the regional composition of the social cost of carbon, the Trump Administration has decided that its climate impacts on the rest of the world are irrelevant for US policy.

This is the second paper to estimate the social cost of carbon per country. Ricke et al. (2018) base their estimates on the work by Burke et al. (2015) and Dell et al. (2012),[1] who regress economic growth on temperature (see also Lemoine and Kapnick, Burke et al., 2018, Pretis et al., 2018). Weather is, from an economic perspective, random. The impact of weather is therefore arguably identified. However, the impact of a weather shock is not the same as the impact of climate change (Dell et al., 2014). Climate is what you expect, weather is what you get. Adaptation to weather shocks is therefore limited to immediate responses—put up an umbrella when it rains, close the flood doors when it pours. Adaptation to climate change extends to changes in the capital stock—buy an umbrella, invest in flood gates. In other words, weather studies estimate the short-run elasticity, whereas the interest is in the long-run elasticity. See Deryugina and Hsiang (2017) and Lemoine (2018) for the strict conditions under which weather variability is informative about climate change.

Ricke et al. (2018) further assume that climate change affects economic growth, rather than the level of economic activity (Fankhauser and Tol, 2005, Piontek et al., 2018). This

[1] Ricke et al. (2018) find little difference between the social cost carbon based on the impact functions of Burke et al. (2015) and Dell et al. (2012). However, Burke's impact estimates are much higher than Dell's. There are three reasons for Ricke's remarkable result. Firstly, Dell finds that rich countries are not affected by weather shocks. In the base specification, Burke makes no such differentiation; in an alternative specification, the impact of weather shocks is lower in richttps://www.overleaf.com/project/5b8a4cfd6845d969c62d7918h countries, but not zero. Ricke puts the threshold between rich and poor at $20,715 per person per year, referring to this as the "median income" in 1980. Using the same data source, the World Bank, I find that the country-weighted median was $1566/p/yr, the population-weighted median $275/p/yr in 1980. Ricke's inexplicably high threshold overestimates the impact according to Dell. Kate Ricke (personal communication, 2019) has acknowledged this mistake. Secondly, Burke argues that the growth effect depends on the level of the temperature, whereas Dell argues it depends on the change in temperature. This implies that, in a scenario without climate change, Burke would see different growth rates in hot and cold countries, but Dell would not. Ricke does not recalibrate the growth scenarios when switching from Burke to Dell. Thirdly, Burke and Dell estimate their impact functions on past weather, which is stochastic. Ricke uses GCM output, but removes the annual variability. This does not matter for the Dell impact function, which is linear, but it does for the quadratic impact function of Burke. Let's assume that the annual temperature is normally distributed $T_t \sim \mathcal{N}(\mu_t, \sigma^2)$. If the impact function is $I_t = \alpha \Delta T_t$ (Dell's) then $\mathbb{E} I_t = \alpha \Delta \mu_t$. Setting $\sigma = 0$ is immaterial for the estimate of the expected impact. However, if $I_t = \beta T_t + \gamma T_t^2$ (Burke's) then $\mathbb{E} I_t = \beta \mu_t + \gamma(\sigma^2 + \mu_t^2)$. Setting $\sigma = 0$—that is, removing the stochasticity—underestimates the expected impact. Within each run of their Monte Carlo analysis, Ricke incongruently uses the mode rather than the mean. I did not replicate Ricke's estimates with these three errors corrected, so I do not know which of the three explains most of the lack of divergence between Burke and Dell.

is known to substantially increase estimates of the social cost of carbon (Moyer et al., 2014, Dietz and Stern, 2015, Moore and Diaz, 2015). The empirical evidence suggests that the growth effect of weather is small (Letta and Tol, 2018). Newell et al. use cross-validation tests to show that weather shocks affect the level of economic activity, rather than its growth rate.

Therefore, this paper is based on estimates of the impact of *climate change*, rather than *weather shocks*, on the *level* of economic activity, rather than on the *growth rate* of the economy. It follows from the above discussion that the estimates here are very different from those by Ricke et al. (2018).

The paper proceeds as follows. Section 2 discusses the total impact of climate change. Section 3 defines the social cost of carbon, and details its calculation. Section 4 presents the estimates of the national social costs of carbon. Section 5 concludes.

2. The total impact of climate change

Figure 1 shows the 27 published estimates of the total economic impact of climate change. See also Howard and Sterner (2017) and Nordhaus and Moffat (2017). The change in the global annual mean surface air temperature is on the horizontal axis, the welfare equivalent income change on the horizontal one. The interpretation is that a global warming of 2.5°C would make the average person feel as if she had lost 1.3% of her income.

2.1. Methods

These estimates were derived as follows. Models of every description were used to estimate the many impacts of climate change for all parts of the world, the values of these impacts were estimated, quantities and prices were multiplied and added up (d'Arge, 1979, Nordhaus, 1982, 1991, 1994a, Fankhauser, 1995, Tol, 1995, Berz, Nordhaus and Yang, 1996, Plambeck and Hope, 1996, Tol, 2002, Nordhaus and Boyer, 2000, Hope, 2006, Nordhaus, 2008). This direct cost is a poor approximation of the change in welfare, for instance because it ignores price changes, and because it omits interactions between sectors, such as a change in water resources affecting agriculture.

Other studies use the same physical impact estimates to shock a computable general equilibrium model (Bosello et al., 2012, Roson and van der Mensbrugghe, 2012). These estimates thus include both price changes and interactions between economics sectors and between economies. The welfare measure is proper and exact. However, impacts are limited to the national accounts, misrepresenting subsistence agriculture and omit direct welfare impacts.

Other estimates are based on regressions of economic indicators on climate, be it income (Mendelsohn et al., 2000, Nordhaus, 2006), household expenditure (Maddison, 2003), self-reported happiness (Rehdanz and Maddison, 2005, Maddison and Rehdanz, 2011) or sector-specific indicators (Mendelsohn et al., 2000). These studies are based on actual (rather than modelled) behaviour, but swap space and time.

Nordhaus (1994b) elicited the views of *supposed* experts.

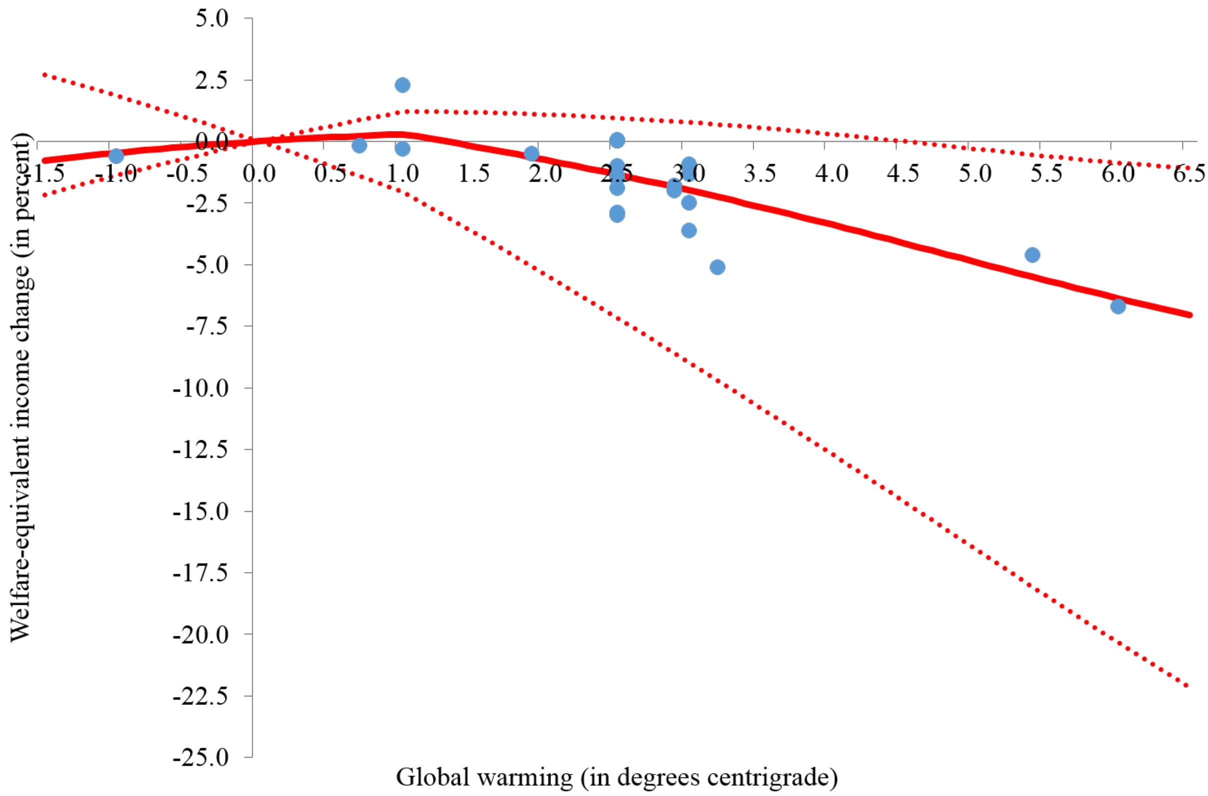

Figure 1: The global total annual impact of climate change.

2.2. Combining estimates

Besides the primary estimates, Figure 1 also shows a curve. Seven alternative impact functions were fitted to the data. See Table 1. Assuming normality of the residuals, the loglikelihood was computed for each model. The curve shown is the Bayesian average of the seven models. A piecewise linear model is the best fit to the data, and the average curve indeed looks like that. The near-linearity of the impact function is driven by the two moderate estimates for high warming.

Only 7 of the 27 estimates have a reported standard deviation, or an upper and lower bound. I imputed upper and lower bounds from twice the reported standard deviations. I assume that the upper and lower bounds are linear functions of the temperature, with slopes 0.92%GDP/°C and 2.33%GDP/°C on the cold and hot side, respectively. This is roughly a 95% confidence interval.

2.3. Results

Figure 1 contains many messages. There are only 27 estimates, a rather thin basis for any conclusion. Statements that climate change is the biggest (environmental) problem of humankind are not well-supported and, as argued below, probably false.

The 11 estimates for 2.5°C, which we may reach in 60-80 years time, show that researchers disagree on the sign of the net impact. Climate change may lead to a welfare gain or loss.

Table 1: Alternative models of the total impact of climate change.

Name	Function	Weight	SCC
Golosov	$-4.16 \cdot 10^{-175} \left(e^{e^T} - e\right)$	0.0%	\$0.00/tC
Ploeg	$-0.02 \left(e^T - 1\right)$	0.0%	\$3.85/tC
Hope	$-0.71T$	0.2%	\$28.14/tC
Nordhaus	$-0.19T^2$	8.7%	\$22.48/tC
Tol (parabolic)	$-0.12T - 0.16T^2$	10.2%	\$23.85/tC
Weitzman (7)	$-0.21T^2 - 5.79 \cdot 10^{-6}T^7$	13.6%	\$25.62/tC
Weitzman (6)	$-0.22T^2 - 3.71 \cdot 10^{-5}T^6$	14.2%	\$25.52/tC
Tol (piecewise linear)	$0.74T I_{T<1.01} + (0.74 \cdot 1.01 - 1.41T) I_{T\geq 1.01}$	53.2%	-\$86.77/tC

At the same time, researchers agree on the order of magnitude. The welfare change caused by climate change is equivalent to the welfare change caused by an income change of a few percent. The average of the estimates is negative. That is, a century of climate change is about as bad as losing a year of economic growth.

Considering all 27 estimates, it is suggested that initial warming is positive on net, while further warming would lead to net damages. The initial benefits are due to reduced costs of heating in winter, reduced cold-related mortality and morbidity, and carbon dioxide fertilization, which makes plants grow faster and more drought resistant. This does not imply that greenhouse gas emissions should be subsidized. The *incremental* impacts turn negative around 1.1°C global warming. Because of the slow workings of the climate system and the large inertia in the energy sector, a warming of 2°C can probably not be avoided and a warming of 1°C can certainly not be avoided—we may already have reached that point. That is, the initial net benefits of climate change are *sunk benefits*. We will reap these benefits no matter what we do to our emissions. For more pronounced warming, the negative impacts dominate, such as summer cooling costs, infectious diseases, and sea level rise.

The uncertainty is rather large, however. The error bars in Figure 1 depict the 90% confidence interval. This is probably an underestimate of the true uncertainty, as experts tend to be overconfident and as the 27 estimates were derived by a group of researchers who know each other and each other's work well.

The uncertainty is right-skewed. Negative surprises are more likely than positive surprises of similar magnitude. This is true for the greenhouse gas emissions: It is easier to imagine a world that burns a lot of coal than a world that rapidly switches to wind and solar power. It is true for climate itself: Feedbacks that accelerate climate change are more prevalent than feedbacks that dampen warming. The best estimate for the climate sensitivity, the eventual warming due to a doubling of atmospheric carbon dioxide, is 2.5°C, with a range of 1.5°C to 4.5°C. The impacts of climate change are more than linear: If climate change doubles, its impacts more than double. Many have painted dismal scenarios of climate change, but no one has credibly suggested that climate change will make us all blissfully happy. In that light, the above conclusion needs to be rephrased: A century of climate change is no worse than losing a decade of economic growth.

The right extreme of Figure 1 is interesting too. At 3.0°C of warming, impacts are negative, deteriorating, and (perhaps) accelerating. It is likely that the world will warm beyond 3.0°C. Yet, beyond that point, there are few estimates only. There is extrapolation and speculation.

2.4. Distribution of impacts

Thirteen of the twenty-two studies referred to above include estimates of the regional impacts of climate change and, in the studies involving David Maddison, national impact estimates. Regressing the estimated regional impact for 2.5°C warming on per capita income and average annual temperature, with dummies for the studies, I find that

$$I_c \propto 1.68(0.80) \ln y_c - 0.45(0.14) T_c \quad (1)$$

where I_c is the impact in country c (in %GDP), y_c is its average income (in 2010 market exchange dollars per person per year), and T_c is the average annual temperature (in degrees Celsius). Hotter countries have more negative impacts. Richer countries have more positive impacts. Of course, Equation (1) does not capture the special vulnerability of delta and island nations. I use this equation to impute national impacts, making sure that the regional or global totals match those in the original estimates.

Figure 1 shows the world average impact for 27 studies. Figure 2 shows results for individual countries for 2.5°C warming. Countries are ranked from low to high per capita income and low to high temperature. In Figure 1, the world total impact is roughly zero. In Figure 2, the majority of countries show a negative impact. However, the world economy is concentrated in a few, rich countries. The world average in Figure 1 counts dollars, rather than countries, let alone people.

Figure 2 suggests that poorer countries are more vulnerable to climate change than are richer countries. There are a few exceptions to this—such as Mongolia, which is poor but so cold that warming would bring benefits, and Singapore, which is rich but a low-lying island on the equator—but by and large the negative impacts of climate change are concentrated in the developing economies.

There are three reasons for this. First, poorer countries are more exposed. Richer countries have a larger share of their economic activities in manufacturing and services, which are typically shielded (to a degree) against the vagaries of weather and hence climate change. Agriculture and water resources are far more important, relative to the size of the economy, in poorer countries.

Second, poorer countries tend to be in hotter places. This means that ecosystems are closer to their biophysical upper limits, and that there are no analogues for human behaviour and technology. Great Britain's future climate may become like Spain's current climate. The people of Britain would therefore adopt some of the habits of the people of Spain, and build their houses like the Spaniards do. Houses in Spain are designed to keep the heat out,

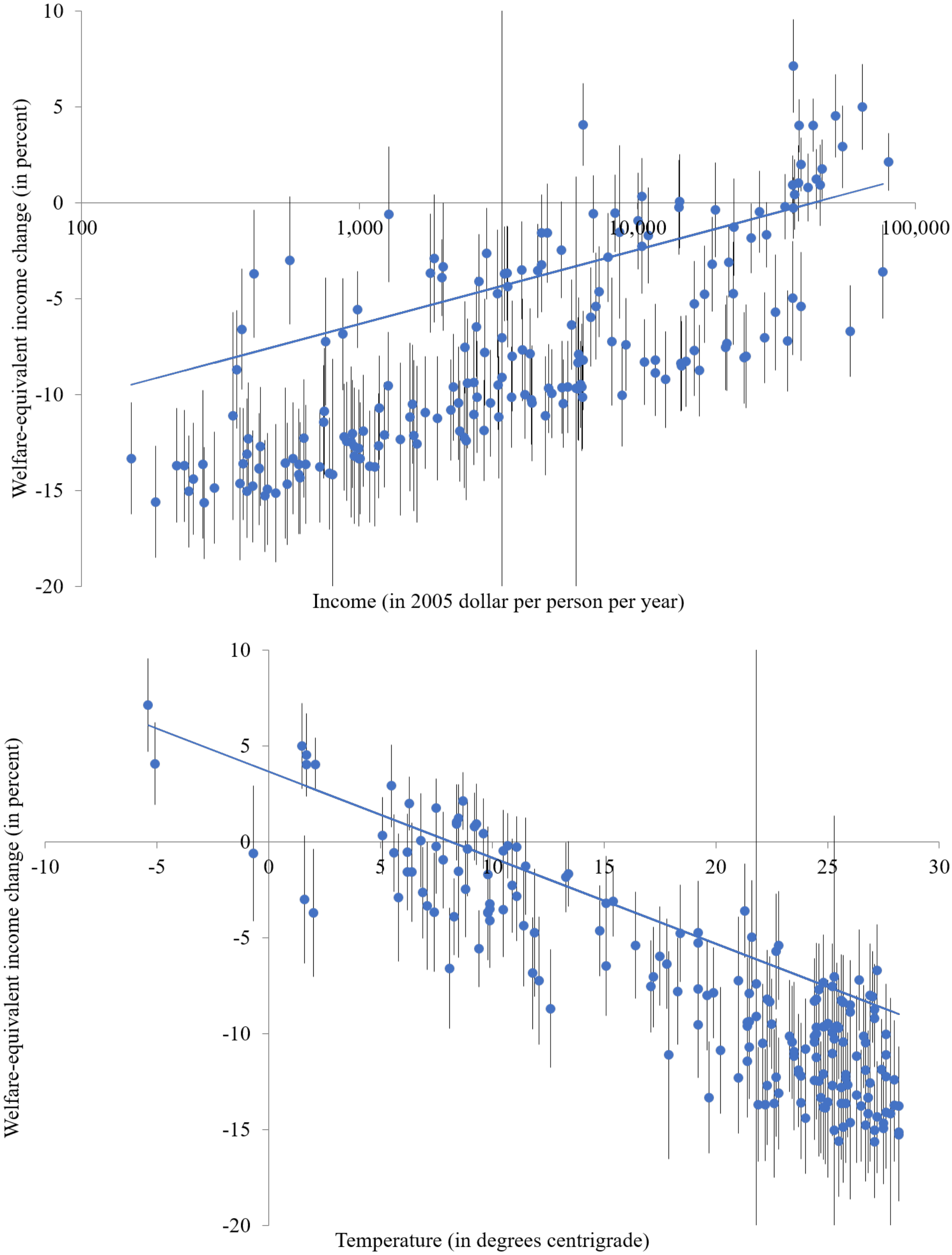

Figure 2: The economic impact of climate change for a 2.5°C warming for all countries as a function of their 2005 income (top panel) and temperature (bottom panel).

whereas houses in the UK are build to keep the heat in. It makes sense to sleep through the heat of the day and, as digestion heats up the body, take the main meal in the cool of the night. If the hottest climate on the planet gets hotter still, there are no examples to copy from; new technologies will have to be invented, behaviour will have to be adjusted by trial and error.

Third, poorer countries tend to have a limited *adaptive capacity* (Adger, 2006, Yohe and Tol, 2002). Adaptive capacity is the ability to adapt. It depends on a range of factors, such as the availability of technology and the ability to pay for those technologies. Sea level rise is a big problem if you do not know about dikes, or if you do but you cannot afford to build one. Flood protection has been known for thousands of years. Modern technology is at its summit in the Netherlands. Dutch engineers will happily share their expertise—for a fee. Adaptive capacity also depends on human and social capital. Coastal protection is both a natural monopoly and a public good, and so requires a competent government. An ounce of prevention is worth a pound of cure, but prevention requires that you are able to recognize problems before they manifest themselves (i.e., predict the future) and that you are able to act on that knowledge (i.e., analytical capacity is connected to policy implementation). Furthermore, the powers that be need to care about the potential victims. A country's elite may be aware of the dangers of climate change and have the wherewithal to prevent the worst impacts, but if those impacts would fall on the politically and economically marginalized, or if the victims think that floods are due to the wrath of God rather than the incompetence of politicians, the elite may choose to ignore the impacts.

3. The Social Cost of Carbon

3.1. Definition

The social cost of carbon is defined as the monetary value of the first partial derivative of global, net present welfare to current carbon dioxide emissions. It is sometimes calculated as a true marginal along a welfare-optimizing emissions trajectory, and so equals the Pigou (1920) tax on carbon dioxide. More often, the social cost of carbon is approximated as a normalized increment along an arbitrary emissions path. Essentially, you compute the impacts of climate change for a particular scenario; you slightly increase emissions in 2018 and compute the slightly different impacts; you take the difference between the two series of future impacts; discount them back to today; and normalize the net present value of the difference with the change in emissions.

Formally

$$SCC_c = \left(\frac{P_{c,0}}{C_{c,0}}\right)^{\eta} \frac{\partial}{\partial E_0} \sum_t \frac{1}{(1+\rho)^t} \frac{P_{c,t}}{1-\eta} \left(\frac{C_{c,t}}{P_{c,t}}\right)^{1-\eta} \tag{2}$$

where SCC is the social cost of carbon at time 0, E_s denote emissions, $P_{c,t}$ population in country c at time t, and C consumption; ρ is a parameter, the pure rate of time preference, and η is the rate of relative risk aversion.

Carbon dioxide stays in the atmosphere for a long time, and the climate is a dynamic system. Therefore, an additional tonne of carbon dioxide emitted today will have a long-lasting impact, that needs to be discounted to today. This is the summation. Utility is discounted at rate ρ, consumption at rate $\rho + g_P + \eta g_C$, where g_P is the growth rate of the population and g_C is the growth rate of consumption. The first partial derivative is welfare to emissions. The social cost of carbon is expressed in dollar per tonne of carbon. The first element in Equation (2) normalizes the marginal impact on expected net present welfare with the marginal utility of consumption at the time of emission.

3.2. Model

I wrote Matlab code to combine the impact models in Table 1 with the SRES (Nakicenovic and Swart, 2000) and SSP (Riahi et al., 2017) scenarios of population, income and emissions, the Maier-Reimer and Hasselmann (1987) carbon cycle model and the Schneider and Thompson (1981) climate model. Readers are free to download, run, manipulate and share the code.

3.3. Scenarios

The scenarios are build following the Kaya identity: population, per capita income, energy intensity of the economy, and carbon intensity of energy supply. The national scenarios extrapolate observed trends (see below) and are rescaled to match the four core SRES scenarios and the five SSP scenarios, as defined by the model averages from the IIASA database.

The national population growth rate is the weighted average of the latest observed growth rate and the growth rate of the SRES and SSP scenarios. The weight placed on the observations is near one in the first scenario year, and falls linearly to almost zero in the final scenario year. The size of the global population then does not match the SRES and SSP scenarios. Therefore, each national population is scaled, by the same factor, to make sure the scenarios are aligned.

Economic output follows a Cobb-Douglas production function, with a output elasticity of 0.8 with respect to labour. The labour force is assumed proportional to population size. The capital stock depreciates at 10% per year. The savings rate is 20%. Total factor productivity grows by 5.9% per year minus 0.0048 times the natural logarithm of per capita income. These numbers follow from regressing the change in total factor productivity on per capita income, both taken from the Penn World Tables. Total factor productivity growth is capped from below at 1%. This implies income convergence. The size of the global economy then does not match the SRES and SSP scenarios. Therefore, each national economy is scaled, by the same factor, to make sure the scenarios are aligned.

The energy intensity of the economy and the carbon intensity of the energy sector follow a log-log regression of intensity on per capita income, with an income elasticity of -0.39 for energy intensity and an income elasticity of -0.32 for carbon intensity. National energy use and carbon dioxide emissions are scaled so that the global totals match the SRES and SSP scenarios.

4. Results

4.1. Base

The base case uses the parabolic impact function, the SSP2 scenario, a pure rate of time preference of 1%, and a rate of risk aversion of 1. The global social cost of carbon is

$23.85/tC. As the assumed impact function is strictly negative, the social cost of carbon is strictly positive. All national social costs of carbon are therefore a fraction of the global social cost. Bigger countries have a larger national cost. The national social cost of carbon is $5.70/tC for India, $3.05/tC for China, $1.16/tC for Ethiopia, $1.12/tC for Bangladesh, $1.05/tC for Pakistan, $0.85/tC for Indonesia, $0.33/tC for the EU, and $0.15/tC for the USA. These eight countries[2] together make up 56% of the global social cost of carbon.

Figure 3 plots the national social cost of carbon per capita against per capita income in 2015. The line is regular and smooth. A per capita social cost is a meaningless indicator, but Figure 3 reveals that population size and per capita income explain almost all variation in the social cost of carbon between countries.

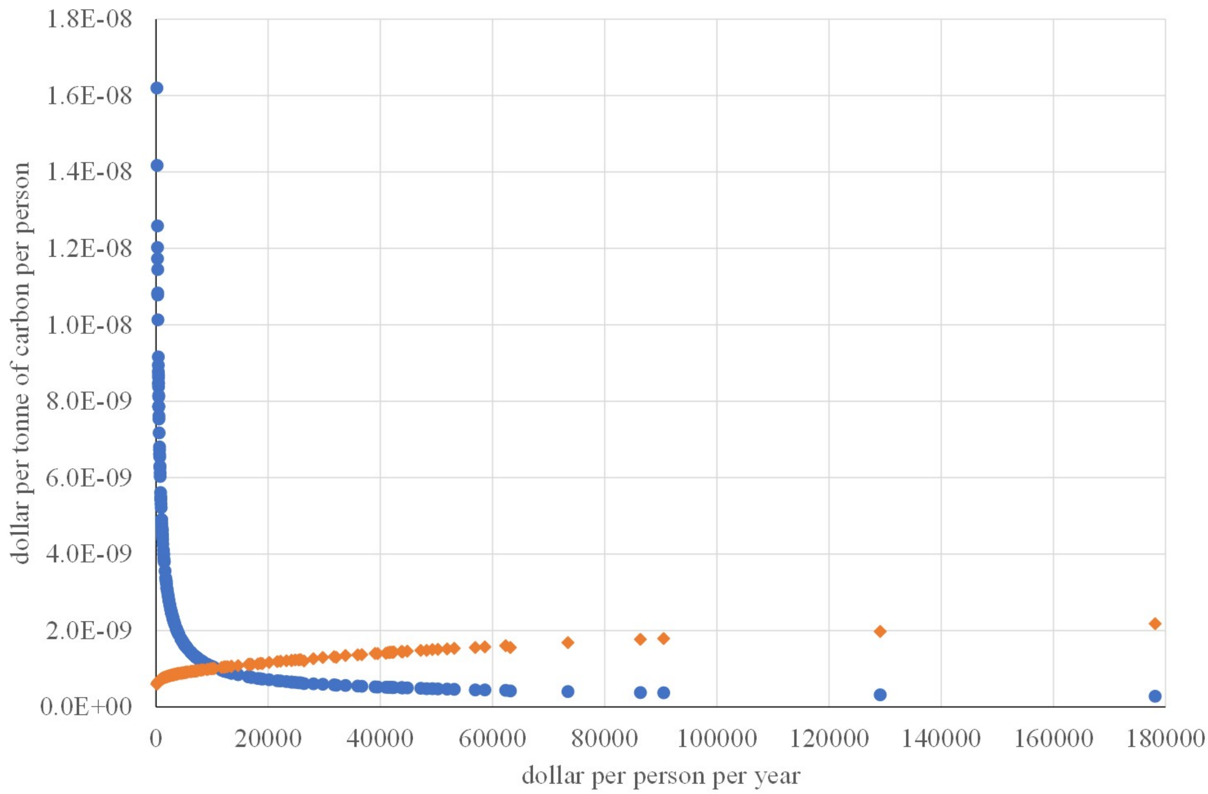

Figure 3: The per capita social cost of carbon plotted against per capita income for an income semi-elasticity of -1.68 (blue dots) and -0.88 (orange triangles).

4.2. Discount rates

In the base specification, the pure rate of time preference is 1% per year and the rate of risk aversion is 1. The global social cost of carbon is $23.85/tC. This increases to $29.72/tC for a 0.1% pure rate of time preference and falls to $11.55/tC for 5%. As has been seen in

[2]Climate policy a a matter for the European Union rather than its Member States.

numerous previous papers, the social cost of carbon is highly sensitive to the pure rate of time preference.

The Ramsey (1928) Rule has that the consumption discount rate equals the pure rate of time preference plus the rate of risk aversion times the growth rate of consumption: $r = \rho + \eta g$. This implies that the pure rate of time preference is more (less) important for countries that grow more slowly (faster).

Because the economic growth scenarios as constructed strictly converge, this can be illustrated with the richest and poorest country in the sample. The global social cost of carbon is 2.57 times as big for a 0.1% pure rate of time preference than for a 5% one; for Luxembourg, this ratio is 3.47; for Afghanistan, it is 2.56.This highlights that the global social cost of carbon is dominated by poor countries. Figure 4 illustrates this. The social cost of carbon of faster growing economies are less sensitive to the pure rate of time preference.

The Ramsey Rule also implies that faster (slower) growing economies are more (less) sensitive to the assumed rate of risk aversion. If the rate of risk aversion is 0.5, rather than 1.0, the global social cost of carbon rises to \$38.44/tC; for a rate of risk aversion of 2.5, it is \$8.93/tC. The ratio is 4.31. This suggests that the social cost of carbon is more sensitive to the rate of risk aversion than to the pure rate of time preference, but it is hard to compare like with like for two poorly constrained parameters.

For Afghanistan, the poorest and assumedly fastest growing country, the ratio is 4.30; for Luxembourg, the richest and assumedly slowest growing country, the ratio is 4.13. Portugal is the most sensitive country, with a ratio of 4.67. Figure 4 illustrates that there is a U-shaped relationship between the sensitivity of the national social cost of carbon to the rate of risk aversion and the assumed growth rate of the economy. The reason for this is as follows. If a country grows faster, it discounts the future harder, and this is more pronounced as the utility function is more curved. This explains the upward slope for countries with an average income above \$20,000 per person per year in 2015. However, countries that grow faster also become less vulnerable to climate change more quickly, and their impacts are concentrated in the nearer future. The discount rate therefore becomes less important. This effect dominates for countries with an income below \$20,000. It explains the downward slope.

4.3. Constant discount rate

The US government uses a constant consumption discount rate (IAWGSCC, 2013), against the advice of experts (Arrow et al., 2013, 2014). A constant discount rate is inconsistent with theory, and invariant between scenarios. It is also invariant between countries, unless the international capital market is perfect (which it is not). This in turn means that a constant discount rate introduces an implicit penalty or premium on the impact in particular countries.

Figure 5 illustrates this. It shows the ratio of the national social cost of carbon for a pure rate of time preference of 1% per year to the national social cost of carbon for a constant discount rate of 4.9%. For both nominator and denominator, I assume the parabolic impact model and scenario SSP2. The constant discount rate equals 4.9% so that the US social cost of carbon equals \$0.15/tC, as above. Figure 5 plots this ratio against the assumed economic

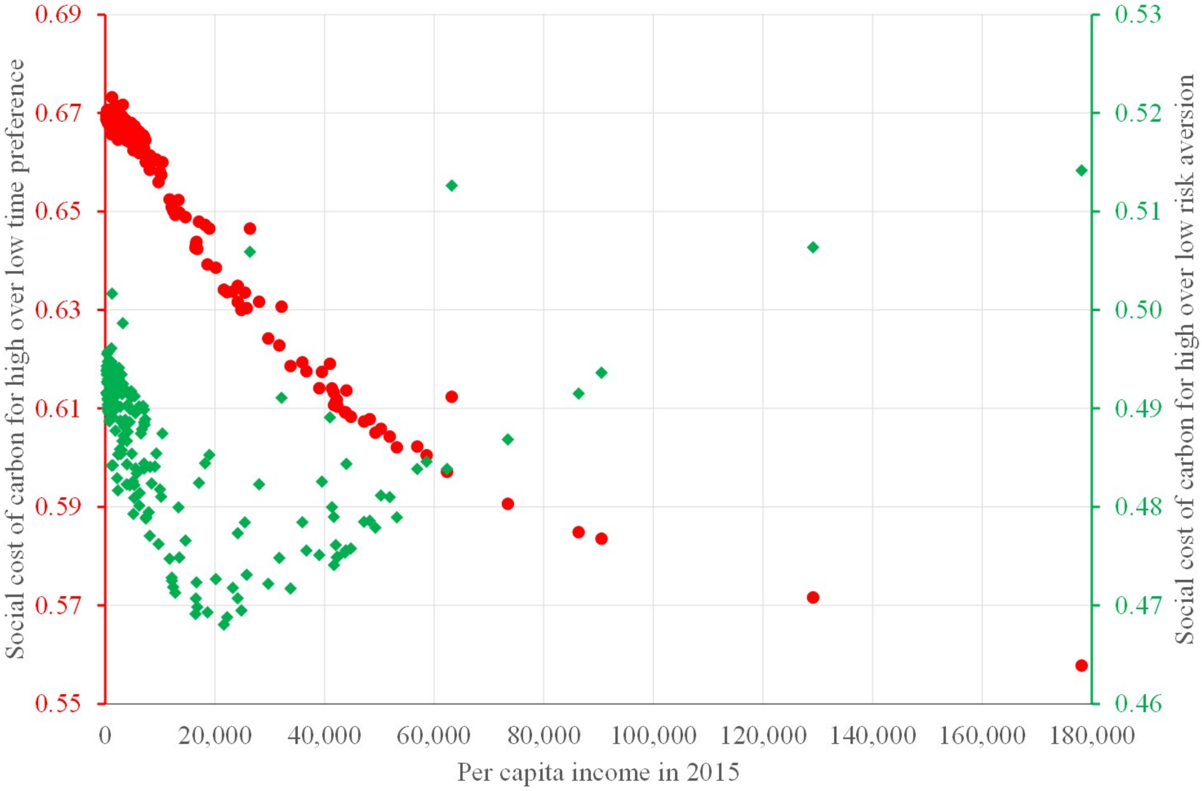

Figure 4: The ratio of the social cost of carbon for a 1% pure rate of time preference to a 3% rate (red dots, left axis) and for a risk aversion of 2 over the social cost of carbon for a risk aversion of 1 as a function of per capita income in 2015 (green diamonds, right axis).

growth rate. A constant discount rate overemphasizes (underemphasizes) the impact of climate change in fast-growing (slow-growing) countries.

Figure 6 shows the national social cost of carbon estimates. Only the 30 countries with largest social cost of carbon are included. The graph displays the results for the SSP2 scenario, the parabolic impact model, and a Ramsey discount rate with a 1% pure rate of time preference and a risk aversion of one. It also shows results for a constant discount rate. I use two calibrations. In the first, the discount rate is 4.9% per year, so that the US social cost of carbon is \$0.15/tC as above. The global social cost of carbon is then \$28.56/tC, higher than above. In the second calibration, the discount rate is 5.7% so that the global social costs of carbon is \$23.85/tC as above. The US social cost of carbon then falls to \$0.13/tC. In either calibration, a constant discount rate as used in IAWGSCC (2013) puts a heavier weight on impacts in countries that are projected to grow faster than the USA. In the global calibration, US impacts are additionally suppressed.

4.4. Impact function

The default impact function is the parabolic one displayed in Table 1. That table also shows the global social cost of carbon. The Weitzman, Nordhaus and Hope models give

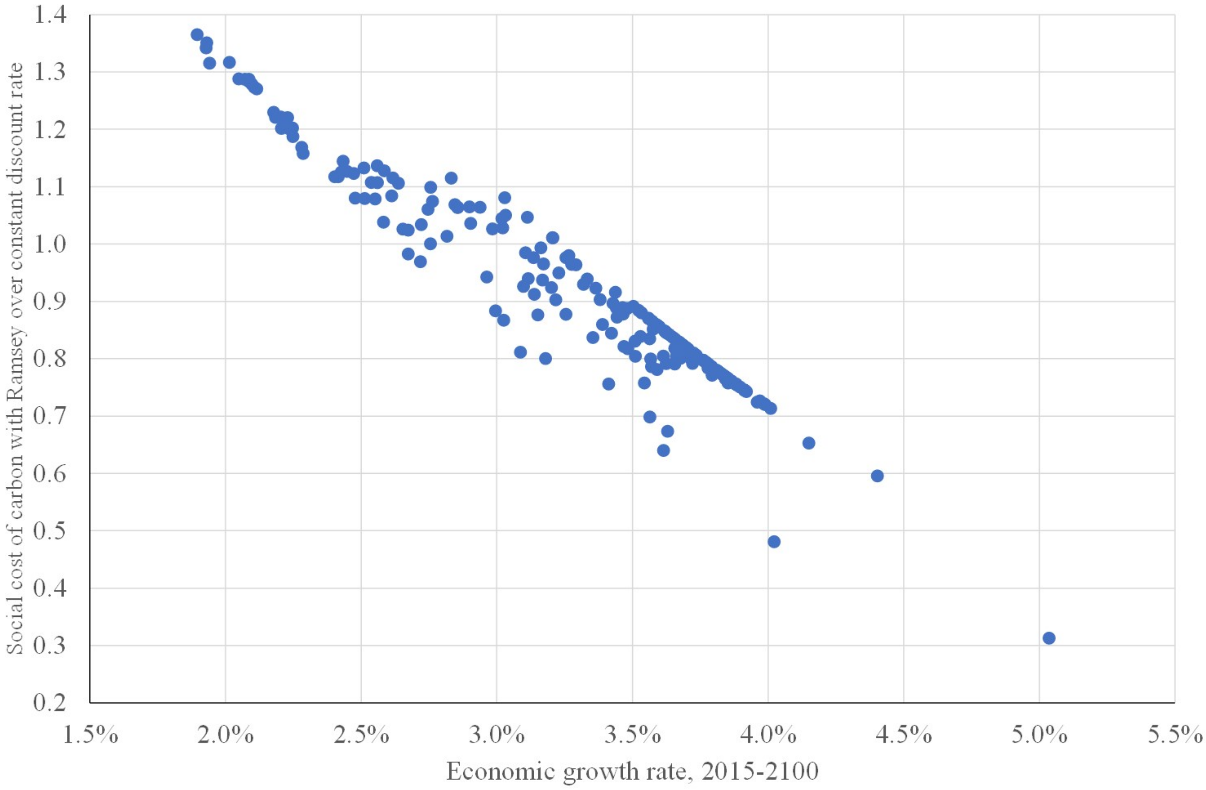

Figure 5: The ratio of the social cost of carbon with a Ramsey discount rate to the social cost of carbon with a constant discount rate as a function of the assumed growth rate of the economy.

similar results, with higher estimates for the more nonlinear specifications. This patterns breaks with the highly non-linear models of Ploeg and Golosov. The latter model has essentially zero damage below a threshold and infinite damage above. The social cost of carbon is therefore zero unless the extra tonne of carbon pushes the climate over the threshold. The Ploeg impact model is a less extreme version of this. The national pattern of social costs of carbon is very similar to the pattern from the parabolic model.

The piecewise linear model has a global social cost of carbon of -\$86.77/tC. The pattern of national social costs is indistinct. For each country, the social cost is between 3.2 and 3.7 times as large for the parabolic model, and the opposite sign. The sign flips because the piecewise linear model has that climate change is initially net beneficial. The high income elasticity implies that later costs are relatively small.

4.5. Scenario dependence and convergence

There are two aspects to a scenario. First, how fast will climate change, and thus how much damage will be done? Second, how fast will incomes grow, and vulnerability to climate change fall? As economic growth drives emissions growth, these two effects at least partly offset each other.

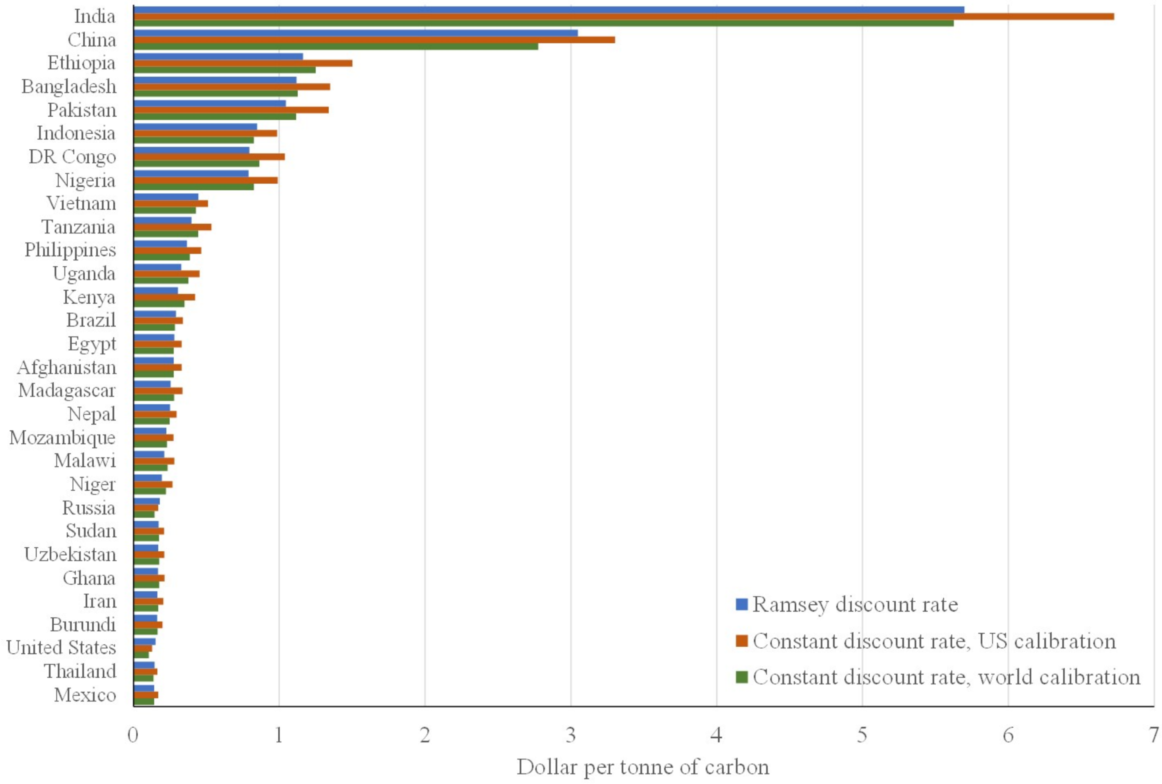

Figure 6: The 30 largest national social costs of carbon with a Ramsey discount rate and two equivalent constant discount rates.

The SSP2 scenario is the default scenario. All scenarios are deemed equally unlikely. The default scenario is the median of the newer SSP scenarios. Table 2 shows the global social cost of carbon for all scenarios. Estimates range between $14.55/tC and $55.20/tC. The default scenario is somewhere in the middle. The earlier SRES scenarios are somewhat higher than the later SSP scenarios.

The national results scale with the global estimates. The social cost of carbon of countries rich and poor vary in almost the same way as the aggregate does. The pattern across countries is largely independent from scenario choice.

In the default scenarios, poorer countries grow faster. This is corroborated by some but not all data. Dropping this assumption, letting all countries grow at the same rate, leads to a global social cost of carbon of $28.38/tC, a slight increase. Figure 7 plots the change in the national social cost of carbon against per capita income in 2015. Countries with an average income above (below) $28,000 per person per year see their social cost of carbon fall (rise). Poorer countries grow faster with convergence, and thus become less vulnerable and discount the future harder. The effects are small, however, because these effects become pronounced only in the more distant future.

Scenario	Social cost of carbon
SRES A1	\$19.54/tC
SRES A2	\$55.20/tC
SRES B1	\$25.20/tC
SRES B2	\$34.21/tC
SSP1	\$17.64/tC
SSP2	\$23.85/tC
SSP3	\$41.79/tC
SSP4	\$25.42/tC
SSP5	\$14.55/tC

Table 2: The global social cost of carbon for nine alternative scenarios.

climate sensitivity	social cost of carbon	income elasticity	social cost of carbon
0.5°C/2×CO_2	\$1.30/tC	0	\$31.00/tC
1.5°C/2×CO_2	\$7.11/tC	-0.08	\$23.81/tC
2.5°C/2×CO_2	\$17.20/tC	-0.88	\$6.44/tC
3.0°C/2×CO_2	\$23.85/tC	-1.68	\$23.85/tC
4.5°C/2×CO_2	\$50.20/tC	-2.48	\$441.33/tC
1.5°C/2×CO_2	\$86.18/tC	-3.28	\$21688.93/tC

Table 3: The global social cost of carbon for alternative climate sensitivities and alternative income elasticities of impact.

4.6. Income elasticity

Table 3 shows the sensitivity of the global social cost of carbon to the income elasticity of the impact of climate change. The social cost of carbon falls is very sensitive to this parameter. If development does not affect vulnerability, the global social cost of carbon is \$31.00/tC. The social cost of carbon initially falls, as society becomes less vulnerable with economic growth. However, the social cost of carbon starts rising for a higher income elasticity. This is because a higher income elasticity implies greater climate impacts in poorer countries in the near term. The social cost of carbon rises sharply as the income elasticity increases.

Changes in the national social costs of carbon are different from the changes in the global social cost. This is illustrated in Figure 3. For the default income elasticity of -1.68, richer countries have lower social costs of carbon. For an income elasticity of -0.88, richer countries have higher social costs of carbon.

4.7. Climate sensitivity

Table 3 shows the sensitivity of the global social cost of carbon to the climate sensitivity. The social cost of carbon rises steeply with the assumed equilibrium warming due to a double of atmospheric carbon dioxide.

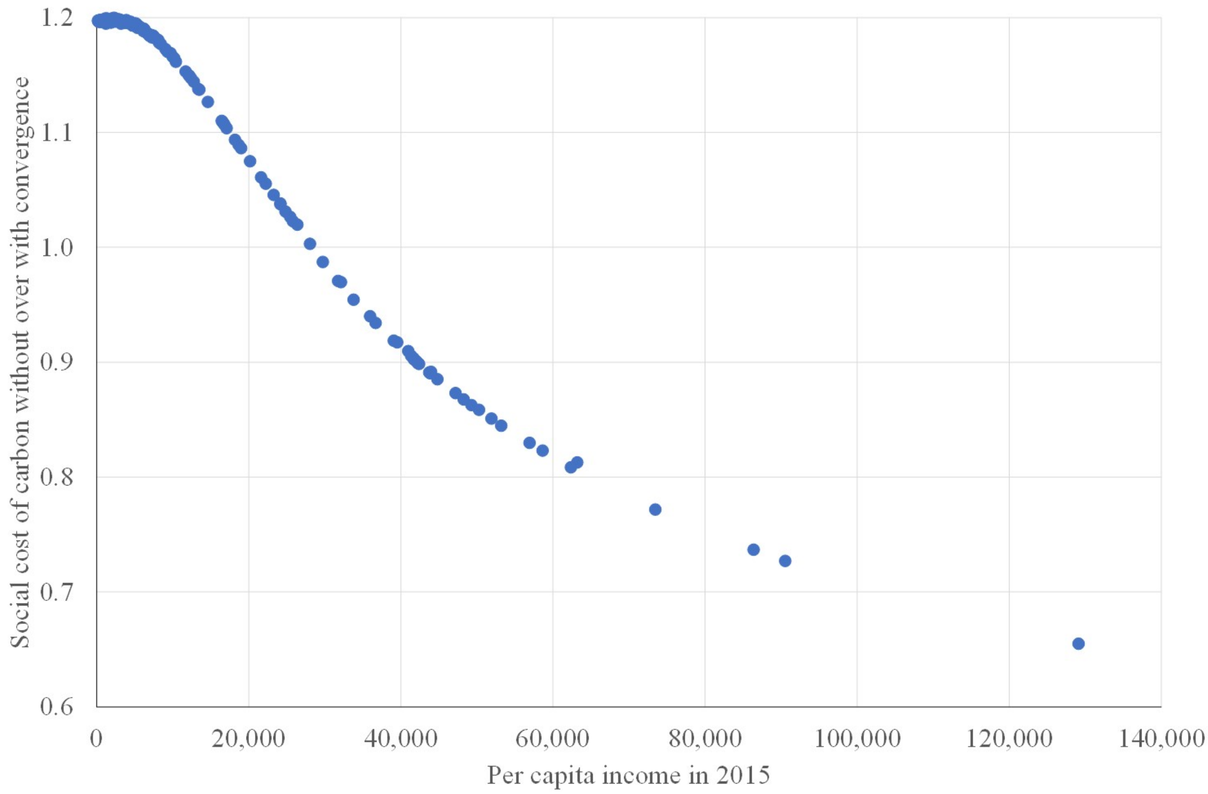

Figure 7: The ratio of the social cost of carbon with income convergence to the social cost of carbon without income convergence as a function of per capita income in 2015.

National social costs of carbon go up and down with the global estimate. The spatial pattern does not change. This follows from the functional form; see Table 1. National impact models have different parameters but the same specification at the global impact model, and therefore respond in the same way to a change in temperature.

4.8. Imputation and calibration

In the base specification, the parameters of the national impact functions are derived from the global parameters, per capita income, and the income elasticity. However, Equation (1) has two elements, income and temperature. I therefore recalibrate the national impact functions using both. The problem with this procedure is that it changes signs. Always negative impacts become always positive for 55 countries and 7 out of 8 impact function. The inverted-U-shape of the piecewise linear impact function becomes a U-shape.

It is therefore no surprise that the global social cost of carbon falls to \$15.81/tC. India's social cost of carbon falls from \$5.70/tC to \$4.55/tC, because its high vulnerability is now explained by heat and poverty rather than by poverty alone. The US social cost of carbon falls from \$0.15/tC to -\$0.78/tC, a carbon subsidy.

In the base specification, the impact functions are calibrated on the global impact estimates and national impact estimates imputed from the global estimates, using the estimated income elasticity. There is no obvious reason to do things in this order. I therefore use the income elasticity to impute national impacts from the primary estimates, making sure that the national numbers add up to the primary estimates for the regions, and calibrate the impact function to the imputed national estimates.

The base specification has imputation *after* calibration, the alternative imputation *before* calibration. A pragmatic advantage of the base specification is that sensitivity analysis on the income elasticity (see above) is trivial. The alternative specification uses more information from the primary impact studies, and may thus be seen as the preferred order. However, the regional details in the primary studies are very uncertain, and this is carried over into the parameters of the national impact functions. The base specification regularizes the primary estimates and is thus less sensitive to outliers.

The global impact function has two negative parameters and is thus always negative. So are the national impact functions imputed from this. In contrast, only 31 of the calibrated national impact functions are always negative. 35 have an inverted U-shape, with the typical optimal temperature relatively close to today's. The remaining 123 countries' impact functions are U-shaped, but with the worst temperature much above today's; that is, these countries see negative impacts of climate change, their impacts worsen with greater warming, but the incremental impacts fall with greater warming. This specification is strange. Under extreme warming (not considered here) incremental impacts and, eventually, impacts will turn positive. Marginal impacts (the focus here) are sensitive to the curvature of the impact function. I therefore prefer imputation *after* calibration.

As could be expected from the above, the estimates are quite sensitive to the change in order. The global social cost of carbon is \$3.38/tC for imputation before calibration, instead of \$23.85/tC for imputation after calibration. Figure 8 shows the national results. The national cost of carbon falls by an order of magnitude for China and India, the two top countries. For 34 countries, the sign flips: The national cost of carbon is negative, calling for a carbon subsidy. These carbon subsidies are small. The main effect is the sharp reduction in the bigger countries.

5. Discussion and conclusion

This paper presents estimates of the national cost of carbon for almost every country. Such estimates are relevant if governments pursue "my country first" policies. I imputed national climate change impact functions from global impact functions and the income elasticity implied by regional estimates of the impact of climate change. The national social cost of carbon is largest in poor countries with large populations—India, China, Ethiopia, Bangladesh, Pakistan, and Indonesia. The EU and the USA rank 7^{th} and 8^{th}. The national social cost of carbon is less sensitive to the pure rate of time preference in faster growing economies, and more sensitive to the rate of risk aversion. The global social cost of carbon is sensitive to the assumed impact function, climate sensitivity, and scenario, but the pattern of national social costs is not. The assumption of income convergence raises (lowers) the national social cost of carbon of poorer (richer) countries. The assumed income elasticity

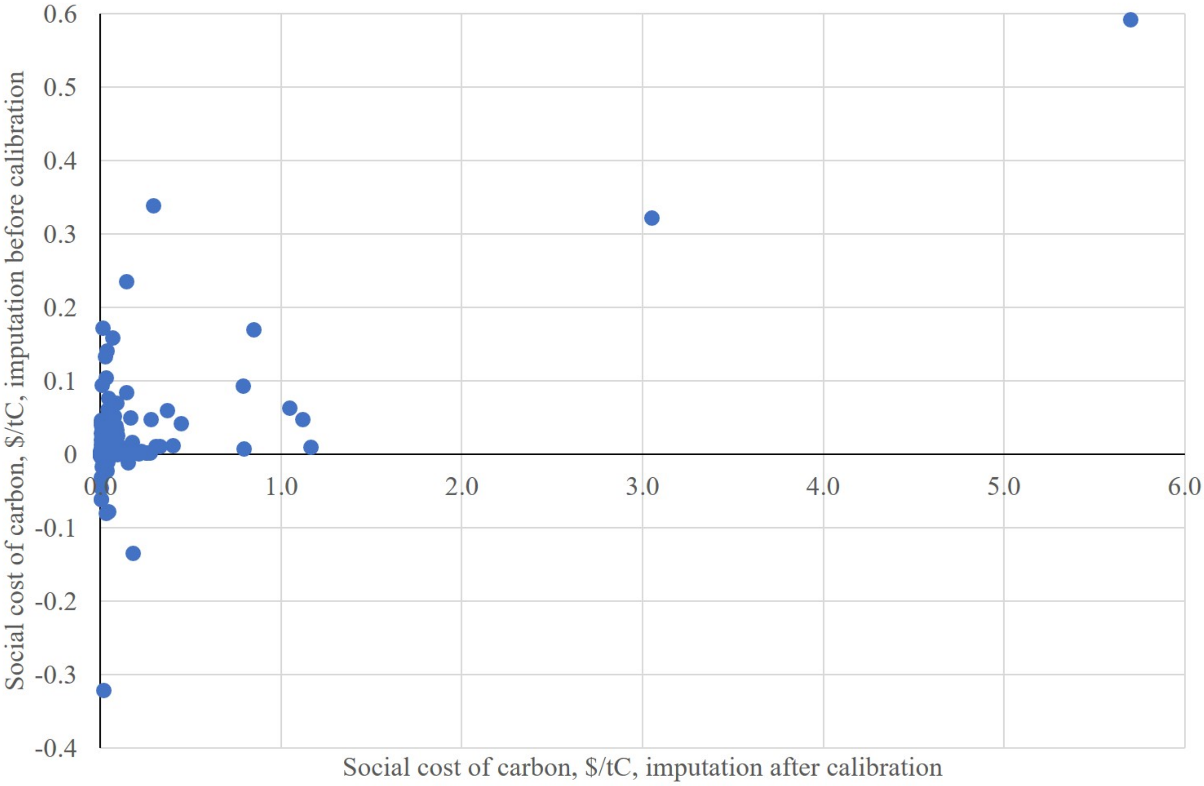

Figure 8: The national cost of carbon for imputation *after* calibration against imputation *before* calibration.

of climate change impacts is the key parameter, more important than the assumed discount rate, for both the global social cost of carbon and the pattern of national social costs.

Unfortunately, although there is near universal agreement that poorer countries are more vulnerable to climate change, few have estimated an income elasticity. A key parameter in the analysis is thus poorly constrained by empirical evidence. This should be a high priority in future research. Another priority is to replace the impact function used here by impact functions. This is important because different attributes of climate change—carbon dioxide fertilization, ocean acidification, sea level rise, actual climate change—have different dynamics and different net present marginals. Different components of the impact function respond differently to development—air conditioning rises faster than income, agriculture slower; air conditioning is affected by the urban heat island effect, agriculture is not. The estimates above ignore uncertainty, about emissions, climate change, and impacts. Estimates ignore distributional issues within countries, and empathy towards people from other countries. All that is deferred to future research.

Two findings of this paper will withstand the refinements of further research. National social costs of carbon are much smaller than the global social costs of carbon. Large, poor countries would impose the highest carbon taxes if acting in the national self-interest.

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