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Abstract

This paper presents a novel way to disentangle inequality aversion over time from inequality aversion between regions in the computation of the Social Cost of Carbon. Our approach nests a standard efficiency based Social Cost of Carbon estimate and an equity weighted Social Cost of Carbon estimate as special cases. We also present a methodology to incorporate more fine grained regional resolutions of income and damage distributions than typically found in integrated assessment models. Finally, we present quantitative estimates of the Social Cost of Carbon that use our disentangling of different types of inequality aversion. We use two integrated assessment models (FUND and RICE) for our numerical exercise to get more robust findings. Our results suggest that inequality considerations lead to a higher (lower) SCC values in high (low) income regions relative to an efficiency based approach, but that the effect is less strong than found in previous studies that use equity weighting. Our central estimate is that the Social Cost of Carbon increases roughly by a factor of 2.5 from a US perspective when our disentangled equity weighting approach is used.

JEL-Codes: D630, H430, Q540.

Keywords: social cost of carbon, inequality, climate change, discounting, equity weighting, integrated assessment model.

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1 Introduction

Studies that estimate the Social Cost of Carbon (Greenstone et al., 2013; Nordhaus, 2014) aggregate climate change impacts that accrue to societies at very different stages of development: a single Social Cost of Carbon estimate is the sum of the marginal damages to all countries at all future times, so it includes for example harms to a rich developed society like the US today and a poor developing country like Mozambique today. But it also includes impacts to these same countries in a hundred years, and typically they are assumed to have dramatically changed in terms of socio-economic development over such a long time horizon (Nakicenovic and Swart, 2000).

Any type of cost-benefit or policy analysis that covers such a heterogeneous set of affected parties will at some point face the question whether (and if yes, how) the large income differences between the affected parties should be taken into consideration for the analysis. The most common type of applied analysis in the economics of climate change ignores income differences between countries by deferring to the Kaldor-Hicks potential compensation criterion (or some variant of it): such an analysis tries to identify policies that maximize the size of the economic pie and relegates any distributional objectives to a separate analysis and non-climate policy instruments (Nordhaus and Yang, 1996).

At the same time there exists a long-standing literature in climate economics that incorporates distributional equity objectives into the analysis of climate policy. This literature has its roots in the literature on distributional weights in cost-benefit analysis (Little and Mirrlees, 1974; Mirrlees, 1978), but runs under the headline of "equity weighting" in the climate economics literature (Azar and Sterner, 1996; Fankhauser et al., 1997; Azar, 1999; Anthoff et al., 2009b; Anthoff and Tol, 2010; Dennig et al., 2015). Equity weighted Social Cost of Carbon estimates have been produced by the groups that maintain the three major cost-benefit integrated assessment models DICE/RICE (Nordhaus, 2011), FUND (Anthoff et al., 2009a) and PAGE (Hope, 2008), and when the United Kingdom decided to use a Social Cost of Carbon in their regulatory process in the early 2000s they used an equity weighted Social Cost of Carbon (Watkiss and Hope, 2011).

Existing equity weighting studies assume a social welfare function (SWF) that exhibits inequality aversion over per capita consumption levels both over time and between individuals. The level of inequality aversion in these setups is determined by a single parameter, and consequently one cannot represent different degrees of inequality aversion say over time and between countries or regions.

The first contribution of this paper is to disentangle intertemporal inequality aversion from regional inequality aversion. We propose a modified social welfare function that is based on separate parameters for inequality aversion over time and inequality aversion between individuals or regions. In some ways this is a similar project to the disentangling of risk aversion and intertemporal fluctuation aversion (Epstein and Zin, 1989), but for a different set of parameters in the SWF.

Our new welfare specification is able to nest both a purely efficiency based approach that ignores distributional questions between individuals and the existing equity weighting approach as special cases of our more general welfare function. Our new specification also makes it easier to use existing estimates of preferences over distributions of income to pin down the parameters of the welfare function. One can calibrate the between individuals inequality aversion parameter by looking at studies that either estimate an inequality aversion parameter from observed income tax schedules or observations of altruistic giving (Evans, 2005; Clarkson and Deyes, 2002; Tol, 2010; Johansson-Stenman et al., 2002). For the inequality aversion parameter over time (intertemporal fluctuation aversion), one can refer to market observations (e.g., based on consumption-savings decisions) or normative reasoning (Cline, 1992; Nordhaus, 2007; Dasgupta, 2008). From a theoretical point of view there is no reason to assume that these two types of inequality aversion should be equal, and the empirical literature indeed finds vastly different estimates for the two parameters. Our welfare specification allows incorporation of this fact into the computation of the Social Cost of Carbon in a consistent way.

The second contribution of the paper is a new way to incorporate detailed distributional data and assumptions about income and damages into coarse regional integrated assessment models. Typical integrated assessment models divide the world into 10-16 regions. While heterogeneity between regions is therefore explicitly accounted for, these models assume away any income inequality within a given region of the model. We present concise analytic expressions that augment the discount factors used to compute the Social Cost of Carbon that incorporate different distributional assumptions on the sub-regional distribution of income and climate impacts. We then use these analytical results with a typical integrated assessment model to compute an equity weighted Social Cost of Carbon that takes inequality at a sub-regional level into account.

The third part of the paper presents Social Cost of Carbon estimates using this new welfare function and compares them to the existing equity weighting and efficiency based Social Cost of Carbon estimates. We use the integrated assessment models FUND 3.9 (Waldhoff et al., 2014) and RICE-2010 (Nordhaus, 2010) for our numerical exercise. We use multiple models to make sure our results are not dependent on the particular assumptions (both structural and parametric) made in a single numerical integrated assessment models. We chose the two models based on their ability to estimate a Social Cost of Carbon, their ability to produce regional results and their open source availability.

2 Discounting and equity weighting

Most welfare economic studies of climate policy that use Integrated Assessment Models (IAMs) are based on a Utilitarian Social Welfare Function (SWF) of the discounted utility form. Social Welfare of all individuals $i = 1..I$ can then be written as

$$W = \sum_{t=0}^{T} \sum_{i=1}^{I} U(c_{it})(1+\rho)^{-t} \tag{1}$$

where c_{it} is consumption of individual i at time t, ρ denotes the pure rate of time preference and T the end of the planning horizon. It is well known that regional inequality aversion, risk aversion[1], and intertemporal fluctuation aversion are all determined by the curvature of the utility function U in this framework and thus coincide. For instance, for the standard case of constant relative risk aversion (CRRA) utility $U(c) = c^{1-\eta}(1-\eta)^{-1}$, all three types of inequality aversion are determined by the single parameter η.[2]

In numerical Integrated Assessment Models (IAMs), all variables are computed for R regions with population sizes P_{rt} and therefore, a slightly different version of (1) is used. Implicitly, consumption is assumed to be equally distributed within each given region equal to the average consumption per capita level c_{rt}. Moreover, we denote by $P_t = \sum_{r=1}^{R} P_{rt}$ the size of world population at time t. The SWF then becomes

$$W = \sum_{t=0}^{T} \sum_{r=1}^{R} P_{rt} U(c_{rt})(1+\rho)^{-t} \tag{2}$$

We will use this welfare function in order to evaluate the impacts (damages or benefits) from climate change, which are derived from numerical models together with assumptions about the socioeconomic variables. The numerical models provide an estimate of the effect of one additional ton of CO_2 emitted today. This effect will be experienced at

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[1] We abstract from risk and uncertainty in this paper.

[2] For the case of $\eta = 1$, the utility function is $U(c) = log(c)$ which is the limit of $U(c) = \frac{c^{1-\eta}-1}{1-\eta}$ as η tends to one. To improve readability we leave out the constant additive term.

all future times and in all regions, and is denoted by marginal damages D_{rt}. We express the effect as damages, i.e. positive numbers are a harmful impact whereas negative values indicate benefits from global warming. We further assume that D_{rt} is expressed as an economic consumption loss, so that one can easily compare it to the assumed baseline consumption levels. Combining the disaggregated estimate of marginal damages with the SWF (2) and a CRRA utility function enables us to compute the welfare impact of a series of regional and temporal marginal damages. Basically, marginal damages at date t in region r are weighted by discounted marginal utility of consumption, i.e. by $U'(c_{rt})(1+\rho)^{-t} = c_{rt}^{-\eta}(1+\rho)^{-t}$. These weighted marginal damages estimates can then be summed over time and regions to arrive at an aggregated measure of marginal damage, which is expressed in utility units.

For most real world applications it is convenient to have marginal damages expressed in monetary terms, rather than in utility units. In a final step, the marginal damage estimate therefore must be converted into monetary units. In principle one would just divide the marginal damage estimate expressed in utility units by marginal utility of income or consumption in the present to convert from utility to monetary units. Income inequality in the present however implies that the marginal utility of income is different between regions and therefore the conversion depends on the choice of the reference or normalization region. Unless potentially very large transfers equating marginal utilities are allowed[3] this yields different monetary values for different reference regions of the aggregated marginal damages as shown in Anthoff et al. (2009a).

Fankhauser et al. (1997) proposed to convert the obtained values from utility into monetary terms using marginal utility of present average world per-capita consumption. Any given region x can however be used using its marginal utility today $c_{x0}^{-\eta}$. Note that the choice of the region x does not alter the basic cost benefit analysis interpretation of the results. Rather, it is a constant multiplicative term and merely yields a monetary interpretation of the result allowing a direct comparison with abatement costs in the given region (see Anthoff et al. (2009b) for a more detailed discussion). In order to make the numerical results comparable with previous studies we take the U.S. as reference region x throughout this paper.

To summarize this method, we can write the Social Cost of Carbon SCC_x, that is the damage of one additional ton of CO_2 emissions in the present expressed as a welfare

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[3] Alternatively, Negishi weights can be used in the SWF specification to equate marginal welfare gains from income in different regions, see Nordhaus and Yang (1996).

equivalent change in consumption in region x, as

$$SCC_x = \sum_{t=0}^{T}\sum_{r=1}^{R}\frac{c_{rt}^{-\eta}}{c_{x0}^{-\eta}}(1+\rho)^{-t}D_{rt}. \tag{3}$$

This formulation is the equity weighting scheme used in Anthoff et al. (2009b), Hope (2008), and Nordhaus (2011). Damages in a region with lower than average consumption per capita are relatively over-weighted due to decreasing marginal utility. Moreover, in this formulation, equity weights and the social discount rate are inseparable. Nordhaus (2011) refers to this approach as the "conceptually and philosophically more appropriate" intertemporal approach, in contrast to the "cross-sectional approach" advocated by Fankhauser et al. (1997). We agree in that this is the correct perspective from a welfare perspective and take the intertemporal approach as our starting point.

For the remainder of this chapter, we will derive a version of SCC_x that allows to separate regional inequality aversion from intertemporal inequality aversion. In the next chapter we will then further modify the equation to take inequality within regions into account.

In general, the value of the Social Cost of Carbon can be expressed using the welfare function (2) in the following way

$$SCC_x = \left(\frac{\partial W}{\partial c_{x0}}\right)^{-1}\sum_{t=0}^{T}\sum_{r=1}^{R}\frac{\partial W}{\partial c_{rt}}D_{rt}. \tag{4}$$

The first step is to modify the SWF such that one can distinguish regional inequality aversion from intertemporal inequality aversion. Our approach is in the spirit of the recursive model by Kreps and Porteus (1978) and Epstein and Zin (1989). The authors developed a preference model allowing for distinct time and risk preferences. In our context, the qualitatively similar concepts of uncertainty and inequality allow us to use a similar concept in the dynamic context considered. The results however require a different interpretation, most notably due to the fact that there is no uncertainty about today while inequality prevails also today.

Preferences by the social planner are now characterized by two functions: firstly, at any point in time, welfare is evaluated by aggregating consumption across regions using the utility function $U(c_{rt})$. This utility function captures inequality aversion between regions and is used to compute the equally-distributed equivalent level of consumption $c_t^{ede} = U^{-1}\left(\sum_{r=1}^{R}\frac{P_{rt}}{P_t}U(c_{rt})\right)$, see Atkinson (1970). It can be interpreted as the value of per-capita consumption that, if it were equally distributed across regions, would yield the exact same level of welfare as the observed levels of per-capita consumption.

Secondly, welfare is aggregated over the time horizon using the time aggregation function $V(c_t^{ede})$ which aggregates the equally-distributed equivalent levels of consumption over time. Finally, exponential utility discounting is used to compute the present value of global welfare. That is, our welfare specification W^R, where the superscript R refers to the regional inequality that is considered, can be written as

$$W^R = \sum_{t=0}^{T} P_t V \left[U^{-1} \left(\sum_{r=1}^{R} \frac{P_{rt}}{P_t} U(c_{rt}) \right) \right] (1+\rho)^{-t}. \tag{5}$$

Using isoelastic specifications for both functions as $V(c_t^{ede}) = (1-\eta)^{-1}(c_t^{ede})^{1-\eta}$ and $U(c_{rt}) = (1-\gamma)^{-1}{c_{rt}}^{1-\gamma}$ as in the Epstein-Zin specification (Weil, 1990), the SWF reads

$$W^R = \sum_{t=0}^{T} P_t \frac{1}{1-\eta} \left(\sum_{r=1}^{R} \frac{P_{rt}}{P_t} c_{rt}^{1-\gamma} \right)^{\frac{1-\eta}{1-\gamma}} (1+\rho)^{-t} \tag{6}$$

where η can be interpreted as inverse of the elasticity of substitution (or intertemporal inequality aversion) whereas γ represents the degree of regional inequality aversion. This welfare function has previously been used in the context of the consumption discount rate in Emmerling (2011).

It can be easily shown that W^R is equivalent to W if $\eta = \gamma$, i.e. the welfare function previously used in equity weighting studies. Using this particular parameterization of the welfare function W^R to derive the expression for the Social Cost of Carbon by applying the definition of SCC_x from (4) leads to the standard equity weighted Social Cost of Carbon equation (3). If, on the other hand, $U(c_{rt})$ is an affine function exhibiting regional inequality neutrality (i.e., in the isoelastic specification, setting $\gamma = 0$), we get that $W^R = \sum_{t=0}^{T} P_t V \left(\sum_{r=1}^{R} \frac{P_{rt}}{P_t} c_{rt} \right) (1+\rho)^{-t}$. In this formulation welfare only depends on global average per capita consumption levels, i.e. any inequality in consumption between regions is ignored in the welfare evaluation. The corresponding Social Cost of Carbon expression discounts world marginal damages with one Ramsey discount rate that depends on the global per capita consumption growth rate. This case is equivalent to a standard efficiency based estimate of the Social Cost of Carbon, as for example obtained by the DICE model.

In general, however, we obtain a new formula SCC^R for the Social Cost of Carbon by using the same definition of (4). After some reformulations it can be shown that

$$SCC_x^R = \sum_{t=0}^{T}\sum_{r=1}^{R}\left(\frac{c_t^{ede}}{c_0^{ede}}\right)^{\gamma-\eta}\frac{c_{rt}^{-\gamma}}{c_{x0}^{-\gamma}}(1+\rho)^{-t}D_{rt} \tag{7}$$

where $c_t^{ede} = \left(\sum_{r=1}^{R}\frac{P_{rt}}{P_t}c_{rt}^{1-\gamma}\right)^{\frac{1}{1-\gamma}}$ represents the global 'equally distributed equivalent' level of consumption taking into account regional inequalities.[4]

We can rewrite this equation such that we can distinguish the relevant driving forces that determine the weights attached to the individual impacts at each point in time and in each region:

$$SCC_x^R = \sum_{t=0}^{T}\sum_{r=1}^{R}\left(\frac{c_{rt}/c_{r0}}{c_t^{ede}/c_0^{ede}}\right)^{\eta-\gamma}\frac{c_{r0}^{-\gamma}}{c_{x0}^{-\gamma}}\frac{c_{rt}^{-\eta}}{c_{r0}^{-\eta}}(1+\rho)^{-t}D_{rt} \tag{8}$$

First, the standard Ramsey discount factor in each region $\frac{c_{rt}^{-\eta}}{c_{r0}^{-\eta}}(1+\rho)^{-t}$ is used to convert all values into present values in the respective region. Second, the equity weight $\frac{c_{r0}^{-\gamma}}{c_{x0}^{-\gamma}}$ convert each region's present values into a welfare equivalent change of consumption in region x that is used as the reference region (e.g., as in Azar and Sterner (1996)). The exact role of the equity weight depends on the relative rank in the income distribution of the regions as of today: the weight will be larger than one if it converts an impact from a poorer region to a wealthier reference region, but will be lower than unity if it converts a present value impact from a richer region to a poorer reference region. If $\gamma = \eta$, those are the only determinants that finally allow to aggregate the impacts into one value, since the remaining term is just equal to unity in this case. In that case we are back to the standard equity weighted values used throughout the literature (Fankhauser et al. (1997), Anthoff et al. (2009a) and Hope (2008)).

If the two parameters are different, we get the additional weighting factor $\Omega_{rt} \equiv \left(\frac{c_{rt}/c_{r0}}{c_t^{ede}/c_0^{ede}}\right)^{\eta-\gamma}$. If $\gamma < \eta$, i.e. regional inequality aversion is lower than intertemporal inequality aversion, this factor is greater than one for a region that is growing faster than the world on average. This is intuitive since in this case regional inequality concerns are less pronounced and therefore weights assigned to countries are higher for regions that relatively richer at time t in the future. If, on the other hand, regional inequality concerns are larger, i.e., $\gamma > \eta$, the factor Ω_{rt} is smaller than unity for countries that

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[4] This interpretation refers to the distribution of income only between regions, but weighted by the population size. This is what Bourguignon et al. (2006) refers to as 'international distribution of income' or 'Concept 2 Inequality'.

become relatively richer in the future. Given that now regional inequality concerns are more important than intertemporal inequality aversion, a higher weight is given to impacts that occur in regions that are becoming poorer in the future relatively to world average at that point. Moreover, as we decrease γ to zero, we get a smooth transition to the unweighted value ($\gamma = 0$), where only global average per capita consumption is considered and any regional differences are ignored.

3 Inequality within regions

The previous section developed an approach that takes inequality between regions into account when estimating the Social Cost of Carbon. Yet, the regional disaggregation in numerical models is largely an arbitrary choice, and it thus seems equally arbirtrary to ignore any inequality within the regions of a given numerical model. Focusing on countries or individuals as units of observations seems to be more appropriate on these grounds. The argument for using individuals as the unit of observation is easily made: the original idea of a utilitarian welfare function is to aggregate welfare of individuals. The argument for using countries as the unit of observation is less direct. After all, one could argue that country borders are as arbitrary as the regional composition in a numerical model. However, there is a crucial difference: countries typically have institutions that potentially address distributional objectives, whereas supra-national regions typically do not. Moreover, since regions are heterogeneous also in terms of how many countries are comprised into one region, it seems natural to argue that inequality aversion between regions and between countries should be identical. Otherwise, the composition of regions would alter the results, which does not seem consistent. Taking into account inequality this way can essentially be done in a similar fashion as between regions.

Now consider a region r where consumption c_{irt} at date t is distributed according to some distribution $F_{rt}(c)$ where the index "irt" indicates that we implicitly consider individuals (or countries) i within region r at time t. Average per capita consumption in this region is given by $\int c_{irt} dF_{rt}$ where the integral is computed over the domain of $F_{rt}(c_{irt})$. Since we use the same[5] degree of inequality aversion γ between and within

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[5] From a technical point of view, disentangling the two different inequality aversion parameters between and within regions would be relatively straightforward, but does not seem normatively attractive since the units considered are countries in both cases. Note that the standard approach of disregarding inequality between countries within regions amounts to assuming different degrees of inequality aversion.

regions, this simply changes the welfare function (5) to

$$W^{RC} = \sum_{t=0}^{T} P_t \frac{1}{1-\eta} \left(\sum_{r=1}^{R} \frac{P_{rt}}{P_t} \int c_{irt}^{1-\gamma} dF_{rt} \right)^{\frac{1-\eta}{1-\gamma}} (1+\rho)^{-t}, \tag{9}$$

where W^{RC} now takes into account global inequality in general and not merely between regions.

While past and present GDP data are readily available for a large set of individual countries, using forecasts based on historical data for long time horizons is problematic, in particular since small differences in projected growth rates can imply dramatic changes for the estimated inequality between countries. Instead, we show how an aggregate measure of inequality can be equivalently used to characterize inequality within regions. We use forecasts of within region inequality to investigate what effect that inequality has on estimates of the Social Cost of Carbon. While the Gini coefficient of inequality (Gini, 1921) is probably the most widely used measure of inequality, many other proposals have been made in the literature, for example the additively decomposable Atkinson index (Atkinson, 1970) or the family of the generalized entropy indices (Shorrocks, 1980). All of these indices can be traced back to a particular welfare function specification and thus by choosing one of them one implicitly takes on a welfarist judgment. Given that our welfare specification is Utilitarian with an isoelastic utility function, the family of Atkinson (1970)'s inequality indices is the natural choice, as they are derived precisely in that framework.

The Atkinson index of inequality in any region r with a per-capita level of consumption of c_{rt} is defined as

$$I_{rt}(\gamma) = 1 - \frac{c_{rt}^{ede}}{c_{rt}} \text{ where } c_{rt}^{ede} = \left(\int c_{irt}^{1-\gamma} dF_{rt} \right)^{\frac{1}{1-\gamma}} \tag{10}$$

and where γ denotes the degree of inequality aversion between countries.[6] It can be interpreted as the percentage of per-capita income that would provide the same total welfare than the actual income distribution if it were equally distributed. The "equally distributed equivalent level of consumption" c_{rt}^{ede} introduced above can hence be expressed as $c_{rt}^{ede} = c_{rt}(1 - I_{rt}(\gamma))$.

Since typically one does not have individual data on consumption, we assume a particular distribution of consumption within each region. The log-normal distribution

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[6] For the case of logarithmic utility ($\gamma = 1$), c_{rt}^{ede} is calculated as $c_{rt}^{ede} = exp\left(\int ln(c_{irt}) dF_{rt} \right)$.

has been found the preferred distribution to model income or consumption distributions, see Atkinson and Brandolini (2010) and Provenzano (2015). We assume thus that within any region that $c \sim LN(\mu_{rt}, \sigma_{rt}^2)$ where the parameters depend both on the region and point in time. For the log-normal distribution, the Atkinson index is $I(\gamma) = 1 - e^{-0.5\gamma\sigma_{rt}^2}$. Now we can use the definition of V_x in (4) with the difference that now marginal utility in any region is not anymore considered at the per capita level of consumption but rather computed over the full distribution.

Apart from the inequality in consumption, the distribution of impacts from climate change is the second main driver for the social cost of carbon. It is therefore crucial what we assume about the distribution of impacts within the population and we consider two different cases. We denote by d_{irt} the damages or impacts accruing to individual i in region r at time t so that in this region, the total damages can be written as $D_{rt} = \sum_i d_{irt}$.

Firstly, we consider how the evaluation would look like if damages were equally distributed on a per capita basis, that is, where $d_{irt} = D_{rt}/P_{rt}$. However, the damage of climate change are not likely to be evenly distributed between countries or individuals (Tol, 2002; Tol et al., 2004; Kverndokk and Rose, 2008; Yohe et al., 2006). Therefore, we secondly consider a damage function approach where the distribution of damages can be captured by an income elasticity. While the intra-regional distribution of impacts is an ongoing research field (Mitchell et al., 2002; Mendelsohn et al., 2006; Yohe et al., 2006; Gall, 2007; Mendelsohn and Saher, 2011; Burke et al., 2015), reliable estimates on the country level are not yet readily available. However, we can use the the damage function already used at the regional level and apply it on the within-region scale between countries, which is our second approach. We formulate the solution by introducing an adjustment factor Δ_{rt} to correct the total impacts given by D_{rt} used in (7). In the second case, impacts are depending on the consumption level using a damage function approach within regions. Denoting by $d(c)$ a damage function depending on consumption, now the marginal value of damages within each region can be computed as $\int c_{irt}^{-\gamma} d(c_{irt}) dF_{rt}$. Given that we want the total damages to remain unchanged, the adjustment factor needs to be appropriately rescaled, which yields $\Delta_{rt} = \frac{\int c_{irt}^{-\gamma} d(c_{irt}) dF_{rt}}{\int c_{irt}^{-\gamma} dF_{rt} \int d(c_{irt}) dF_{rt}}$. A typical specification for the damage function is an isoelastic function with a constant income elasticity. For instance, the damage functions used in FUND can be written as a function of consumption of the form $d(c_{rt}) \propto c_{rt}^{\alpha}$ where the proportionality depends on the change in mean temperature. The special case of proportional damages ($\alpha = 1$) is frequently used, as in Nordhaus' DICE model.

In the appendix, we show that a very similar mathematical expression to this case can be derived based on specific distributional assumptions about consumption and impacts and their correlation, notably using a bivariate log-normal distribution, which allows for a straightforward calibration.

We now compute the equivalent to the definition of the SCC as in (7) based on the welfare specification (9) and derive analytical solutions. The following proposition summarizes the main result of this paper, where we show for the two different assumptions about the distribution of impacts, how the Social Cost of Carbon can be expressed based on standard regional disaggregated variables by only adding the Atkinson inequality index.

Proposition 1. *The Social Cost of Carbon taking into account inequality of consumption* c_{irt} *and damages* d_{irt} *within regions can be computed as*

$$S^{RI} = \sum_{t=0}^{T}\sum_{r=1}^{R}\left(\frac{c_t^{ede}}{c_0^{ede}}\right)^{\gamma-\eta}\frac{c_{rt}^{-\gamma}}{c_{x0}^{-\gamma}}(1-I_{rt}(\gamma))^{-(\gamma+1)}\Delta_{rt}D_{rt}(1+\rho)^{-t} \tag{11}$$

where Δ_{rt} *captures the distribution of climate change impacts within regions which is given for equal damages and the damage function approach as*

$$\Delta_{rt} = \begin{cases} 1 & \text{if } d_{irt} = d_{rt} \forall i \\ (1-I_{rt}(\gamma))^{2\alpha} & \text{if } d_{irt} \propto c_{irt}^{\alpha} \end{cases}$$

Proof. Consider the first case for $\Delta_{rt} = 1$. Based on the definition of the SCC in (7), the only difference is that the sum of impacts is now considering the full distribution of consumption within regions, i.e., $\sum_{t=0}^{T}\sum_{r=1}^{R}\int \frac{\partial W}{\partial c_{irt}} d_{irt} dF_{rt}$. First, using the welfare specification (9) we can compute the marginal welfare change of one unit additional unit of consumption in region country c of region r as $\frac{\partial W}{\partial c_{irt}} = P_{rt}\left(c_t^{ede}\right)^{\gamma-\eta} c_{irt}^{-\gamma} F'_{rt}(c_{irt})(1+\rho)^{-t}$, where c_t^{ede} represents the global equally-distributed equivalent level of consumption based on the global level of inequality. Using the subgroup decomposability of the Atkinson measure of inequality, it can be written as $c_t^{ede} = \left(\sum_{r=1}^{R}\frac{P_{rt}}{\sum_{r=1}^{R}P_{rt}}\left[c_{rt}(1-I_{rt}(\gamma))\right]^{1-\gamma}\right)^{\frac{1}{1-\gamma}}$, where the definition of $I_{rt}(\gamma)$ is given by (10). Taking the sum over all regions and integrating over each region's income distribution, note that the only term that depends on the distribution within the region is $c_{irt}^{-\gamma}$, so that we can compute its mean value as $\int c_{irt}^{-\gamma} dF_{irt}$. Due to the log-normal assumption about the distribution of consumption, this value can be computed analytically as $\int c_{irt}^{-\gamma} dF_{rt} = e^{-\gamma\mu_{rt}+\gamma^2\sigma_{rt}^2/2}$. From the definition of the Atkinson measure of inequality on the other hand, we have that $(1 - I_{rt}(\gamma)) = e^{-0.5\gamma\sigma_{rt}^2}$, and after several reformulations, one gets that the average marginal utility in region r can be expressed using per-capita consumption c_{rt} and the degree of inequality $I_{rt}(\gamma)$ as $c_{rt}^{-\gamma}(1 - I_{rt}(\gamma))^{-(\gamma+1)}$. Substituting this expression in the definition of $\frac{\partial W}{\partial c_{irt}}$ back in the definition of the SCC in (4), we finally get for the case where $d_{irt} = D_{rt}/P_{rt} \forall i$ (or that $\Delta_{rt} = 1$) the definition of the Social Cost of Carbon as (11). For the second case based on the damage function, we use the same approach but now take into account that $d(c_{rt}) \propto c_{rt}^{\alpha}$. Using the assumption of a log-normal income distribution within each region r, we can along the lines of the first part of the proof compute Δ_{rt} analytically and get in this case that $\Delta_{rt} = (1 - I_{rt}(\gamma))^{2\alpha}$. $\square$

Whether or not in the case with damage function we have that $\Delta_{rt} > 1$ depends on the parameter α. For $\alpha = 0$ we have $\Delta_{rt} = 1$ and are back to the case of constant damages as before. A positive income elasticity implies $\Delta_{rt} < 1$ or that evaluated damages are lower than if they were constant on a per capita basis. By computing the derivative of Δ_{rt} with respect to α, we get $\frac{\partial \Delta_{rt}}{\partial \alpha} = 2(1 - I_{rt}(\gamma))^{2\alpha} ln(1 - I_{rt}(\gamma))$, which is always negative so that the SCC is always decreasing in α if damages are non-negative ($D_{rt} \geq 0 \forall r, t$ would be sufficient), or at least not “too” positive over the time horizon.

Besides the effect through the adjustment factor of impacts Δ_{rt}, inequality affects the social cost of carbon also through the term depending on $I_{rt}(\gamma)$ in (11). One particular case, however, leads to both effects to exactly cancel each other so that considering inequality within regions does yield the exact same value for the SCC as the standard definition in (8): if $\gamma + 1 = 2\alpha$ holds (and $\gamma = \eta$ or that no disentangled welfare function is used)[7], inequality aversion and the elasticity of damages are such that inequality does not matter for the SCC. For instance, with the specification $\gamma = 1$ and $\alpha = 1$, this condition is satisfied and we have that the SCC based on regional aggregates is identical to the one if one where to consider the intra-regional distribution. This result could be used as a justification for the standard approach used in integrated assessment models. Finally, one can observe that the SCC in the second case is only affected by α through the term $(1 - I_{rt}(\gamma))^{2\alpha-(\gamma+1)}$. That is, any combination of γ and α leading to the same exponent of this term will lead to the identical value for the social cost of carbon.

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[7] Otherwise, the equally distributed equivalent level of consumption is still different due to income inequality across regions. For the reasonable case of $\eta > \gamma$, the first term on the right-hand side of (11) is smaller than one if the certainty-equivalent level of consumption increases over time, so that the equivalence will be reached at a lower value of α.

To sum up, Proposition 1 provides formulas for the marginal social cost of emissions evaluated in region x taking into account income inequality between and within regions. Moreover, inequality aversion between regions and countries (γ) and intertemporal inequality aversion (η) are now separate parameters of the model. The classical case given by (3) is obtained by choosing $\gamma = \eta$ and a degenerate distribution for F_{rt}. From the point of data requirements, only data on consumption inequality for each region as measured by the Atkinson index is needed in order to compute the Social Cost of Carbon. This model is therefore particularly useful in order to examine the sensitivity of standard estimates of the Social Cost of Carbon with regard to the spatial resolution employed and the restrictiveness of preferences of inequality aversion.

4 Inequality Data

The measurement of inequality involves several important analytical considerations to be clarified. First, three different concepts of inequality at the global level have been distinguished (Milanović, 2005). The first concept, often called international inequality, refers to inequality between countries where each country is represented by a single observation independent of its population size. The second concept, between-country inequality or population-weighted inequality, considers inequality between countries using population weights ("Concept 2"). The third concept, global inequality, reflects inequality among world citizens taking all world citizen as individual observations. In this paper, the second concept is the appropriate one, given that we use country level data and don't consider within-country inequality. Moreover, since the aggregation for the computation of the Social Cost of Carbon considers impacts for all individuals, the population weights should be used as in concept two.

Over the last decades, inequality[8] has decreased mainly, but not exclusively, due to the high economic growth rates in China. Inequality continued to decline after the year 2000, even if we exclude China. One reason for this convergence in terms of "Concept 2" inequality is the relatively high growth rate of India over the last decade. Yet, convergence in this sense also occurred in other world regions (Sala-I-Martin, 2002). It is noteworthy that the trend for global inequality according to the third concept is less clear due to a potential increase of inequality within countries due to increasing skill premia differentials (Sala-I-Martin, 2006). However, since we are interested only in cross-country inequality here, we can abstract from this issue. In this paper and

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[8] In the following, we always use the concept of "Concept 2" inequality for inequality measures.

the context of global climate change policies, it is in particular the differences between countries that is relevant: Firstly, national tax and transfer schemes are arguably more efficient in implementing a desired, if not optimal, income distribution than climate policy. Secondly, national policies are likely to be implemented in order to achieve a somehow fair sharing of the costs of abatement policies within countries. Therefore it seems a meaningful first step to focus on inequalities between countries.[9]

Besides the different definitions of global inequality, a second conceptual issue is the choice of the measure of inequality. While the arguably most widely used measure is the Gini-coefficient, other measures include the Atkinson index, the Theil index, the coefficient of variation, or the variance of log income[10], and others, as well as certain ratios of different percentiles of income (e.g., the decile or quintile ratio). Many of the indices can be linked to an implicit welfare specification. Since in the context of integrated assessment modeling the isoelastic utility function is virtually omnipresent, we use the Atkinson family of inequality indices $I(\gamma)$.[11] Moreover, this index satisfies subgroup-decomposability so we can easily decompose inequality between and within world regions. Historically, the evolution of the different indices of inequality over time has been remarkably similar for the Gini, Atkinson, and Generalized entropy indices so that this choice, while allowing consistency from a welfare perspective, does not seem to limit the interpretations of the results. Figure 1 shows the evolvement inequality since 1990.[12]

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[9] Adding within-country inequality to the picture would be straightforward based on equation (9). However, we leave this extension for future research. Dennig et al. (2015) develop a first attempt in this direction.

[10] Note that these three indices are special cases of the class of the Generalized entropy index

[11] As we explain in the subsequent section reviewing the literature, we use a parameter of $\gamma = 0.7$ when reporting this index throughout this section.

[12] Data source: World Development Indicators 2015 for 147 countries, PPP-adjusted GDP in constant international US-$ of 2011.

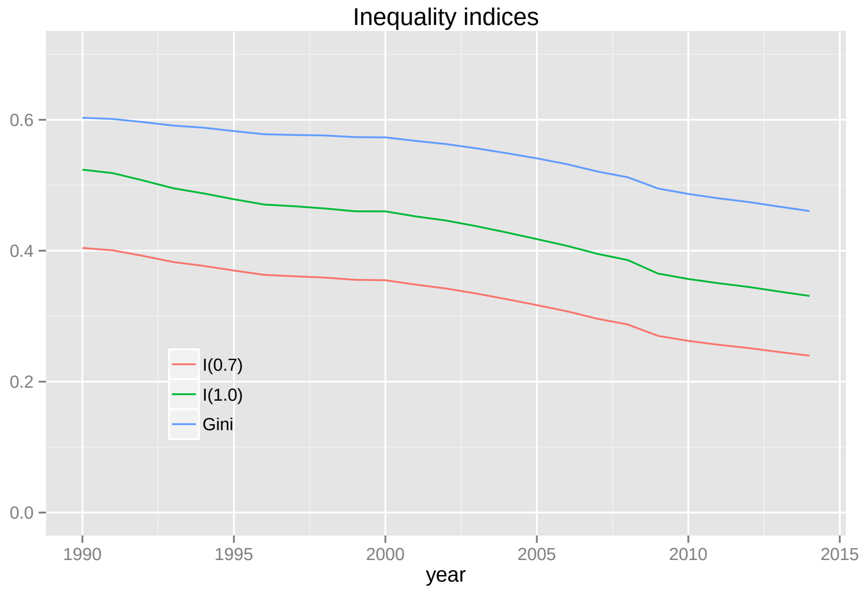

Figure 1: Global inequality between countries, 1990-2014.

A third important conceptual issue is the conversion of national currency data in order to compare income or consumption levels between countries. For inequality considerations, the use of PPPs seems more appropriate since it takes into account the different relative price levels across countries and thus describes relative standards of living across countries more accurately. If one wants to make claims about the welfare people get from their incomes, these should be adjusted for purchasing power because people get welfare from consumption, and consumption is purchased at the prices paid in their country of residence (Sala-I-Martin, 2002). Since at market exchange rates a large number of non-tradable goods are relatively less expensive in developing countries, using nominal or market exchange rates would overstate the (current) degree of inequality between countries compared to the measurements using PPPs. For the model simulations considered in this paper, it is noteworthy that while RICE is based on PPPs, FUND uses market exchange rates.[13] Therefore we use the respective exchange rate concept for each model, noting that this will have a impact on the measurement of inequality and its impact on the results. However, this can also provide a means of comparing both approaches and highlight the differences between both approaches. The following Table 1 summarizes the regional inequality indices computed for the regions that are used in both integrated assessment models used in this paper (RICE and

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[13] See Tol (2006) for a further discussion on the role of exchange rates in this context.

FUND) for the year 2014:

FUND Region	$I(0.7)$	$Gini$	$GDP(pc)$
United States of America	0.000	0.000	51011$
Canada	0.000	0.000	35810$
Western Europe	0.004	0.052	34772$
Japan and South Korea	0.021	0.099	29887$
Australia and New Zealand	0.000	0.000	43219$
Central and Eastern Europe	0.022	0.136	12767$
Former Soviet Union	0.147	0.295	14313$
Middle East	0.073	0.226	19932$
Central America	0.047	0.144	10755$
South America	0.024	0.099	12250$
South Asia	0.024	0.108	3063$
Southeast Asia	0.075	0.191	9739$
China plus	0.030	0.055	7710$
North Africa	0.019	0.113	7280$
Sub-Saharan Africa	0.240	0.457	2841$
Small Island States	0.066	0.148	9966$
World	0.240	0.461	14317$

RICE Region	$I(0.7)$	$Gini$	$GDP(pc)$
US	0.000	0.000	51011$
OECD-Europe	0.004	0.052	34772$
Japan	0.000	0.000	33916$
Russia	0.000	0.000	21664$
Non-Russia Eurasia	0.103	0.279	8841$
China	0.007	0.016	8011$
India	0.000	0.000	2987$
Middle East	0.075	0.227	19845$
Africa	0.241	0.468	3570$
Latin America	0.032	0.119	11806$
OHI	0.055	0.215	30957$
Other non-OECD Asia	0.155	0.341	6059$
World	0.240	0.461	14317$

Table 1: Inequality indices and GDP per capita in USD (2011, PPP) for FUND and RICE regions in 2014

One observation is that the inequality within most regions is lower than on the global level. This results from the fact that the modeling regions are mostly chosen as to reflect some degree of geographic and economic similarity. Moreover, there is quite some heterogeneity across regions. While the global picture shows strong convergence since the 1980s, the regional patterns differ substantially. While inequalities decrease in Western and Eastern Europe, between Japan and South Korea as well as in North Africa, this does not hold true for all regions. In particular, divergence has occurred within Sub-Saharan Africa, the Middle East, South East Asia and the Small Island States. Overall, inequality across regions is very high considering the per-capita GDP of between about 2.000 USD and 40.000 USD.

In order to introduce inequality into the calculation of the Social Cost of Carbon, we need to make assumptions about inequality in the future. Notably, we need per-country GDP and population projections to derive “Concept 2” inequality measures. Here, we make use of the inequality prediction that has been produced for a large-scale exercise of socioeconomic projections. The so-called Shared Socioeconomic Pathways (SSPs) have been developed as a reference to explore the long-term consequences of climate change and the climate policy strategies (Moss et al., 2010). This process started with the definition of five story lines describing five very different, but still reasonable "futures" in terms of global and regional developments of technological progress, market developments, convergence, and population dynamics. These five scenarios provide within itself consistent future developments that include scenarios of low economic and population growth, different income inequality dynamics, and of high growth and divergence in terms of population growth and economic development. Based on these five story lines, population and GDP projections have been developed by the International Institute of Applied Systems Analysis (IIASA) (KC and Lutz, 2015) for the population projections and the OECD for the GDP scenarios (Crespo Cuaresma, 2015). The scenario SSP2 is characterized as "middle of road" scenario, so that in this paper we will consider the inequality evolvement based on this scenario. Comparing the implications in terms of income inequality, the results can be broadly seen in line with the few studies that try to project convergence: the results of Bussolo et al. (2008) using a CGE model to assess convergence in the future suggest that until 2030, inequality indeed decreases. Sala-I-Martin (2002) also estimated that convergence is continuing due to the catch-up of several poorer countries while at some point inequality could level off or even start to rise again.

This continued convergence is reflected in the regional baseline projections used in most of climate change models. The assumptions about regional economic growth implicit in the FUND and RICE model already imply significant convergence across regions. Figure 2 summarizes the predictions of inequality over the 21st century[14] according to both models between the respective model regions (dashed lines). Moreover, using the SSP2 inequality predictions within the model regions, we compute the global inequality for both models and compare it to the global inequality implied by the SSP2 (solid lines).[15]

First, note that in FUND the computed inequality is much higher due to the use of market exchange rates (MERs). Second, even between RICE and the SSP2 country-level data, inequality measures are slightly different due to different data sources and near-term projections of regional GDP. We explicitly do not harmonize the assumptions

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[14] The projections of the SSPs extend until the year 2100. Since the modeling time horizons of the IAMs go up to the year 2300 with a stylized GDP modelisation after 2100, we assume that inequality within regions remains constant after the year 2100.

[15] All indices are based on consumption per capita. For the SSP2, which predicts only GDP, we assume a constant savings rate of 20%.

here in order to keep the models' characteristics. Therefore, the notable feature that we introduce in the models is a significant convergence between countries over the 21st century. Comparing inequality between and within regions, one sees that considering country inequality adds about 0.05 to the Atkinson index. That is, the strong speed of convergence is mainly captured by the difference in growth rates between industrialized and developing country groups or regions.

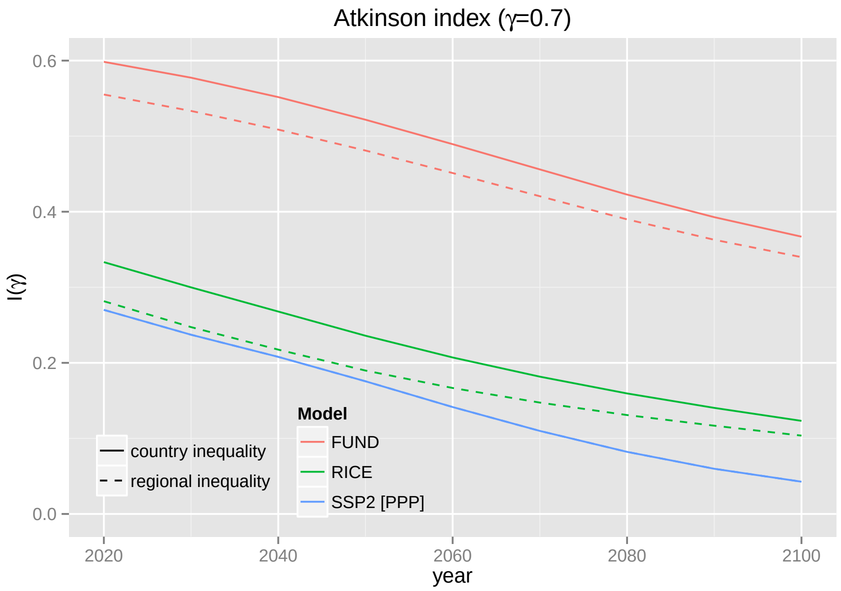

Figure 2: Worldwide inequality measured by $I(0.7)$ between regions and all countries

Based on these inequality projections, we can compute the "equally distributed equivalent" (EDE) and compare it to the per-capita GDP values. Figure 3 shows both per-capita consumption and the EDE level of consumption taking into account global inequality at the country level.[16] Overall, there is a significant growth projected although at a decreasing rate. The predicted convergence further increases the EDE over time. However, it should also be emphasized that these results are based on projections. In particular, they rest on the strong assumption regarding convergence between world regions, which is maintained in most of the applied literature. Still, it provides an educated guess different from simplistic assumptions about the total disappearance or aggravation of inequalities. We therefore use this benchmark scenario in the numerical analysis to compute the social cost of carbon.

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[16] The difference between the SSP2 and RICE on the one hand and FUND on the other reflects again the fact the MERs are used within FUND.

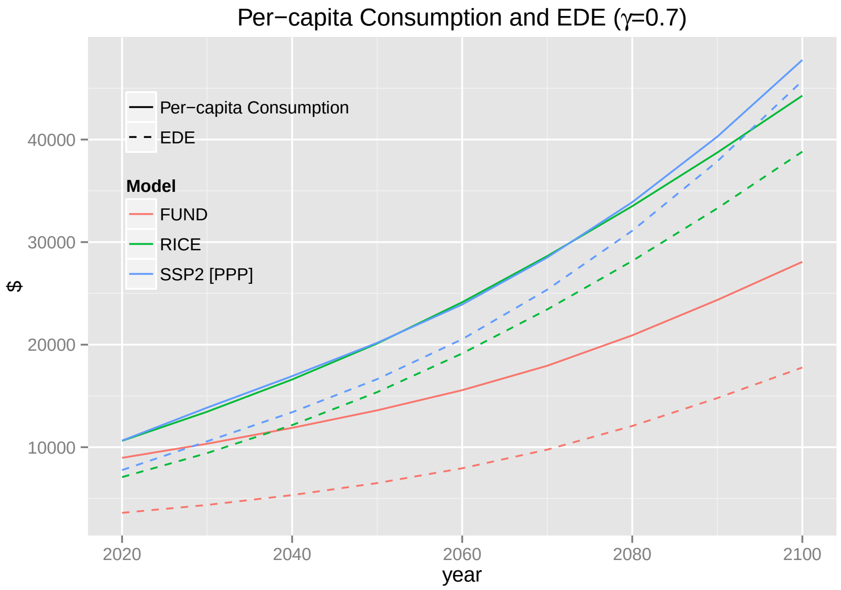

Figure 3: Per-capita Consumption and EDE based on global inequality

5 Numerical models and preference calibration

In order to implement the analytical formula derived above, we use two widely used integrated assessment models to estimate the Social Cost of Carbon, namely FUND 3.9 and RICE 2010.

The FUND model (Climate Framework for Uncertainty, Negotiation, and Distribution) was created primarily to estimate the impacts of climate policies in an integrated framework. It takes exogenous scenarios of important economic variables as inputs and then perturbs these with estimates of the cost of climate policy and the impacts of climate change. The model has 16 regions and contains explicit representation of five greenhouse gases. Climate change impacts are monetized and include agriculture, forestry, sea-level rise, health impacts, energy consumption, water resources, unmanaged ecosystems, and storm impacts. Each impact sector has a different functional form and is calculated separately for each of the 16 regions. The model runs from 1950 to 2300 in time steps of 1 year. The source code, data, and a technical description of the model are public and open source (www.fund-model.org), and the model has been used by other modeling teams before (e.g., Revesz et al. (2014)).

The RICE model is the regional version of Bill Nordhaus' DICE integrated assessment model. RICE divides the world into 12 regions, and models each region as a closed Ramsey-Koopmans economy. CO_2 emissions are a by-product of production of the final good. The model contains a simple carbon cycle and climate component that drive damage functions for each region. There is one damage function for each region that estimates aggregate impacts in that region as a function of global average temperature. The model runs from 2005 to 2595 in time steps of 10 years. We use the 2010 version of RICE that is described in Nordhaus (2010). The model is also open source and can be downloaded from Nordhaus' webpage.

One crucial assumption when running the models to compute the SCC is the parametrization of the preference parameters discussed in the theory sections. For the rate of pure time preference ρ, we use a central value of 1.5% per year and present a sensitivity analysis that encompasses the range of values used in other studies of climate change. While some philosophers and economists argue in favor of a pure rate of time preference of (almost) 0% as in the Stern (2006) review, many economists would support higher rates e.g., Arrow et al. (1996). Our main justification for 1.5% as a central value is that in combination with our central choice of the elasticity of intertemporal substitution, interests rates in RICE roughly match observed interest rates, see Nordhaus (2010). In addition, we keep the default parameterization of RICE with this choice, and thus focus on the effect of regional inequality aversion alone[17].

For the inverse of the elasticity of intertemporal substitution η, the literature on discounting and climate change has virtually never considered values less than 0.7 or larger than 2. In this section, we choose the value of 1.5 to make the results comparable to previous studies based on RICE. Using a lower value for η together with a higher value of ρ would yield a similar consumption discount rate and hence similar results. Moreover, using a higher value like $\eta = 2$ would even strengthen our argument that η and γ should be disentangled: while such a high value would be in line with previous choices for the inverse of the elasticity of inter-temproal substition, it would imply implausibly high regional inequality aversion (see below). Together with the region-specific growth rate, the two parameters ρ and η determine the (implicit) consumption discount rate used within each region.

Regarding the value of regional inequality aversion γ, Pearce (2003) suggested values between 0.5 and 1.2 in the context of climate change. In a recent study based on official development assistance between countries, Tol (2010) estimated γ to be around 0.7. The U.S. Census Bureau (2010) considers values only between 0.25 and 0.75 for inequality measurement in the United States. Moreover, as pointed out by Tol (2005),

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[17] FUND does not have a default central value for the pure rate of time preference.

the industrialized countries do not reveal as much concern for the poor as is implied by the equity weights using higher values of γ. Overall, the literature suggests lower values for γ than for η, and most likley values less than unity. This is in line with the results of Atkinson et al. (2009) who, based on a survey, find that individuals typically have a lower value of γ than η. Therefore, a value equal or even larger than one for γ seems hard to justify and we consider a baseline value of $\gamma = 0.7$.

6 Results

In the following we compute the Social Cost of Carbon with and without regional inequality considerations and for different parameter specifications. All results are shown in 2014 U.S. Dollars. The main results use the U.S. as the reference region when converting from utility to a monetary metric. These results are therefore directly comparable with present-value US mitigation costs, but cannot be directly compared to mitigation costs in other regions. This would either require a further conversion or the choice of a different reference region in the first place.[18] We revisit the choice of reference region in the sensitivity analysis that is discussed later.

Figure 4 shows the SCC for the standard equity weighting case (equation 3) and our disentangled approach (equation 8) for different levels of inequality aversion. The standard case is shown in blue where regional and intertemporal inequality aversion are identical, i.e. a higher regional inequality aversion also implies a higher intertemporal inequality aversion. The green line shows the disentangled case. Here, only regional inequality aversion is varied, and intertemporal inequality aversion is kept constant at $\eta = 1.5$. The SCC is highly non-linear in inequality aversion for both specifications. In the standard case, regional and intertemporal inequality aversion are linked, and the net effect of higher inequality aversion is thus ambiguous: higher intertemporal inequaliy aversion will decrease the Social Cost of Carbon through a higher consumption discount rate, but higher regional inequality aversion will increase the SCC because impacts in poorer regions now receive more weight in the SCC. This explains the U-shaped curve in RICE for the standard equity weighting case: for low γ values, the effect of γ on the discount rate is stronger than on the equity weights, whereas the reverse is true for higher values of γ. For the disentangled case, the effect of regional inequality aversion is monotonic: higher regional inequality aversion always leads to a higher SCC since now

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[18] The choice of reference region does not change any cost-benefit analysis results when we apply the same reference region in all cases when computing equity weighted results.

only the equity weighting is changed whereas intertemporal inequality aversion (and thus the discount rate) is held constant. Note that if a poor region is chosen as the reference region, this effect goes in the opposite direction, i.e. the SCC would decrease monotonically in regional inequality aversion.

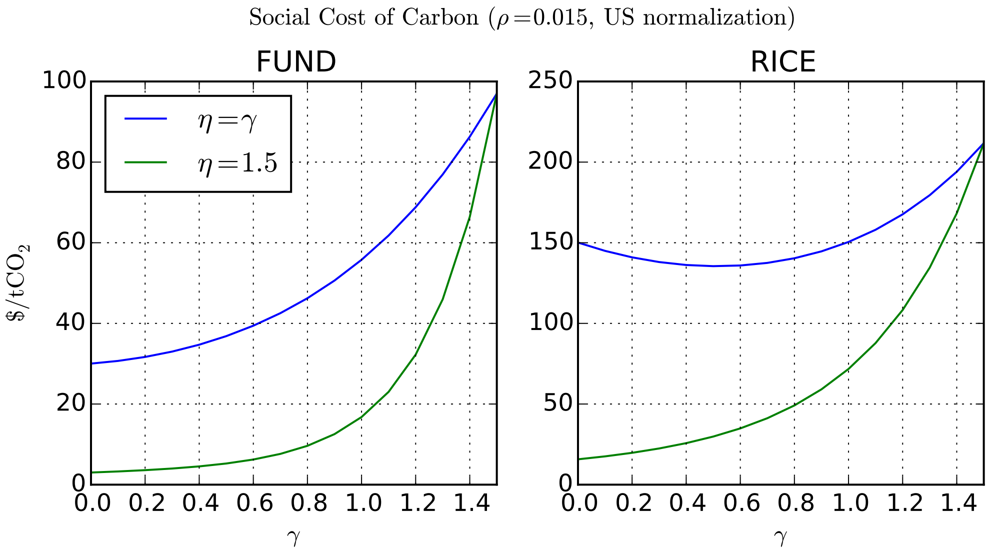

Figure 4: Social Cost of Carbon for different levels of regional inequality aversion

So far, we only considered inequality between the regions of the numerical models. Now we consider inequality between all countries between and within each model's regions. We combine this with different assumptions about the income elasticity of impacts and compute the SCC according to (11). Maintaining our central value of $\gamma = 0.7$, Figure 5 presents the SCC for different values of the income elasticity of damages α (where $\alpha = 0$ corresponds to the case of $\Delta_{rt} = 1$). The figure shows three distinct cases: a) no inequality, b) inequality only between model regions, but perfect equality within each model region, and c) inequality between countries. The no inequality cases corresponds to a standard efficiency analysis that ignores income differences between regions, whereas the regional inequality case corresponds to the previous figure. The no inequality and regional inequality cases are independent of α since α only determines how damages are allocated along the income distribution within a region. First, note that considering inequality significantly increases the SCC, roughly by a factor of 2-3. The difference between values based on regional inequality and country inequality are comparably small for our calibration. As expected from the results in section three, the SCC is moreover decreasing in the value of α. For each model there is some value ofα for which the SCC based on regional and country inequality coincide.

With regard to the choice of the parameter α, so far very few studies have been undertaken. In Anthoff and Tol (2012) the values of the computed income elasticities vary between -1 and $+3$ with a mean of 0.99. The average values within each region however lie almost all in the range 0.9 to 1.3. Considering a value of α close to unity thus seems a reasonable assumption, so that considering within-region inequality will lead to a reduction of the SCC, albeit a comparable small one. For larger values of α, we obtain a lower Social Cost of Carbon than when impacts are equally distributed. The reason for this effect is that absolute impacts are higher in richer countries (for instance for $\alpha = 1$ where impacts relative to income are constant). Due to the equity considerations, however, these impacts are given a lower weight leading to a lower value for the SCC. Overall, the inclusion of country inequality is a second-order effect for the SCC, while the consideration of inequality and disentanglement of preferences has a first-order effect.[19]

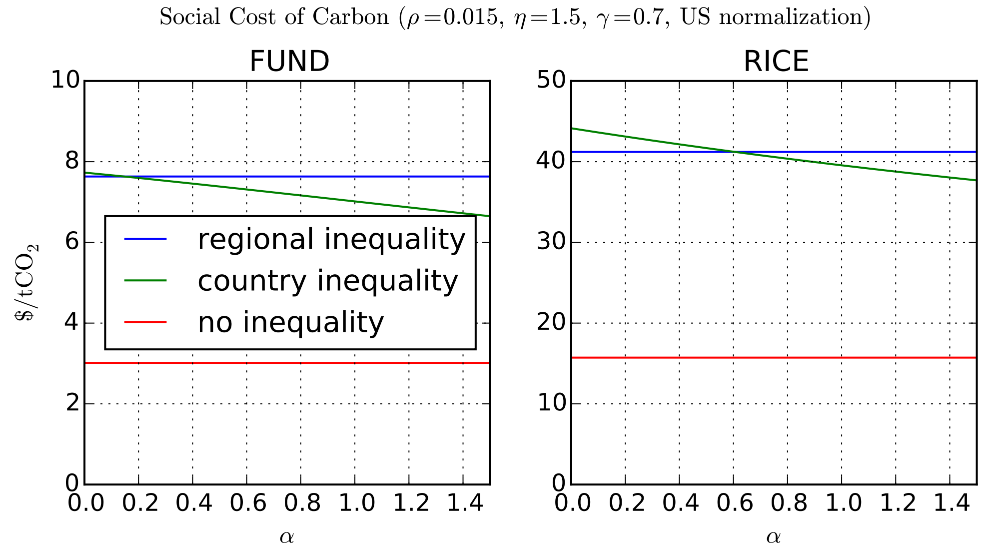

Figure 5: Social Cost of Carbon with inequality at the country level

So far we reported all SCC values using the U.S. as reference region. Figure 6 shows results for the other model regions as reference regions. Notably, for the case without

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[19] Note that as a special case, as discussed before, for $\alpha = 1$ and $\eta = \gamma = 1$, the SCC estimates with and without considering the distribution of consumption and impacts within regions will exactly be equal.

regional inequality aversion ($\gamma = 0$), the choice of reference region makes no difference for the SCC. For higher levels of regional inequality aversion, the SCC estimate increases for high income regions and decreases for low income regions, see Anthoff et al. (2009a) or Nordhaus (2011). Earlier studies were not able to show the effect of an increase of γ on the spread of SCC estimates between different reference regions, because any change in regional inequality aversion also changed the discount rate in these earlier studies. With our disentangled specification, the spread between regions increases non-linearly in the degree of regional inequality aversion γ. Nevertheless, for values of γ that we consider in this paper, the spread between different reference regions is much smaller than the spreads reported in Hope (2008), Anthoff et al. (2009a) or Nordhaus (2011). The main reason for this difference is that these studies had to make a choice of either picking a degree of regional inequality aversion higher than the literature suggests (so that their intertemporal inequality aversion is reasonable), or choosing a degree of intertemporal inequality aversion lower than the literature suggests, but achieving a reasonable degree of regional inequality aversion. In particular, the value of intertemporal inequality aversion used in most studies has been considerably higher than the values of intra-regional inequality aversion suggested by the literature above. With the disentangled SCC formulation in this paper, one can simultaniously choose reasonable numbers for both types of inequality aversion, which leads to a potentially smaller spread between different reference regions compared to earlier studies.

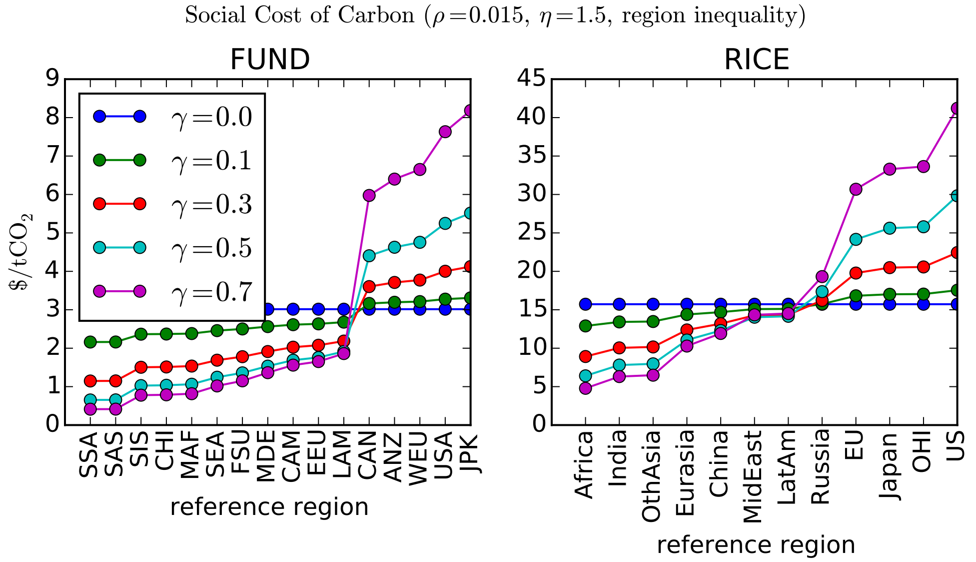

Figure 6: Social Cost of Carbon for different reference regions

Due to the long time horizon of climate change, one crucial parameter for the evaluation in a CBA framework is the pure rate of time preference. Besides our base value of $\rho = 1.5\%$, we compute the SCC also using a very high and very low value.[20] Table 2 shows the corresponding SCC values. As expected, a lower discount rate leads to a (much) higher value of the SCC in general. Concerning the relative impact of country and regional inequality[21], the relative sizes are similar in all three cases.

ρ	FUND		RICE	
	$\gamma = 0$	$\gamma = 0.7$	$\gamma = 0$	$\gamma = 0.7$
0.001	15.5	43.6	63.1	157.1
0.015	3.0	7.6	15.7	41.2
0.03	0.3	-0.6	6.6	18.0

Table 2: Social Cost of Carbon for different pure rate of time preference rates (regional inequality for $\gamma = 0.7$)

To sum up our main results in Table 3, we take as a starting point the models' default SCC value, which is obtained without considering regional inequality using our baseline specification with $\rho = 1.5\%$ and $\eta = 1.5$. In this case, the Social Cost of Carbon is computed for FUND at 3\$ and for RICE at about 16\$ per ton of CO_2, which are in the range of the values computed e.g. in U.S. IAWG (2010) for policy making in the United States. Taking into account inequality across regions based on the disentangled welfare function with $\gamma = 0.7$, these values increase to about 8\$ and 41\$. Finally, taking into account also inequality within regions has a minor impact and slightly reduces the SCC. For our preferred specification of $\{\rho = 1.5\%, \eta = 1.5, \gamma = 0.7, \alpha = 1\}$, we finally obtain SCC values of $7.0\$/tCO_2$ for FUND and $39.5\$/tCO_2$ for RICE. The small effect of considering also within-region inequality indicates that a sufficiently large and well-chosen set of regions allows to account for most of the effect due to income and impact disparities at the global level. Moreover, it is noteworthy that while the absolute values are rather different between the two different models, the relative effects of inequality at different levels are very similar in both models.

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[20] Note that using different values for ρ implies different region-specific consumption discount rates since we maintain $\eta = 1.5$ in all cases. The range of plus/minus 1.5 percentage points we consider is however relatively small so that the resulting discount rates can be justified.

[21] Since we saw that the difference between the case with and without within-region inequality is very low, we only report the case with regional inequality.

	parameter specification	FUND	RICE
model base value	$\eta = 1.5$, $\rho = 0.015$	3.0	15.7
disentangled inequality aversion	and $\gamma = 0.7$	7.6	41.2
and country inequality	and $\alpha = 1.0$	7.0	39.5

Table 3: Social Cost of Carbon estimates in US-\$ (2014), main results

7 Conclusion

In this paper we discuss the role of inequality aversion and how it can be integrated in the computation of the Social Cost if Carbon. We extend previous results by disentangling regional inequality aversion from intertemporal preferences. Moreover, we show how inequality between countries can be considered even using more aggregated numerical models. The disentanglement of preferences is crucial to separate equity effects from the discount rate, whereas previous equity-weighted results were characterized by a fixed link between regional inequality aversion and the consumption discount rate. When considering intra-regional inequality, we moreover consider that impacts are not equally distributed, but rather consider the income elasticity of impacts in order to take into account regional differences.

We derive an analytical formula for the Social Cost of Carbon with inequality considerations and use two well-known integrated assessment models, RICE and FUND, in order to numerically compute the resulting values for the SCC. The results confirm that equity-weighting significantly affects the results, and hence that equity is a prime concern in climate policy. However, the exact implementation is crucial and in particular the parametrization of inequality aversion can give rise to misleading results.

For the value of the Social Cost of Carbon, we find that equity weighting increases the estimated value, even though for a reasonable value of $\gamma = 0.7$, the effect is less pronounced than in previous studies. Taking into account differences between countries rather than regions, this effect is slightly reduced due to a reduction in the speed of convergence when considering individual countries. For our baseline specification, we get for RICE (and FUND) a base value for the SCC of 15.7(3.0)\$. With the disentangled inequality aversion formula, this value increases to 41.2(7.6)\$. Taking into account also within-region inequality, this value decreases slightly to 39.5(7.0)\$ per ton of CO_2.

Intuitively speaking, our findings reconcile the results that equity weighting implies a higher SCC as in Fankhauser et al. (1997), Tol (1999) or Anthoff et al. (2009a) with the view that due to convergence, considering inequality should give rise to a higher discount rate and thus a lower SCC as in Hope (2008), Gollier (2015) or Nordhaus (2011), or in the famous Schelling (1995) conjecture.

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Appendix A: The bivariate lognormal case

As discussed in the main text, an alternative way of deriving the results of this paper based on the income elasticity of damages approach is modeling the dependence structure between income and climate change impacts, which can be represented using measures of dependence of the two distributions such as the correlation coefficient. Specifying the distribution of climate change impacts and correlation with consumption, this allows a parsimonious specification based on available data sets on distributions of impacts, consumption and their correlation to include distributional issues into integrated assessment models. In particular, a specifying a bivariate log-normal distribution of income and impacts from climate change point in time t and in any region r seems like reasonable approximation allowing for different degrees of dispersion of impacts. Most importantly, the relatedness of consumption and damages is captured by a single parameter ρ_{rt}. From a methodological viewpoint, this specification is similar to the modeling of an asset which is correlated with consumption as in the Consumption-CAPM model in Finance, see e.g., Cochrane (2005), from which be borrow the methodology in this case.

That is, we consider a joint distribution of consumption and damages within regions. In particular, consider a bivariate log-normal distribution of income and impacts from climate change as

$$(c_{irt}, d_{irt}) \sim LN\left(\mu_{c_{rt}}, \mu_{d_{rt}}, \sigma^2_{c_{rt}}, \sigma^2_{d_{rt}}, \rho_{rt}\right)$$

at any point in time t and in any region r. While being very reasonable for consumption, note that this assumption precludes negative impacts, i.e., beneficial effects to accrue within this given region. Still, the assumption allows for fat tails and different degrees of dispersion of impacts. This assumption allows to capture the relationship between consumption and damages by a single parameter, similar to the Consumption-CAPM model in Finance. Based on this distributional assumption, we can compute the average marginal utility of damages analytical using a similar definition of Δ_{rt} in the analogue for the result of Proposition 1. After several reformulations one can then show that we can derive the term Δ_{rt} as follows:

$$\Delta_{rt} = e^{-\gamma \rho_{rt} \sigma_{d_{rt}} \sigma_{c_{rt}}} = e^{-\gamma Cov(log c_{irt}, log d_{irt})} = (1 - I(\gamma)_{rt})^{2\rho_{rt}\sigma_{d_{rt}}/\sigma_{c_{rt}}}. \qquad (12)$$

This factor is greater than one if the correlation between impacts and consumption is negative and vice versa. Having data on the national level or even on a finer resolution, one can estimate Δ_{rt} using the distribution and correlation structure estimated from this data.[22] Comparing this formula with the one of Proposition 1, one can easily see that in

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[22] Based on estimates of regional impacts and income or consumption data, Δ_{rt} can easily be estimated based on their correlation and first and second moments as $\Delta_{rt} = (Corr(c_{crt}, d_{crt}) CV(c_{crt}) CV(d_{crt}) + 1)^{-\gamma}$.

the second case of a damage function with elasticity parameter α, the two approaches lead to exactly the same results for $\alpha = \rho_{rt}\sigma_{d_{rt}}/\sigma_{c_{rt}}$. That is, this specification allows a more flexible form for estimating both the dispersion and correlation with consumption of damages than the income or consumption elasticity case, while in the end leading to the same model. Also, it can be easily seen that it collapses to the second case based on a damage function with constant relative damages ($\alpha = 1$), if we specify (the logarithm of) damages and consumption with equal variances and a perfect positive correlation. Finally, we get back to the case of equal damages ($\Delta_{rt} = 1$) if consumption and damages are uncorrelated ($\rho_{rt} = 0$).