

TI 2013-130/VIII
Tinbergen Institute Discussion Paper



Modified Ramsey Discounting for Climate Change

Richard S.J. Tol

University of Sussex, United Kingdom; Faculty of Economics and Business Administration, VU University Amsterdam, and Tinbergen Institute, The Netherlands.

Tinbergen Institute is the graduate school and research institute in economics of Erasmus University Rotterdam, the University of Amsterdam and VU University Amsterdam.

More TI discussion papers can be downloaded at <http://www.tinbergen.nl>

Tinbergen Institute has two locations:

Tinbergen Institute Amsterdam
Gustav Mahlerplein 117
1082 MS Amsterdam
The Netherlands
Tel.: +31(0)20 525 1600

Tinbergen Institute Rotterdam
Burg. Oudlaan 50
3062 PA Rotterdam
The Netherlands
Tel.: +31(0)10 408 8900
Fax: +31(0)10 408 9031

Duisenberg school of finance is a collaboration of the Dutch financial sector and universities, with the ambition to support innovative research and offer top quality academic education in core areas of finance.

DSF research papers can be downloaded at: <http://www.dsf.nl/>

Duisenberg school of finance
Gustav Mahlerplein 117
1082 MS Amsterdam
The Netherlands
Tel.: +31(0)20 525 8579

MODIFIED RAMSEY DISCOUNTING FOR CLIMATE CHANGE

Richard S.J. Tol^{a,b,c,d}

^a *Department of Economics, Jubilee Building, University of Sussex, Falmer, BN1 9SL, United Kingdom, r.tol@sussex.ac.uk*

^b *Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands*

^c *Department for Spatial Economics, Vrije Universiteit, Amsterdam, The Netherlands*

^d *Tinbergen Institute, Amsterdam, The Netherlands*

3 September 2013

Abstract

The Ramsey rule for the consumption rate of discount assumes a transfer of money of a (representative) agent at one point in time to the same agent at another point in time. Climate policy (implicitly) transfers money not just over time but also between agents. I propose three alternative modifications of the Ramsey rule to account for this. Taking the Ramsey rule as given, I derive an intuitively clear but ad hoc modification. Using the assumptions underlying the Ramsey rule, I derive a consistent but more elaborate modification. If the discount rate is differentiated by victim, the consistent modified Ramsey rule is simpler and identical to regional equity weights. I apply the modified Ramsey rules to estimates of the marginal damage costs of carbon dioxide emissions. The results confirm that optimal climate policy has differentiated carbon taxes. Results also show that the standard Ramsey rule drastically underestimates the social cost of carbon.

Key words

Climate change, social cost of carbon, discount rate, Ramsey rule, equity

JEL Classification

H43, D63, Q54

1. Introduction

Climate change is a long term problem. The discount rate is therefore a crucial parameter in any economic assessment of the options for climate policy (Arrow et al. 1996). The discount rate is typically set by the Ramsey equation (Ramsey 1928), which has three parameters: the rate of pure time preference, the rate of risk aversion, and the growth rate of per capita consumption. The discussion on the rate of pure time preference has been voluminous (Arrow et al. 2013; Nordhaus 2007; Pearce et al. 2003; Stern 2008), but the

rate of risk aversion attracted less attention in the context of climate change (Anthoff et al. 2009b;Anthoff et al. 2009c;Weitzman 2007). The per capita growth rate has been largely ignored in setting the appropriate discount rate for climate policy. This paper argues that it should not be.

Ramsey discounting is typically introduced as follows. To an individual, \$100 in ten years time is worth less than \$100 today because (1) she is impatient and (2) she expects to be richer in 10 years time. Income growth is evaluated at the margin by the product of the growth rate of monetary income and the curvature of the utility function. Income growth is thus transformed into utility growth. This measures how much we appreciate additional income. To a society, the arguments are the same, but then for an appropriately representative agent.

In the reasoning behind Ramsey discounting for individuals, money is hypothetically transferred from the present self to a future self. For societies, the transfer is from a representative agent at present to a representative agent in the future.¹ The question “who does this agent represent?” is ignored. There is an implicit assumption that the givers and receivers of the transfer are efficiently, equitably or randomly spread among the population.

This implicit assumption is completely wrong for climate policy. International agreements clearly state that the rich should take the lead in (paying for) greenhouse gas emission abatements (United Nations 1992). All empirical evidence has that the poor would suffer most from climate change and hence benefit most from mitigation (Tol 2009). Therefore, a hypothetical agent who represents mitigation effort is very different from an agent who represents climate change impacts. Put differently, we do not invest in greenhouse gas emission reduction for the sake of our children and grandchildren, but rather for the sake of the children and grandchildren of the current poor (Schelling 1992;Schelling 2000). This paper considers the implications for Ramsey discounting and hence for climate policy.

There is not a lot of literature on this. Schelling raised the issue. (Fleurbaey and Zuber 2012) argue along the same lines, but their analysis is looser than what follows. (Gollier 2010) shows that changes in the income distribution should affect the money discount rate, but does not consider policies that affect the income distribution.

The paper proceeds as follows. Section 2 sets up the definitions and relates to previous literature. Section 3 briefly presents the model. Section 4 discusses the numerical results that illustrate the impact of modified Ramsey discounting. Section 5 concludes.

2. Modified Ramsey rules

2.1. The standard Ramsey rule

¹ Note that there is a tacit assumption that the transfer can be earmarked. This assumption is difficult to maintain between generations (Lind and Schuler 1998).

The Ramsey rule can be derived as follows. Let ε denote the present value of \$1 dollar received in t years time, and let r be the consumption discount rate:

$$(1) \quad \varepsilon = e^{-rt}$$

The Ramsey rule follows from equating the marginal utility now to the marginal utility then, or:

$$(2) \quad U_{C_0} \varepsilon = e^{-\rho t} U_{C_t}$$

where U is the utility function, U_C is its first partial derivative to consumption C at times 0 and 1, and ρ is the rate of pure time preference or the utility discount rate. As above, ε is the discount factor.

The consumption discount rate then follows from

$$(3) \quad \varepsilon = \frac{e^{-\rho t} U_{C_t}}{U_{C_0}} = \frac{e^{-\rho t} C_t^{-\eta}}{C_0^{-\eta}} = \frac{e^{-\rho t} C_0^{-\eta} e^{-\eta g t}}{C_0^{-\eta}} = e^{-(\rho + \eta g)t}$$

where the second step follows from assuming a utility function with a constant relative rate of risk aversion (CRRA). Combining (1) and (3), the Ramsey rule emerges

$$(4) \quad r = \rho + \eta g$$

2.1. An ad hoc modification of the Ramsey rule

Let's add indices

$$(5) \quad r_{i,t} = \rho + \eta g_{i,t}$$

so that r is the discount rate of agent i at time t , and g is the growth rate of consumption. Typically, agent i transfers money to a later self so that

$$(6) \quad g_{i,t} = \left(\frac{C_{i,t}}{C_{i,0}} \right)^{1/t} - 1$$

where C is consumption.

If agent i embarks on greenhouse gas emission reduction, she implicitly transfers money to other agents, who live later. Let us define an agent j , whose income equals

$$(7) \quad C_{j,t} := \frac{\sum_r d_{r,t} C_{r,t}}{\sum_r d_{r,t}}$$

where d is the marginal damage suffered from climate change. That is, the consumption of the agent is the weighted average consumption of all agents, with the share in marginal damages as weights. This agent's consumption is representative, at the margin, for the consumption of the beneficiaries of climate policy.

Then, the discount rate is

$$(8) \quad r_{i,t} = \rho + \eta g_{i,t} \text{ with } g_{i,t} = \left(\frac{C_{j,t}}{C_{i,0}} \right)^{1/t} - 1$$

That is, the relevant growth rate is growth rate of consumption of the representative beneficiary with respect to the relative consumption of investor and beneficiary.

Note that representative beneficiary does not have a fixed identity, but changes over time with the impact of climate change – see Equation (7).

Discount factors are multiplicative, $e^{-(\rho+\eta g)t} e^{-(\rho+\eta h)s} = e^{-\rho(t+s)-\eta(gt+hs)}$. The discount factor that corresponds to Equation (8) can thus be written as

$$(9) \quad D_{i,t} = e^{-(\rho+\eta g_{i,t})t} = e^{-\eta \Delta_{i,j}} e^{-(\rho+\eta g_{j,t})t} \text{ with } \Delta_{i,j} = \frac{C_{j,0}}{C_{i,0}} - 1 \text{ and } g_{j,t} = \left(\frac{C_{j,t}}{C_{j,0}} \right)^{1/t} - 1$$

That is, the discount factor is decomposed into the discount factor the beneficiary times a transformation of the consumption difference between the beneficiary and the investor. If $i=j$, Equation (9) returns to the standard Ramsey discount factor.

4.2. A consistent modification of the Ramsey rule

Equations (3) and (4) are an intuitively clear but ad hoc modification of the Ramsey discount rate. It takes the Ramsey rule as given, and modifies it for climate policy. However, the Ramsey discount rate is a result – not an assumption.

Consider a transfer over time to another agent. Equation (1) still holds (albeit with consumption discount rate r_i), but (2) is replaced by

$$(10) \quad U_{C_{i,0}} \varepsilon = e^{-\rho t} U_{C_{j,t}}$$

The consumption discount rate then follows from

$$(11) \quad \varepsilon = \frac{e^{-\rho t} U_{C_{j,t}}}{U_{C_{i,0}}} = \frac{e^{-\rho t} C_{j,t}^{-\eta}}{C_0^{-\eta}} = \frac{e^{-\rho t} C_{j,0}^{-\eta} e^{-\eta g t}}{C_{i,0}^{-\eta}} = \left(\frac{C_{i,0}}{C_{j,0}} \right)^{\eta} e^{-(\rho+\eta g)t}$$

where

$$(12) \quad C_{j,0} = \frac{\sum_r d_{r,0} C_{r,0}}{\sum_r d_{r,0}}; g_j = \frac{\sum_r d_{r,t} C_{r,t}}{\sum_r d_{r,t}} \frac{\sum_r d_{r,0}}{\sum_r d_{r,0} C_{r,0}} - 1$$

Equations (11-12) meet some basic requirements: If there is only one actor, $d_{r,t}$ cancels in Equation (12) and (11) reduces to (3). If $\eta=0$, $r_i=\rho$ as in the original Ramsey rule – that is, under risk-neutrality, the consumption rate of discount equals the pure rate of time preference. See below for further interpretation.

4.3. A differentiated, consistent modification of the Ramsey rule

The modified Ramsey rules use an agent who is representative for those who suffer the impacts of climate change. At the same time, the (modified) Ramsey discount rate varies over time and between alternative scenarios of economic growth. There is no reason why the discount rate should not also be differentiated between the victims of climate change.

If the investor in climate policy has a different discount rate for each person affected by climate change, then the standard Ramsey rule should be used for future periods, as there is no reason why the investor should use a different trade-off than the victim herself. In the initial period, however, a correction is made for the consumption difference between the investor and the victim. As shown in the Appendix, this is Equation (5) but applied to an individual beneficiary (rather than a representative one).

The social cost of carbon is then calculated as:

$$(13) \quad SCC_i^A = \sum_r \left(\frac{c_{j,0}}{c_{r,0}} \right)^\eta SCC_r = \sum_r \left(\frac{y_{j,0}}{y_{r,0}} \right)^\eta \int_t d_{r,t} e^{-(\rho+\eta g_{r,t})t} dt$$

This is identical to regional equity weighting (Anthoff et al. 2009a). I use that term below because it has historical precedence and because “differentiated, consistent modified Ramsey discount rate” is an ugly mouthful.

4.4. Comparing the modifications

I first compare the ad hoc modification of the Ramsey rule (Equation 9) to the consistent modification (Equation 11). In both cases, the growth rate of consumption is convoluted with the growth rate of marginal impacts. Both discount factors combine equity weighing and consumption growth of the representative beneficiary. The functional forms are different, however: Equation (11) has a power function in the consumption ratio; Equation (5) has an exponential function in the relative consumption difference.

Equity weights have been used before in the climate literature. Equity weighing has that the net present, globally aggregated impact is the weighted sum of the net present, regional impacts. For a global planner (Fankhauser et al. 1997; Fankhauser et al. 1998), the weights are the ratio of the global average per capita income y_W over the regional average per capita income y_r , raised to the power of the risk aversion η :

$$(14) \quad SCC^P = \sum_r \left(\frac{y_{W,0}}{y_{r,0}} \right)^\eta SCC_r = \sum_r \left(\frac{y_{W,0}}{y_{r,0}} \right)^\eta SCC_r \int_t d_{r,t} e^{-(\rho+\eta g_{r,t})t} dt$$

where SCC_r is the net present value of the marginal damage done by emitting an additional tonne of carbon dioxide.

For a regional planner j (Anthoff et al. 2009a), the ratio is per capita income of the abating region over the per capita income of the impacted region: Equation (13).

There are two differences between the consistent modification of the Ramsey rule to the differentiated, consistent modification. Firstly, the “equity” weight is different – as is immediately clear from comparing Equations (11 – no regional differentiation) and (13 – regional differentiation). Equity weighing (Equations 13 and 14) is driven solely by

consumption differences between regions. The consistent modified Ramsey rule (Equations 11 and 12) is driven by consumption differences between investor and representative beneficiary. Secondly, the discount rate used is different. Equity weighing is based on region-specific growth rates, while the modified Ramsey rule uses an average growth rate.

3. The model

I use version 2.9 of the Climate Framework for Uncertainty, Negotiation and Distribution (FUND). Version 2.9 of FUND has the same basic structure as that of Version 1.6 (Tol 1999; Tol 2001; Tol 2002c), except for the impact module (Tol 2002a; Tol 2002b). The source code and a complete description of the model can be found at <http://www.fund-model.org/>.

Essentially, FUND is a model that calculates damages of climate change and impacts of greenhouse gas emission reduction for 16 regions of the world by making use of exogenous scenarios of socioeconomic variables. The scenarios comprise of projected temporal profiles of population growth, economic growth, autonomous energy efficiency improvements and carbon efficiency improvements (decarbonization), emissions of carbon dioxide from land use change, and emissions of methane and of nitrous oxide. Carbon dioxide emissions from fossil fuel combustion are computed endogenously on the basis of the Kaya identity. The calculated impacts of climate change perturb the default paths of population and economic outputs corresponding to the exogenous scenarios. The model runs from 1950 to 2300 in time steps of a year, though the outputs for the 1950-2000 period is only used for calibration, and the years beyond 2100 are used for the approximating the social cost of carbon under low discount rates. The scenarios up to the year 2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett et al. 1992). For the years from 2100 onward, the values are extrapolated from the pre-2100 scenarios. The radiative forcing of carbon dioxide and other greenhouse gases used by FUND is determined based on Shine *et al.* (1990). The global mean temperature is governed by a geometric buildup to its equilibrium (determined by the radiative forcing) with a half-life of 50 years. In the base case, the global mean temperature increases by 2.5°C in equilibrium for a doubling of carbon dioxide equivalents. Regional temperature increases, which are the primary determinant of regional climate change damages (except for tropical cyclones, as discussed below), are calculated from the global mean temperature change multiplied by a regional fixed factor, whose set is estimated by averaging the spatial patterns of 14 GCMs (Mendelsohn et al. 2000).

The model considers the damage of climate change for the following categories: agriculture, forestry, water resources, sea level rise, energy consumption, unmanaged ecosystems, and human health (diarrhea, vector-borne diseases, and cardiovascular and respiratory disorders). Impacts of climate change can be attributed to either the rate of temperature change (benchmarked at 0.04°C per year) or the level of temperature change (benchmarked at 1.0°C). Damages associated with the rate of temperature change gradually fade because of adaptation (Tol 2002a).

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

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

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

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

4. Results

Table 1 shows the population and per capita income for the 16 regions in FUND for the year 2000, as well as the estimated social cost of carbon for emissions between 2000 and 2009, discounted to 2000. These numbers form the basis for the results below. Note that I use the discrete time version of the modified Ramsey rule (Tol 2011).

Table 2 shows the social cost of carbon for a pure rate of time preference of 1% per year and a consumption elasticity of marginal utility of unity. Results are shown for the five “OECD” “regions” of the FUND model: USA, Canada (CAN), Western Europe (WEU), Japan and South Korea (JPK) and Australia and New Zealand (ANZ). The first row has the regional social cost of carbon, which only considers the impacts on the own region. These numbers are small, as expected, and even negative for the Pacific regions. If Japan, South Korea, Australia, and New Zealand would care only about their own countries, they should subsidize greenhouse gas emissions.

Adding the regional social costs of carbon (of the five regions shown and the eleven not shown), the global social cost of carbon amounts of \$7/tC. This does not account for income differences in the world. Using global equity weights, the social cost of carbon rises to \$24/tC. The second row of Table 2 shows the results with regional equity weights (or differentiated, consistent modified Ramsey discount rates). Global equity weights assume a global social planner. To a first approximation, impacts are valued at the global average. Regional equity weights assume regional social planners. All impacts around the world are valued, to a first approximation, at the values of the region that reduces emissions. As a result, the regionally equity weighted social cost of carbon is much higher: between \$77/tC and \$176/tC. The estimates are ranked in the same order as the regional per capita income, with Australia and New Zealand at the bottom and Japan and South Korea at the top.

The third row of Table 2 shows the social cost of carbon using the ad hoc modification of the Ramsey rule, and the fourth row contains the results for the consistent modification (not differentiated between regions).

With the ad hoc modification, the social cost of carbon is lower than with regional equity weighing, but the regional results are in the same order: The poorest of the rich regions is at the bottom, and the richest at the top. This follows from Equation (4): The larger the difference in income between the evaluating region and the representative region for impacts, the larger the weight in the first period. The economic growth rate used for later periods is independent of the evaluating region – see Equation (4).

With the consistent modification of the Ramsey rule, the social cost of carbon is numerically similar to the regional-equity-weighted estimates. Estimates may be slightly higher or slightly lower. The order is the same, and follows from Equation (5). The initial correction is a weighted average of the income difference in the first period between the evaluating regions and the affected regions. The growth rate used for later periods – see Equation (6) – is the same for all regions.

Figure 1 illustrates the mechanisms behind the estimates of the social cost of carbon for the USA. The incremental impact is initially negative – that is, additional warming is good in the short term – but it rapidly turns positive and grows to some seven cents around 2150 and then levels off as the pulse of carbon dioxide is removed from the atmosphere. If the standard Ramsey rule is applied without equity weighing, the incremental impact is muted, particularly in the long term. With global or regional equity weights, the pattern is the same over time but multiplied by the initial weight. The ad hoc and consistent modified Ramsey rules apply both a different initial weight and use a different discount rate. Figure 1 shows that regional equity weighing and consistent

modified Ramsey rule follow roughly the same pattern (which explains why the estimates of the social cost of carbon are so close) but a different pattern nonetheless.

Figure 2 shows the initial weights applied by the USA to the impacts on all regions, averaged over those regions for a rate of risk aversion of unity. The order of the weights is different than the order of the social cost of carbon. The simple sum gives the lowest at unity (by definition); the social cost of carbon is lowest. However, the global (regional) equity weight gives a higher initial weight than the ad hoc (consistent) modified Ramsey rule but the social cost of carbon is lower. That means that the discount factor over the entire period is lower.

Table 3 repeats Table 2 for a pure rate of time preference of 3% per year instead of 1%. Obviously, the estimates of the social cost of carbon are much lower than for a pure rate of time preference of 1%. The pattern of Table 2 is largely preserved, however. The richest regions have the highest social costs of carbon. The ad hoc modified Ramsey rule has the lowest social costs of carbon. The results consistent modified Ramsey rule are now always lower than those for the regional equity weighting; and the numerical difference between the two is much larger in a relative sense.

Table 4 repeats Table 2 for a rate of risk aversion of 2 instead of 1. The rate of risk aversion has a double role. It determines the weight placed on the income differences between the evaluating region and the impacted regions. Here, the social cost of carbon increases with the rate of risk aversion. The rate of risk aversion also features in the discount rate. Here, the social cost of carbon falls with the rate of risk aversion. The equity effect dominates the discounting effect in all cases. The pattern of Tables 2 and 3 is repeated in Table 4: Richer regions have a higher social cost of carbon.

5. Discussion and conclusion

In this paper, I introduce three modifications of the Ramsey discount rate for use in evaluating greenhouse gas emission reduction. While the original Ramsey rule was designed to evaluate transfers from a current to a future self, the modified Ramsey rules evaluate transfers from a current self, who bears the cost emission abatement, to a future other, who is representative for the beneficiaries of emission reduction. The modified Ramsey rules have two components. In the first period, there is a correction for the income difference of the self (investor in climate policy) and the other (beneficiary of climate policy). In later periods, the income growth rate of the other is used, corrected for shifts in the representativeness of the other. I propose three modifications. The first is ad hoc yet intuitive, the other two are consistent with the welfare theory underlying the original Ramsey rule. The consistent modified Ramsey rules either differentiate between regions or use a weighted average. The differentiated, consistent modified Ramsey rule is identical to the regional equity weights proposed earlier by (Anthoff et al. 2009a).

I apply the modified Ramsey rules to estimates of the social cost of carbon. The modified Ramsey rules lead to substantially higher cost estimates. The ad hoc modification implies lower estimates than the consistent modified Ramsey rules. The results of the (undifferentiated) consistent modification are numerically close to, although generally somewhat lower than estimates using the standard Ramsey rule plus regional equity

weights. The estimated social costs of carbon differ between regions, with richer regions facing higher cost estimates. This confirms that optimal climate policy has different carbon tax rates for different countries (Chichilnisky and Heal 1994; Sheeran 2006).

These results underline the importance of discounting and the distribution of income and impacts for evaluating the appropriate level of a carbon tax. Note that the framework presented here is incomplete. I ignored distributional issues within regions (Baer et al. 2009). I ignored uncertainty (Weitzman 2009). I assumed that the trade-offs between people living at the same time are governed by the same curvature of the utility function as trade-offs between people living at different times (Atkinson et al. 2009). I use strictly utilitarian welfare function for a global planner (Anthoff and Tol 2010). I ignored that population growth (incl. migration) is endogenous (Blackorby and Donaldson 1984). I omitted that, if the discount rate for climate policy is different, this would have an effect on the capital market (Ramsey 1928). These issues are deferred to future research.

Acknowledgements

I had useful discussions on this paper with David Anthoff, Christian Gollier and Gary Yohe. Earlier versions were presented at University College Dublin, Queen's University Belfast, and the Toulouse School of Economics; the audience had many useful suggestions. The 7th Framework Programme of the European Commission DG Research provided welcome financial support through the ClimateCost project.

Table 1. Population and per capita income in 2000, and the estimated regional social cost of carbon for different rates of risk aversion (η) and pure time preference (ρ).

	Population mln	Income \$/p/yr	Social cost of carbon (\$/tC)		
			$\eta=1,$ $\rho=0.01$	$\eta=1,$ $\rho=0.03$	H=2, $\rho=0.01$
USA	278	37317	2.36	0.38	0.67
Canada	31	25927	0.14	0.01	0.03
Western Europe	388	32417	4.71	0.60	1.22
Japan and South Korea	171	49762	-0.80	-1.03	-0.96
Australia and New Zealand	20	21694	0.00	-0.06	-0.04
Eastern Europe	125	3235	0.15	-0.02	-0.02
former Soviet Union	293	2146	1.35	0.30	0.21
Middle East	241	2524	0.12	-0.22	-0.23
Central America	137	2830	0.11	-0.08	-0.09
South America	346	3901	0.32	0.00	-0.02
South Asia	1365	607	0.63	-0.07	-0.09
Southeast Asia	615	1775	1.95	0.33	0.21
China, North Korea and Mongolia	1313	1778	4.15	-0.04	-0.30
North Africa	143	1491	1.12	0.29	0.26
Sub-Saharan Africa	635	476	0.73	0.15	0.13
Small Island States	43	1259	0.07	-0.02	-0.02

Table 2. The social cost of carbon (\$/tC) for five regions of the OECD, for a pure rate of time preference of 1% per year and a rate of the risk aversion of 1.

	USA	CAN	WEU	JPK	ANZ
Regional	2.36	0.14	4.71	-0.80	0.00
Equity weighted ^a	293.48	203.91	254.95	391.37	170.62
Ad hoc mod. Ramsey	159.45	110.78	138.51	212.62	92.70
Consistent mod. Ramsey	297.47	205.70	255.98	388.30	170.47
Simple sum ^b	17.12	Equity weighted ^c			52.38

^a Equity weights with regional normalization.

^a Global social cost of carbon without equity weights.

^c Global social cost of carbon with equity weights.

Table 3. The social cost of carbon (\$/tC) for five regions of the OECD, for a pure rate of time preference of 3% per year and a rate of the risk aversion of 1.

	USA	CAN	WEU	JPK	ANZ
Regional	0.38	0.01	0.60	-1.03	-0.06
Equity weighted ^a	21.64	15.04	18.80	28.86	12.58
Ad hoc mod. Ramsey	17.05	11.85	14.82	22.74	9.91
Consistent mod. Ramsey	19.53	13.50	16.81	25.49	11.19
Simple sum ^b	0.53	Equity weighted ^c			3.86

^a Equity weights with regional normalization.

^a Global social cost of carbon without equity weights.

^c Global social cost of carbon with equity weights.

Table 4. The social cost of carbon (\$/tC) for five regions of the OECD, for a pure rate of time preference of 1% per year and a rate of the risk aversion of 2.

	USA	CAN	WEU	JPK	ANZ
Regional	0.67	0.03	1.22	-0.96	-0.04
Equity weighted ^a	558.56	269.64	421.51	993.28	188.78
Ad hoc mod. Ramsey	186.97	90.26	141.10	332.49	63.19
Consistent mod. Ramsey	489.28	233.97	362.31	833.69	160.69
Simple sum ^b	0.96	Equity weighted ^c			17.79

^a Equity weights with regional normalization.

^a Global social cost of carbon without equity weights.

^c Global social cost of carbon with equity weights.

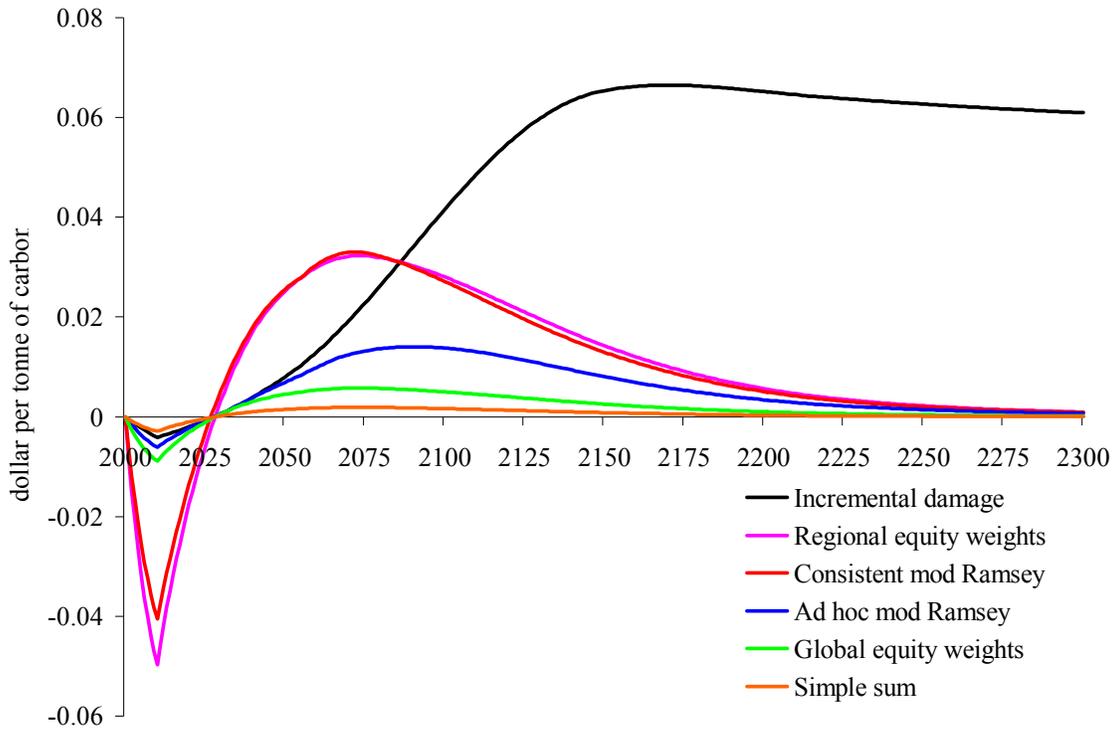


Figure 1. The current and present values of the normalized incremental damage due to increased carbon dioxide emissions in 2005; present values are shown for the standard Ramsey rule of discounting without equity weighing (simple sum) and with regional (USA) and global equity weighing, as well as for the ad hoc modified Ramsey rule and the consistent modified Ramsey rule; the pure rate of time preference is 1% per year; the rate of risk aversion is unity.

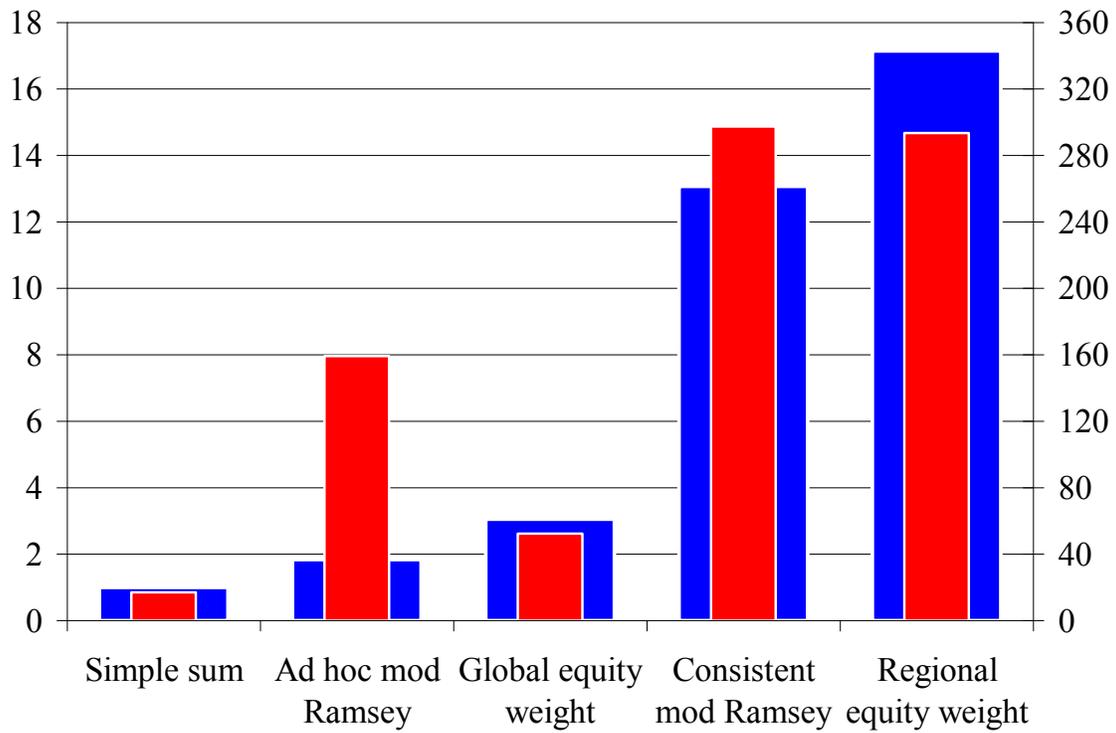


Figure 2. The social cost of carbon (red, narrow bar; right axis) and the initial weight (blue, wide bar; left axis) applied to the incremental damage due to increased carbon dioxide emissions in 2005 for the standard Ramsey rule without equity weighing (simple sum) and with regional and global equity weighing, as well as for the ad hoc modified Ramsey rule and the consistent modified Ramsey rule; the rate of risk aversion is unity.

References

- Anthoff, D., C.J.Hepburn, and R.S.J.Tol (2009a), 'Equity weighting and the marginal damage costs of climate change', *Ecological Economics*, **68**, (3), pp. 836-849.
- Anthoff, D. and R.S.J.Tol (2010), 'On international equity weights and national decision making on climate change', *Journal of Environmental Economics and Management*, **60**, (1), pp. 14-20.
- Anthoff, D., R.S.J.Tol, and G.W.Yohe (2009b), 'Discounting for Climate Change', *Economics -- the Open-Access, Open-Assessment E-Journal*, **3**, (2009-24), pp. 1-24.
- Anthoff, D., R.S.J.Tol, and G.W.Yohe (2009c), 'Risk Aversion, Time Preference, and the Social Cost of Carbon', *Environmental Research Letters*, **4**, (2-2), 1-7.
- Arrow, K.J., W.R.Cline, K.-G.Maeler, M.Munasinghe, R.Squitieri, and J.E.Stiglitz (1996), 'Intertemporal Equity, Discounting, and Economic Efficiency', in *Climate Change 1995: Economic and Social Dimensions -- Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, J.P. Bruce, H. Lee, and E.F. Haites (eds.), Cambridge University Press, Cambridge, pp. 125-144.
- Arrow, K.J., M.L.Cropper, C.Gollier, B.Groom, G.M.Heal, R.G.Newell, W.D.Nordhaus, R.S.Pindyck, W.A.Pizer, P.R.Portney, T.Sterner, R.S.J.Tol, and M.L.Weitzman (2013), 'Determining benefits and costs for future generations', *Science*, **341**, pp. 349-350.
- Atkinson, G.D., S.Dietz, J.Helgeson, C.J.Hepburn, and H.Saelen (2009), 'Siblings, not Triplets: Social Preferences for Risk, Inequality and Time in Discounting Climate Change', *Economics -- the Open-Access, Open-Assessment E-Journal*, **3**, (2009-26), pp. 1-30.
- Baer, P., S.Kartha, T.Athanasίου, and E.Kemp-Benedict (2009), 'The greenhouse development rights framework: Drawing attention to inequality within nations in the global climate policy debate', *Development and Change*, **40**, (6), pp. 1121-1138.
- Blackorby, C. and D.Donaldson (1984), 'Social Criteria for Evaluating Population Change', *Journal of Public Economics*, **25**, (1-2), 13-33.
- Chichilnisky, G. and G.Heal (1994), 'Who should abate carbon emissions?. An international viewpoint', *Economics Letters*, **44**, (4), pp. 443-449.
- Cline, W.R. (1992), *Global Warming - The Benefits of Emission Abatement*, OECD, Paris.
- Fankhauser, S. (1994), 'Protection vs. Retreat -- The Economic Costs of Sea Level Rise', *Environment and Planning A*, **27**, 299-319.

Fankhauser, S., R.S.J.Tol, and D.W.Pearce (1997), 'The Aggregation of Climate Change Damages: A Welfare Theoretic Approach', *Environmental and Resource Economics*, **10**, (3), 249-266.

Fankhauser, S., R.S.J.Tol, and D.W.Pearce (1998), 'Extensions and Alternatives to Climate Change Impact Valuation: On the Critique of IPCC Working Group III's Impact Estimates', *Environment and Development Economics*, **3**, 59-81.

Fleurbaey, M. and S.Zuber (2012), *Climate policies deserve a negative discount rate*, Working Paper **2012-19**, Fondation Maison des Sciences de l'Homme, Paris.

Gollier, C. (2010), *Discounting, inequalities and economic convergence*, Working Paper **3262**, CESifo.

Leggett, J., W.J.Pepper, and R.J.Swart (1992), 'Emissions Scenarios for the IPCC: An Update', in *Climate Change 1992 - The Supplementary Report to the IPCC Scientific Assessment*, 1 edn, vol. 1 J.T. Houghton, B.A. Callander, and S.K. Varney (eds.), Cambridge University Press, Cambridge, pp. 71-95.

Lind, R.C. and R.E.Schuler (1998), 'Equity and Discounting in Climate Change Decisions', in *Economics and Policy Issues in Climate Change*, W.D. Nordhaus (ed.), Resources for the Future, Washington, D.C., pp. 59-96.

Mendelsohn, R.O., M.E.Schlesinger, and L.J.Williams (2000), 'Comparing Impacts across Climate Models', *Integrated Assessment*, **1**, (1), 37-48.

Nordhaus, W.D. (2007), 'A Review of the Stern Review on the Economics of Climate Change', *Journal of Economic Literature*, **45**, (3), 686-702.

Pearce, D.W., B.Groom, C.J.Hepburn, and P.Koundouri (2003), 'Valuing the Future - Recent advances in social discounting', *World Economics*, **4**, (2), 121-141.

Ramsey, F. (1928), 'A Mathematical Theory of Saving', *Economic Journal*, **38**, 543-549.

Schelling, T.C. (1992), 'Some Economics of Global Warming', *American Economic Review*, **82**, 1-14.

Schelling, T.C. (2000), 'Intergenerational and International Discounting', *Risk Analysis*, **20**, (6), 833-837.

Sheeran, K.A. (2006), 'Who Should Abate Carbon Emissions? A Note', *Environmental and Resource Economics*, **35**, 89-98.

Stern, N.H. (2008), 'The Economics of Climate Change', *American Economic Review*, **98**, (2), 1-37.

Tol, R.S.J. (1995), 'The Damage Costs of Climate Change Toward More Comprehensive Calculations', *Environmental and Resource Economics*, **5**, (4), 353-374.

Tol, R.S.J. (1999), 'Spatial and Temporal Efficiency in Climate Change: Applications of FUND', *Environmental and Resource Economics*, **14**, (1), 33-49.

Tol, R.S.J. (2001), 'Equitable Cost-Benefit Analysis of Climate Change', *Ecological Economics*, **36**, (1), 71-85.

Tol, R.S.J. (2002a), 'Estimates of the Damage Costs of Climate Change - Part I: Benchmark Estimates', *Environmental and Resource Economics*, **21**, (1), 47-73.

Tol, R.S.J. (2002b), 'Estimates of the Damage Costs of Climate Change - Part II: Dynamic Estimates', *Environmental and Resource Economics*, **21**, (2), 135-160.

Tol, R.S.J. (2002c), 'Welfare Specifications and Optimal Control of Climate Change: an Application of FUND', *Energy Economics*, **24**, 367-376.

Tol, R.S.J. (2009), 'The Economic Effects of Climate Change', *Journal of Economic Perspectives*, **23**, (2), 29-51.

Tol, R.S.J. (2011), *Modified Ramsey Discounting for Climate Change*, Working Paper **368**, Economic and Social Research Institute, Dublin.

United Nations (1992), *United Nations Framework Convention on Climate Change*, United Nations, Geneva.

Weitzman, M.L. (2007), 'A Review of the Stern Review on the Economics of Climate Change', *Journal of Economic Literature*, **45**, (3), 703-724.

Weitzman, M.L. (2009), 'On Modelling and Interpreting the Economics of Catastrophic Climate Change', *Review of Economics and Statistics*, **91**, (1), 1-19.