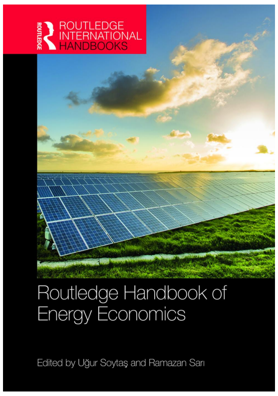

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The impact of climate change and the social cost of carbon

Richard S. J. Tol

1 Introduction

The social cost of carbon is the incremental impact of emitting an additional tonne of carbon dioxide, or the benefit of slightly reducing emissions. When evaluated along an optimal emissions trajectory, the social cost of carbon is the Pigou tax (Pigou, 1920) – that is, the amount greenhouse gas emissions should be taxed in order to restore efficiency. The social cost of carbon is thus a key parameter in the discourse about climate change and what to do about it.

Carbon prices are increasingly used in climate policy (World Bank and Ecofys, 2018). Estimates of the social cost of carbon would be an important input into setting the price right. Unfortunately, as I argue below, it is difficult to put narrow bounds on the social cost of carbon. This is mostly because the social cost of carbon is inherently uncertain and controversial. Partly, however, the uncertainty about the social cost of carbon reflects gaps in knowledge and research.

There have been a number of reviews of the social cost of carbon (Pizer et al., 2014; Guivarch et al., 2016; Metcalf and Stock, 2017; Pindyck, 2017a, 2017b; Revesz et al., 2017) and its application (Rose, 2012; Greenstone et al., 2013; Heyes et al., 2013; Sunstein, 2014; Hahn and Ritz, 2015). Since my earlier surveys (Tol, 2005; Tol and Yohe, 2009; Tol, 2011, 2013, 2018), the volume of papers and estimates has increased further, but recent papers remap known territory without breaking new ground.

In this paper, I discuss conceptual issues around the social cost of carbon and review these new estimates, after assessing what we know about the total economic impact of climate change. Although estimates of the total cost of climate change have no immediate relevance for policy, estimates of the social cost of carbon derive from the total cost. Furthermore, total cost estimate reveal the Schelling Conjecture, which poses a policy dilemma: adapt or mitigate.

2 The total impact of climate change

Figure 16.1 shows the 27 published estimates of the total economic impact of climate change. See Howard and Sterner (2017) and Nordhaus and Moffat (2017) for markedly different assessments of the same literature. The horizontal axis has the change in the global annual mean surface air temperature, a key indicator of climate change. The vertical axis is the welfare equivalent income

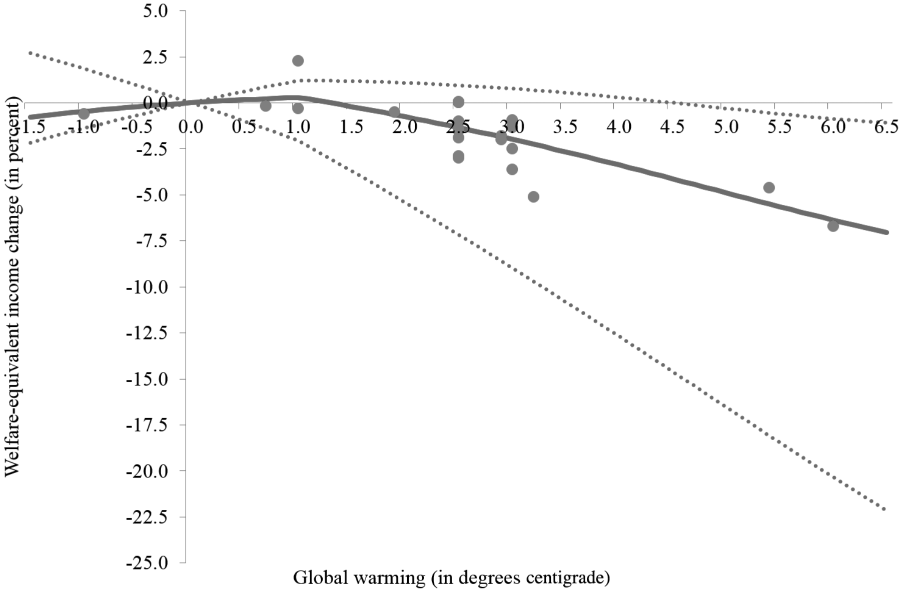

Figure 16.1 The global total annual impact of climate change

change. These numbers should be read as follows: A global warming of 2.5°C would make the average person feel as if she had lost 1.3% of her income (1.3% is the average of the 11 dots at 2.5°C).

2.1 Methods

These estimates were derived as follows. Researchers used models – of every description: process models, optimization models, equilibrium models, statistical models, spatial or temporal analogues – to estimate the many impacts of climate change for all parts of the world in their natural units, estimated the values of these impacts (using either market prices or monetary valuation methods), multiplied the quantities and prices, and added everything up (d'Arge, 1979; Nordhaus, 1982, 1991, 1994a; Fankhauser, 1995; Tol, 1995; Berz, 1996; Nordhaus and Yang, 1996; Plambeck and Hope, 1996; Tol, 2002; Nordhaus and Boyer, 2000; Hope, 2006; Nordhaus, 2008). This is the so-called enumerative method. The result is an estimate of the direct cost – price times quantity – of climate change. The direct cost is a poor approximation of the change in welfare, for instance because it ignores price changes, but it is an approximation nonetheless. The enumerative approach omits interactions between sectors, such as a change in water resources affecting agriculture.

Other studies use the same physical impact estimates that are used in the enumerative studies above, but use these to shock a computable general equilibrium model (Bosello et al., 2012; Roson and van der Mensbrugghe, 2012). These estimates thus include both price changes and interactions between economics sectors, be it through output, intermediate or input markets, and between economies through international trade and investment. The welfare measure used in these studies is typically the Hicksian Equivalent Variation, a proper welfare measure that is, within the model, measured exactly. Computable general equilibrium models are based on the national accounts, and thus misrepresent subsistence agriculture and omit direct impacts of welfare.

Other estimates involve regressions of an economic indicator on climate (Mendelsohn et al., 2000; Nordhaus, 2006). Agricultural land prices, for instance, reflect the productivity of the land and hence the value of the climate that allows plants to grow. You do not just buy the land, but also the sun that shines and the rain that falls on it (Ricardo, 1817). Price differences due to climate variation are used to estimate the direct cost of climate change. Household expenditure patterns (Maddison, 2003) and self-reported happiness (Rehdanz and Maddison, 2005; Maddison and Rehdanz, 2011) have also been used. The main advantage of the statistical method is that it is based on actual behavior (rather than modeled behavior as above). The main disadvantage is that climate variations over space are used to derive the impact of climate change over time. Space and time are different things, though. For instance, trade is much easier over space than over time; and technology and institutions differ more over space than over time.

One estimate elicits the views of *supposed* experts (Nordhaus, 1994b).[1] The question was about the impact of climate change on global output, which can alternatively be interpreted as a measure of economic activity (but not welfare) and a measure of income (and thus welfare).

2.2 Weather and climate

Climate varies only slowly over time – it is, after all, the 30-year average of weather. In empirical studies, the identification of the impact of climate therefore comes from cross-sectional variation. As the climate varies only slowly over space, the cross-section needs to be large. This is problematic as so many other things vary over space too. Ricardian and hedonic methods are therefore vulnerable to spurious associations because of confounding variables. This can be partly overcome with panel data, for confounders that vary over time as well as space – trade policy would be one example, if it has changed within sample, and if trade liberalization is preferentially between countries with similar climates. But panel data cannot help with confounders that do not change much over time – a cultural preference for pastoralism in dry areas would be one example.

In recent years, there have been a number of papers that estimate the impacts of weather on a range of economic indicators (Deschenes and Greenstone, 2007; Burke et al., 2015; Hsiang et al., 2017; Burke et al., 2018). The key advantage of weather impacts is that weather is, from an economic perspective, random. The impact of weather is therefore properly identified. Although the rhetoric in some of these papers would have you believe otherwise, the impact of a weather shock is not the same as the impact of climate change (Dell et al., 2014). See Deryugina and Hsiang (2017) for the conditions under which weather variability is informative about climate change.

Climate is what you expect, weather is what you get. Adaptation to weather shocks is therefore limited to immediate responses – put up an umbrella when it rains, close the flood doors when it pours. Adaptation to climate change extends to changes in the capital stock – buy an umbrella, invest in flood doors. In other words, weather studies estimate the short-run elasticity, whereas the interest is in the long-run elasticity. Extrapolating the impact of weather shocks will not lead to credible results for the impact of climate change.

2.3 Combining estimates

Besides the primary estimates, Figure 16.1 also shows a curve. Seven alternative impact functions were fitted to the data. See Table 16.1. Assuming normality of the residuals, the loglikelihood was computed for each model. The curve shown is the Bayesian average of the seven models. A piecewise linear model is the best fit to the data, and the average curve indeed looks

Table 16.1 Alternative models of the total impact of climate change

Name	*Function*	*Weight*
Golosov	$-4.16 \cdot 10^{-175} (e^{e^{T}} - e)$	0.0%
Ploeg	$-0.02 (e^{T} - 1)$	0.0%
Hope	$-0.71T$	0.2%
Nordhaus	$-0.19T^2$	8.7%
Tol (parabolic)	$-0.12T - 0.16T^2$	10.2%
Weitzman(7)	$-0.21T^2 - 5.79 \cdot 10^{-6}T^7$	13.6%
Weitzman(6)	$-0.22T^2 - 3.71 \cdot 10^{-5}T^6$	14.2%
Tol (piecewise linear)	$0.74TI_{T<1.01} + (0.74 \cdot 1.01 - 1.41T)I_{T\geq 1.01}$	53.2%

like that. The near-linearity of the impact function is driven by the two moderate estimates for high warming.

Only 7 of the 27 estimates have a reported standard deviation, or an upper and lower bound. I imputed upper and lower bounds from twice the reported standard deviations. I assume that the upper and lower bounds are linear functions of the temperature, with slopes 0.92% GDP/°C and 2.33% GDP/°C on the cold and hot side, respectively. I interpret this as a 90% confidence interval.

2.4 Results

Figure 16.1 contains many messages. There are only 27 estimates, a rather thin basis for any conclusion. Statements that climate change is the biggest (environmental) problem of humankind are not well-supported and, as argued below, probably false.

The 11 estimates for 2.5°C, which we may reach in 60–80 years' time, show that researchers disagree on the sign of the net impact. Climate change may lead to a welfare gain or loss. At the same time, researchers agree on the order of magnitude. The welfare change caused by climate change is equivalent to the welfare change caused by an income change of a few percent. The average of the estimates is negative. That is, a century of climate change is about as bad as losing a year of economic growth.

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

The uncertainty is rather large, however. The error bars in Figure 16.1 depict the 90% confidence interval. This is probably an underestimate of the true uncertainty, as experts tend to be overconfident and as the 27 estimates were derived by a group of researchers who know each other and each other's work well.

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

The right extreme of Figure 16.1 is interesting too. At 3.0°C of warming, impacts are negative, deteriorating, and (perhaps) accelerating. It is likely that the world will warm beyond 3.0°C. Yet, beyond that point, there are few estimates only. There is extrapolation and speculation.

2.5 Distribution of impacts

Thirteen of the 22 studies referred to above include estimates of the regional impacts of climate change and, in the studies involving David Maddison, national impact estimates. Regressing the estimated regional impact for 2.5°C warming on per capita income and average annual temperature, with dummies for the studies, I find that

$$I_c = -13.4(8.7) + 1.70(0.79)\ln y_c - 0.46(0.14)T_c \tag{16.1}$$

where I_c is the impact in country c (in % GDP), y_c is its average income (in 2010 market exchange dollars per person per year), and T_c is the average annual temperature (in degrees Celsius). Hotter countries have more negative impacts. Richer countries have more positive impacts. Of course, Equation (16.1) does not capture the special vulnerability of delta and island nations. I use this equation to impute national impacts, making sure that the regional or global totals match those in the original estimates.

Figure 16.1 shows the world average impact for 27 studies. Figure 16.2 shows results for individual countries for 2.5°C warming. Countries are ranked from low to high per capita income and low to high temperature. In Figure 16.1, the world total impact is roughly zero. In Figure 16.2, the majority of countries show a negative impact. However, the world economy is concentrated in a few, rich countries. The world average in Figure 16.1 counts dollars, rather than countries, let alone people.

Figure 16.2 suggests that poorer countries are more vulnerable to climate change than are richer countries. There are a few exceptions to this – such as Mongolia, which is poor but so cold that warming would bring benefits, and Singapore, which is rich but a low-lying island on the equator – but by and large the negative impacts of climate change are concentrated in the developing economies.

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

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

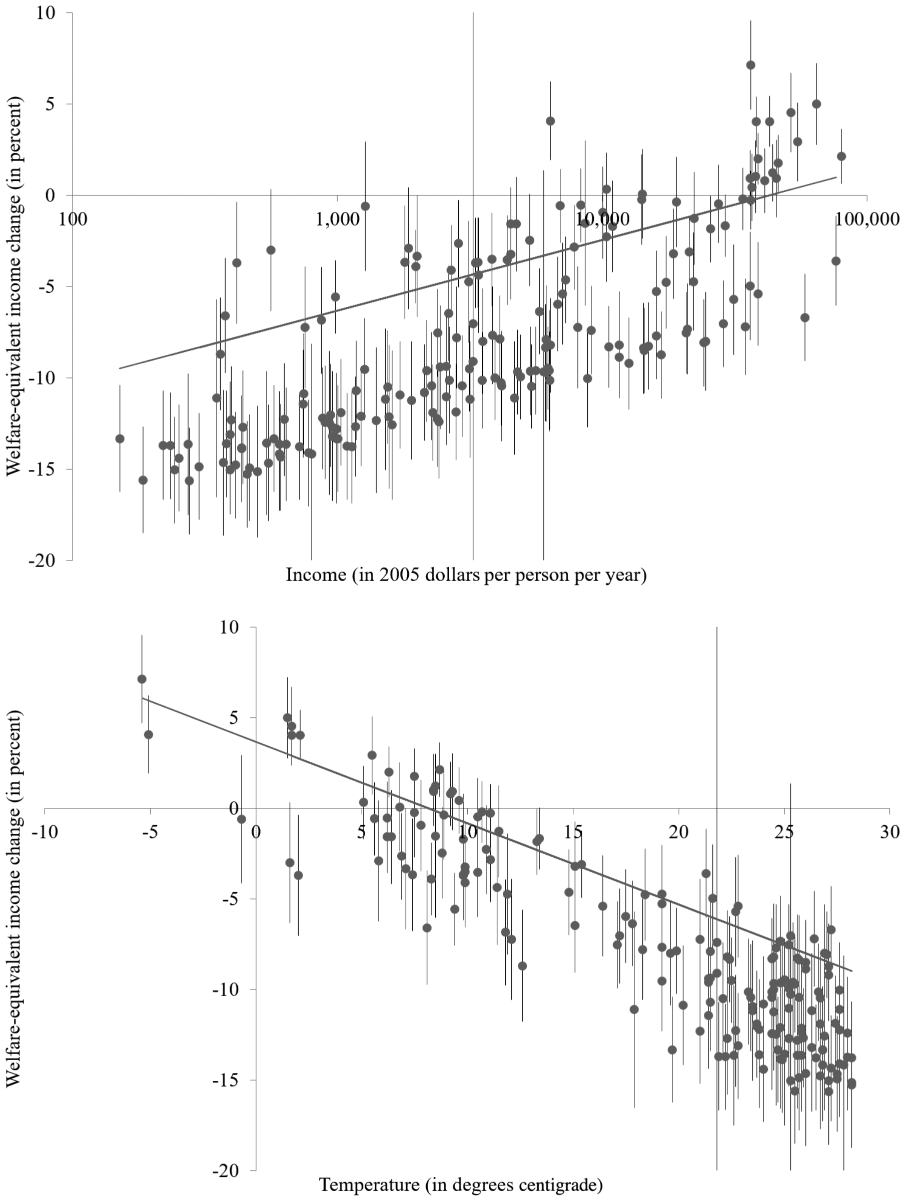

Figure 16.2 The economic impact of climate change for a 2.5°C warming for all countries as a function of their 2005 income (top panel) and temperature (bottom panel)

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

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

Figure 16.2 shows that poorer countries are more vulnerable to climate change. Aggregating results by country hides information. Figure 16.3 again shows the impact of 2.5°C warming. The impacts are further downscaled, to income deciles, based on data from the University of Texas Inequality Project, using the same semi-elasticity used to downscale regional to national impact estimates; see Equation (16.1). Figure 16.3 shows three histograms, weighing the estimates by the share of the number of countries affected, by the share of the number of people affected, and by the share of total economic output affected.

Figure 16.3 reveals that focusing on countries overstates the impact of climate change, as small coastal and island states are heavily affected by sea level rise. Figure 16.3 highlights that the

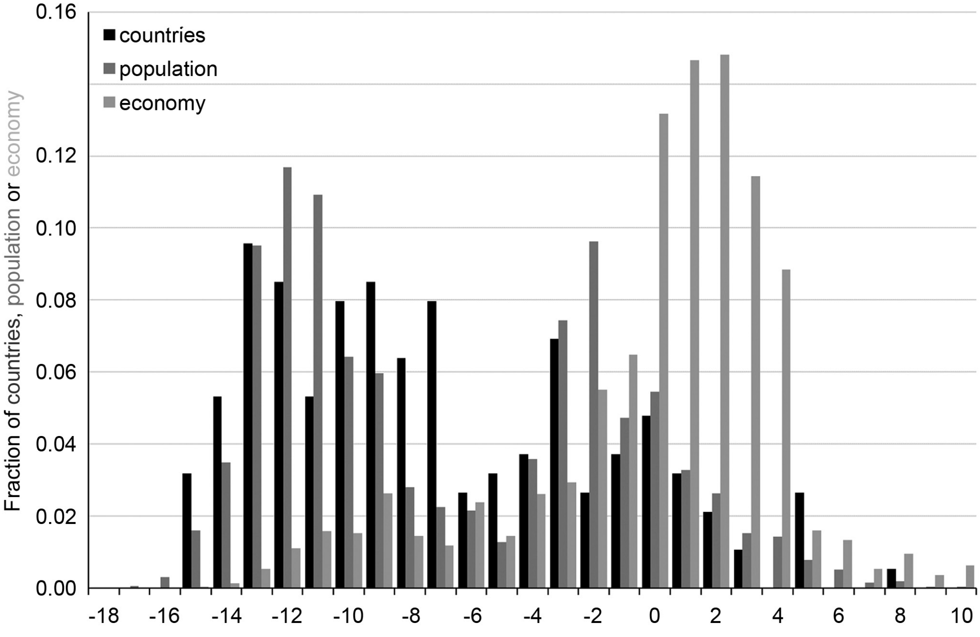

Figure 16.3 The distribution of the annual impact of 2.5°C global warming by country, people, and economy affected

majority of the world population will suffer large negative impacts while the larger share of the world economy will enjoy mild positive impacts.

2.6 Sectoral impacts

Four studies published estimates of the impact of 2.5°C warming by sector. See Table 16.2. Coverage varies between studies. The rightmost column has the average of the published estimates. Adding up these sectoral averages, the total impact is –2.0% of GDP, which is 28% higher than the average of the original studies. Using the sectoral averages to impute missing observations makes the original studies less incomplete. The estimate by Nordhaus and Boyer (2000) is the least complete.

Impacts are found across the economy. There is no sector or impact that dominates the total.

3 The social cost of carbon

3.1 Definition

The social cost of carbon is defined as the monetary value of the first partial derivative of global, net present welfare to current carbon dioxide emissions. It is sometimes calculated as a true marginal along a welfare-optimizing emissions trajectory, and so equals the Pigou (1920) tax on carbon dioxide. More often, the social cost of carbon is approximated as a normalized increment

Table 16.2 Sectoral estimates of the impact of climate change (in percentage of GDP)

	Fankhauser	*Berz*	*Tol*	*Nordhaus*	*Average*
Agriculture	**–0.20**	*–0.19*	**–0.13**	**–0.13**	–0.16
Forestry	**–0.01**	**–0.02**	–0.01	–0.01	–0.01
Energy	**–0.12**	*–0.11*	–0.12	–0.12	–0.12
Water	**–0.24**	*–0.23*	–0.24	–0.24	–0.24
Other market*	**–0.37**	*–0.36*	–0.26	**–0.05**	–0.26
Coastal defense	**0.00**	**–0.01**	**–0.08**	–0.03	–0.03
Dryland	**–0.07**	*–0.07*	**–0.09**	–0.08	–0.08
Wetland	**–0.16**	*–0.16*	**–0.17**	–0.16	–0.16
Coastal*	**–0.24**	*–0.23*	**–0.34**	**–0.32**	–0.28
Ecosystem	**–0.21**	*–0.20*	**–0.19**	–0.20	–0.20
Health	**–0.26**	**–0.40**	**–0.77**	**–0.10**	–0.38
Air pollution	**–0.08**	*–0.08*	–0.08	–0.08	–0.08
Time use	0.29	0.29	0.29	**0.29**	0.29
Settlements	–0.17	–0.17	–0.17	**–0.17**	–0.17
Extreme weather	**–0.01**	**–0.01**	**–0.01**	**–1.02**	–0.27
Migration	**–0.02**	*–0.02*	**–0.12**	–0.07	–0.06
Amenity	–0.33	–0.33	**–0.33**	–0.33	–0.33
Total	–1.61	–1.71	–2.24	–2.47	–2.01
Original	–1.4	–1.5	–1.9	–1.5	–1.6
Ratio	1.15	1.14	1.18	1.65	1.28

Bold face numbers are original estimates, normal face numbers are imputed from the average, italicized numbers are imputed by Berz from Fankhauser. * 'Coastal' and 'Other market' are the sum of the three sectors immediately above.

along an arbitrary emissions path. Essentially, you compute the impacts of climate change for a particular scenario; you slightly increase emissions in 2018 and compute the slightly different impacts; you take the difference between the two series of future impacts; discount them back to today; and normalize the net present value of the difference with the change in emissions.

Formally,

$$SCC = \left(\frac{\sum_c C_{c,0}}{\sum_c P_{c,0}} \right)^{-\eta-\omega+\eta\omega} \frac{\partial}{\partial E_0} \sum_s p_s \sum_t \frac{1}{(1+\rho)^t} \sum_c \frac{P_{c,t,s}}{1-\omega} \frac{1}{1-\eta} \left(\left(\frac{C_{c,t,s}}{P_{c,t,s}} \right)^{1-\eta} \right)^{1-\omega} \tag{16.2}$$

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

There is a lot going on in Equation (16.2). Climate change affects different countries differently. These effects need to be aggregated to a world total. This is the inner summation. The rate of risk aversion η reflects that a dollar to a poor woman is not the same as a dollar to a rich woman. We may follow Atkinson (1970) and care about the distribution of utility. If so, $\omega \neq 0$. Note that the consumption rate of inequality aversion is $\eta + \omega - \eta\omega$, so that we would still care about income differences (but not about utility differences) if $\omega = 0$; see Tol (2010). Carbon dioxide stays in the atmosphere for a long time, and the climate is a dynamic system. Therefore, an additional tonne of carbon dioxide emitted today will have a long-lasting impact, that needs to be discounted to today. This is the middle summation. While utility is discounted at rate ρ, consumption is discounted at rate $\rho + g_P + (\eta + \omega - \eta\omega)g_C$, where g_P is the growth rate of the population and g_C is the growth rate of consumption. The future is uncertain, so the outer summation aggregates across possible states of the world, with η and ω now reflecting risk aversion. Finally, the first partial derivative is welfare to emissions. The social cost of carbon is expressed in dollar per tonne of carbon. The first element in Equation (16.2) normalizes the marginal impact on expected net present welfare with the marginal utility of consumption at the time of emission.

Most estimates of the social cost of carbon are based on a parameterization of Equation (16.2). Alternatives are possible, of course. Constant rates of relative risk aversion are mathematically convenient, but not necessarily realistic (Donkers et al., 2001; Hartog et al., 2002; Cohen and Einav, 2007) and may be problematic under deep uncertainty (Millner, 2013). The rate of risk aversion triples in its role as inequity aversion and time preference (Saelen et al., 2009). Equation (16.2) assumes Knightian risk, but we may want to account for ambiguity aversion too (Lemoine and Traeger, 2016). Preferences are commonly assumed to be time-separable, but other assumptions are possible too (Cai et al., 2016). And we may not accept the Koopmans (1960) axioms of net present welfare (Llavador et al., 2011; Dietz and Asheim, 2012; Tol, 2013). Finally, the social cost of carbon is defined as the global social cost of carbon, implicitly assuming a global social planner, a benevolent philosopher-queen; Anthoff and Tol (2010) explore national attitudes towards global welfare.

The impact of climate change is implicit in Equation (16.2). The chain rule has that

$$\frac{\partial C_{c,t,s}}{\partial E_0} = \frac{\partial C_{c,t,s}}{\partial T_{t,s}} \left(\frac{\partial T_{t,s}}{\partial M_{t,s}} \frac{\partial M_{t,s}}{\partial E_0} + \frac{\partial T_{t,s}}{\partial T_{t-1,s}} \frac{\partial T_{t-1,s}}{\partial M_{t-1,s}} \frac{\partial M_{t-1,s}}{\partial E_0} + \ldots \right) \tag{16.3}$$

if we assume that impacts depend only on the global temperature $T_{t,s}$ and temperature only on its own past and the atmospheric concentration of carbon dioxide $M_{t,s}$. Reality is more complicated, but substituting (16.3) into (16.2) leads to an intractable result. Therefore, most estimates of the social cost of carbon rely on numerical models. Sample code in MATLAB is available.

Some of the controversy concerning the social cost of carbon arises from the complexity of its computation. Golosov et al. (2014) show that the social cost of carbon can be written as a function of total economic output, the pure rate of time preference, elasticity of damage with regard to the atmospheric concentration of carbon dioxide, and the rate of decay of carbon dioxide in the atmosphere. This result hinges on the assumptions that

1. *Utility is logarithmic in consumption.* As shown by Donkers et al. (2001), Hartog et al. (2002) and Cohen and Einav (2007), risk aversion is probably not constant, let alone equal to one.
2. *Time discounting is exponential.* Arrow et al. (2013, 2014) review the arguments against geometric discounting.
3. *The carbon cycle follows a linear difference equation.* Maier-Reimer and Hasselmann (1987) show that the removal of carbon dioxide from the atmosphere cannot be approximated by a linear difference equation.
4. *Climate change impacts are proportional to total output.* Figure 16.2 illustrates that poverty implies vulnerability to climate change – that is, impacts have a negative income elasticity, and so are less than proportional to output.
5. *Climate change impacts are proportional to the exponent of the atmospheric concentration of carbon dioxide.* The equilibrium temperature is logarithmic in the atmospheric concentration, so Golosov assumes that impact is proportional to the exponent of the exponent of temperature. Figure 16.1 suggests that the relationship between temperature and impact is close to linear.
6. *There are no catastrophic risks.* Keller et al. (2004) show that catastrophes break Golosov's smoothness, and hence their simple function for the social cost of carbon.

In sum, none of these assumptions is realistic. Stylized models are great for insight, but insight into irreality is worthless.

3.2 Simple model

I wrote MATLAB code to combine the impact models in Table 16.1 with the SRES (Nakicenovic and Swart, 2000) and SSP (Riahi et al., 2017) scenarios of population, income and emissions, the Maier-Reimer and Hasselmann (1987) carbon cycle model, and the Schneider and Thompson (1981) climate model. Readers are free to download, run, manipulate, and share the code.

Tables 16.3, 16.4, and 16.5 show selected results. Table 16.3 displays the social cost of carbon as a function of the pure rate of time and the rate of risk aversion. As there is no uncertainty in

Table 16.3 Estimates of the social cost of carbon (in 2010 dollars per tonne of carbon)

Time preference/risk aversion	*0.5*	*1.0*	*1.5*	*2.0*	*2.5*
0.001%	55.4	22.4	10.9	6.3	4.1
0.010%	35.4	15.6	8.2	5.1	3.5
0.020%	22.5	10.9	6.3	4.1	2.9
0.030%	15.1	8.0	4.9	3.4	2.5
0.040%	10.6	6.1	3.9	2.8	2.2
0.050%	7.7	4.7	3.3	2.4	1.9

Model = Tol (parabola); scenario = SRES A1; climate sensitivity = 3.0; income elasticity = –0.36.

the model, and one representative agent only, the rate of risk aversion only plays a role in trade-offs between current poverty and future richesse via the Ramsey (1928) rule of discounting. A higher rate of risk aversion thus implies a higher discount rate, as does a higher pure rate of time preference. The results are as expected: The lower the discount rate, the greater the care for the future, the more concern about climate change, and the higher the social cost of carbon.

Table 16.4 shows the social cost of carbon for different impact models and scenarios. Alternative scenarios do not affect the social cost of carbon that much, as the difference between scenarios only become really pronounced in the more distant (and more heavily discounted) future. Although the different impact models are calibrated to the same dataset, there are pronounced differences between models. Golosov's double exponential model advocates a zero carbon tax – it has essentially zero impacts below a temperature threshold, and infinitely large impacts above. Van der Ploeg's single exponential model shows the same behavior, but less extreme, and thus argues for a low social cost of carbon. Tol's piecewise linear model calls for a carbon subsidy – it emphasizes the positive impacts of modest climate change. The results for the remaining five models are relatively close to each other.

Table 16.5 has the social cost of carbon as a function of the two key parameters: The climate sensitivity and the income elasticity of impact. In the base calibration, the climate sensitivity is a warming of 3.0°C per doubling of the atmospheric concentration of carbon dioxide. Should the climate warm faster, the social cost of carbon increases. This relationship is more than linear. In the base calibration, the impact relative to income falls by 3.6% if income rises by 10%. The social cost of carbon falls (rises) if the income elasticity is higher (lower). Again, the relationship is nonlinear: A lower income elasticity has a greater effect than a higher one.

Table 16.4 Estimates of the social cost of carbon (in 2010 dollars per tonne of carbon)

Model/scenario	*A1*	*A2*	*B1*	*B2*	*SSP1*	*SSP2*	*SSP3*	*SSP4*	*SSP5*
Golosov	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ploeg	1.5	2.2	1.5	1.4	1.6	1.7	2.0	1.6	1.6
Hope	8.4	10.2	9.1	9.9	8.8	9.3	10.1	9.5	8.1
Nordhaus	7.7	10.0	8.3	8.7	7.8	8.6	9.6	8.5	7.5
Tol (parabola)	8.0	10.2	8.6	9.1	8.2	8.7	9.8	8.9	7.7
Weitzman (7)	8.8	11.3	9.4	9.9	8.9	9.7	10.9	9.7	8.5
Weitzman (6)	8.7	11.2	9.4	9.9	8.9	9.7	10.8	9.7	8.4
Tol (piecewise linear)	–3.8	–2.5	–4.1	–5.8	–4.6	–4.1	–3.2	–4.5	–3.7

Pure rate of time preference = 0.01%; rate of risk aversion = 1; climate sensitivity = 3.0; income elasticity = –0.36.

Table 16.5 Estimates of the social cost of carbon (in 2010 dollars per tonne of carbon)

Income elasticity/ climate sensitivity	*1.5*	*2.5*	*3.0*	*4.5*
–0.00	3.8	9.5	13.3	28.3
–0.18	3.0	7.3	10.2	21.6
–0.36	2.3	5.7	8.0	16.9
–0.72	1.5	3.7	5.2	11.0

Model = Tol (parabola); scenario = SRES A1; Pure rate of time preference = 0.01%; rate of risk aversion = 1.

Uncertainty and risk aversion

Table 16.5 shows that the social cost of carbon is more than linear in the climate sensitivity. For an income elasticity of –0.36, $SCC = 0.445CS + 0.736CS^2$ is an excellent fit, where CS denotes the climate sensitivity. This immediately implies that, if the uncertainty about the climate sensitivity is symmetric, the mode of the social cost of carbon, displayed in Table 16.5, is smaller than its mean. However, the probability density function of the climate sensitivity is right-skewed and may be fat-tailed. Roe and Baker (2007) argue that $CS = \frac{CS_{f=0}}{1-f}$ where $CS_{f=0} = 1.2K$ and total feedback f is normally distributed. They set its standard deviation to 0.13. If its mean is 0.6, the mode of the climate sensitivity is $3K$, as above.

The mode of the social cost of carbon is \$8.0/tC for $3K$, the mode of the climate sensitivity. The expectation of the social cost of carbon is \$50.6/tC, if the uncertainty about the climate sensitivity follows the Roe-Baker distribution, as described above, and the social cost of carbon is a quadratic function of the climate sensitivity, as described above. Assuming a utility function with a constant rate of risk aversion equal to one, the certainty equivalent of paying the social cost of carbon as a tax is \$51.1/tC, if evaluated for the global average income of \$9,500/person/year in 2010 and the average emissions of 1.3 metric tonnes of carbon per person per year. If the rate of risk aversion is two, the certainty equivalent social cost of carbon is \$51.6/tC.

This illustrates two things. First, as the uncertainty about climate change is large and skewed the wrong way, there is a large difference between the mode and the mean, the best guess and the expectation. The latter matters, of course, for decision analysis.

Second, because the carbon tax that would optimally be levied is small relative to income, the risk premium is relatively small. Uncertainty is more important than aversion to risk.

Combining this insight with the range of estimates in Table 16.4, suggests that ambiguity aversion is similarly of secondary importance – even though experts vigorously disagree. Similar conclusions are drawn by other studies (Welsch, 1995; Eismont and Welsch, 1996; Cameron, 2005; Traeger, 2014; Tol, 2015; Lemoine and Traeger, 2016; Heal, 2017).

3.3 Meta-analysis

Tol (2018) counts 111 studies of the social cost of carbon and 1,213 estimates. Since that survey was completed, 534 estimates have been published in 14 new studies (Ackerman and Munitz, 2016; Adler et al., 2017; Budolfson et al., 2017; Cai et al., 2016; Dayaratna et al., 2017; Dennig et al., 2015; Freeman and Groom, 2014; Freeman et al., 2015; Freeman and Groom, 2016; Hatase and Managi, 2015; Lemoine and Traeger, 2016; Nordhaus, 2017; van der Ploeg, 2015; Rose et al., 2017).

I construct a probability density of the social cost of carbon for all published estimates. The method follows Tol (2013), with the estimates weighted by study characteristics, as in Tol (2005). van den Bergh and Botzen (2014) argue that estimates below \$125/tCO_2 are not credible. Theirs is but one paper. Estimates are therefore weighted by $\frac{N-1}{2N-1} I_{SCC \leq \$422/tC} + \frac{N}{2N-1}\, ISCC{>}\$422/tC$, where $N = 125$ is the number of studies, I is the indicator function, and \$422/tC is their threshold in 2010 dollars. In addition, estimates in excess of \$7,600/tC are excluded, as this would imply a carbon tax that exceeds 100% of GDP (at the global average of the carbon intensity of the economy). Estimates between \$1,150/tC and \$7,600/tC are discounted by a linear function that equals 1 for \$1,150/tC and 0 for \$7,600/tC. If the carbon tax equals \$1,150/tC, 100% of government revenue is from the carbon tax (at the global average of the carbon intensity of the public economy). This assumes that the social cost of carbon is a tax that should be paid. If, on the other hand, the social cost of carbon is interpreted as a marginal welfare loss, then there is no upper bound.

The probability density function (PDF) is a kernel density. The kernel function is a Weibull distribution, a heavy-tailed PDF defined on the positive real line. The mode is set equal to the estimate, the bandwidth to the sample standard deviation. The models developed by Hope and Tol acknowledge the possibility that the impacts of modest climate change may be positive. For these estimates, the kernel function is a Gumbel distribution: defined on the real line, heavy-tailed, and right-skewed. The kernel functions for estimates by other authors are therefore knotted at zero.

Results from the meta-analysis

Figure 16.4 presents the probability density of the social cost of carbon for estimates based on selected pure rates of time preference (PRTP). The higher the discount rate, the lower the concern for the future, and the lower the social cost of carbon: The mode is \$202/tC for a 0% PRTP, \$100/tC for a 1% PRTP, and \$28/tC for a 3% PRTP. Furthermore, as the uncertainty grows as we look further into the future, a lower discount rate implies a loss of confidence, with a standard deviation of \$644/tC for a 0% PRTP, \$471/tC for a 1% PRTP, and \$35/tC for a 3% PRTP. The higher mode and standard deviation come together in the mean social cost of carbon, which is \$686/tC for a 0% PRTP, \$378/tC for a 1% PRTP, and \$43/tC for a 3% PRTP. To provide some context, burning a barrel of oil emits 0.43 metric tonnes of carbon dioxide. A \$28/tC carbon tax is thus equivalent to \$3/barrel, while a \$686/tC carbon tax is equivalent to \$80/barrel. The former carbon tax is small (< 5%) relative to today's price of oil, while the latter tax is on the same order as the oil price. In early May 2018, the price of carbon permits in the European Union

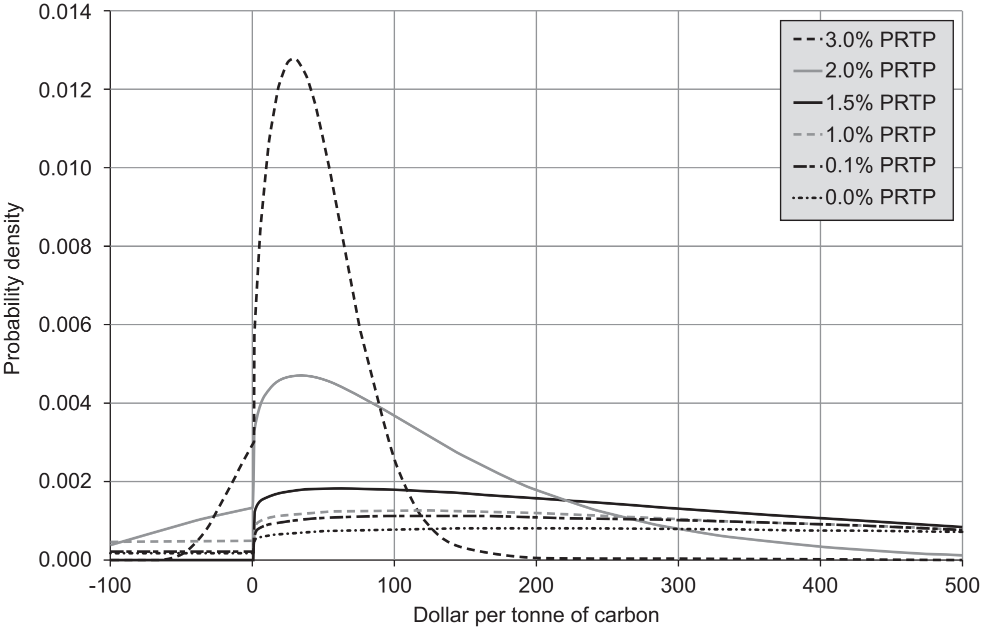

Figure 16.4 Probability density function of the social cost of carbon for alternative pure rates of time preference

Emission Trading System (EU ETS) was $59/tC. In February 2018, permits were auctioned by the California Air Resources Board at $55/tC. This suggests that current climate policy in the most progressive jurisdictions in the world can readily be justified by cost-benefit analysis, and may need to be tightened.

Publication bias

Havranek et al. (2015) argue that lower estimates of the social cost of carbon are less likely to be published than higher estimates. However, the literature on the social cost of carbon does not appear to suffer from confirmation bias. The received wisdom is regularly challenged, at least qualitatively (Tol, 2018). Figure 16.5 shows the median and the 90% confidence interval for estimates of the social cost of carbon published in a particular year and published in previous years. In 8 out of 14 years, new estimates fall outside the 90% confidence interval, 5.7 times more than expected. In this literature, people are not afraid to challenge each other.

Figure 16.5 suggests a gradual decline in the central estimate of the social cost of carbon and a modest tightening of its confidence interval. Downward revisions of the social cost of carbon are not support (because the trends are statistically insignificant) while upward revisions run against the balance of evidence.

3.4 Deep uncertainty

Weitzman (2011) argues that the uncertainty about climate change is so large that the expectation of the social cost of carbon is unbounded. Weitzman's argument is theoretic, but does not seem to be supported by evidence presented here. Moreover, Weitzman's result only holds in partial

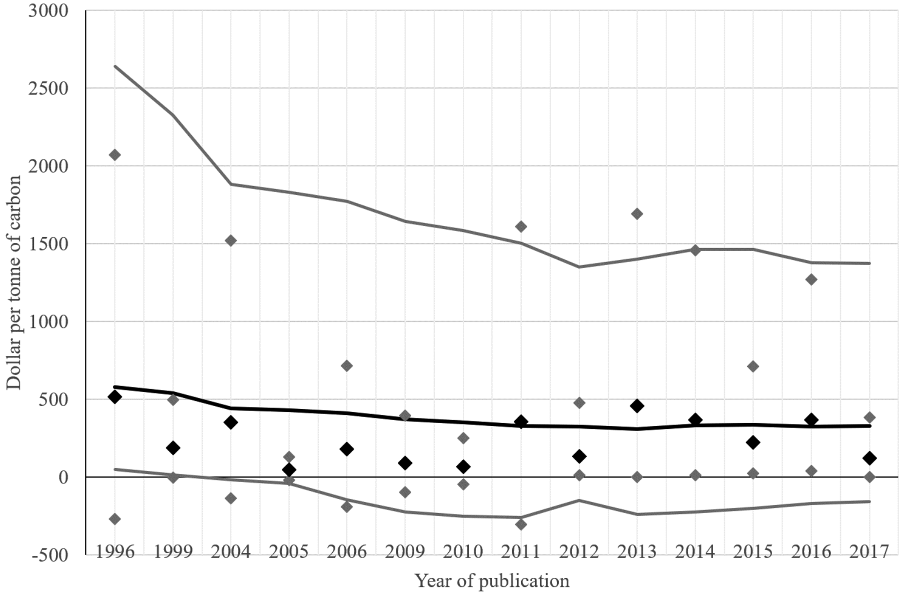

Figure 16.5 The median and the 90% confidence interval of the social cost of carbon as a function of the year of publication. The diamonds show the characteristics of estimates published in the year displayed on the horizontal axis, the lines show estimates for previous years.

equilibrium (Horowitz and Lange, 2014), for zero mitigation (Millner, 2013), and for constant relative risk aversion (Arrow, 2009), while alternative decision criteria do not lead to substantially different policy advice concerning optimal climate policy (Anthoff and Tol, 2014).

3.5 The social cost of carbon over time

Climate change is a dynamic problem, and so is climate policy. It is important to set a price of carbon today. It is at least as important to announce a carbon price for later, so that investors and inventors can anticipate the future demand for carbon-free energy. Figures 16.6 and 16.7 illustrate how the social cost of carbon should change over time.

Figure 16.6 uses the simple model discussed above to compute the social cost of carbon at the start of every decade from 1750 to 2100. Costs are discounted to the year of emission. The pure rate of time preference is 1%, the rate of risk aversion 1. The scenario is SRES A1. The impact model is parabolic; it only allows for negative impacts of climate change (see Table 16.1). The social cost of carbon starts low at $0.26/tC in 1750[2] and rises to $41.77/tC in 2060. Between 2010 and 2050, the social cost of carbon rises by 2%–3% per year.

After 2060, the social cost of carbon falls. This is because the model has its time horizon at 2100. Climate change will probably not stop then, but the model does. With a relatively low discount rate, for later years, an increasingly large share of the net present value is ignored in the estimation of the social cost of carbon. This highlights the interaction between the choice of time horizon and discount rate. Tol and Yohe (2009) show that a pure rate of time preference of 0.1% requires a time horizon of 10,000 years.

Figure 16.7 shows the kernel distribution of the growth rate of the social cost of carbon, using a Normal kernel function with 1.06 times the sample standard deviation over the quint root of the number of observations as bandwidth (Silverman, 1986). The sample is a subsample of the papers used above, restricted to those papers that published estimates of the social cost of carbon

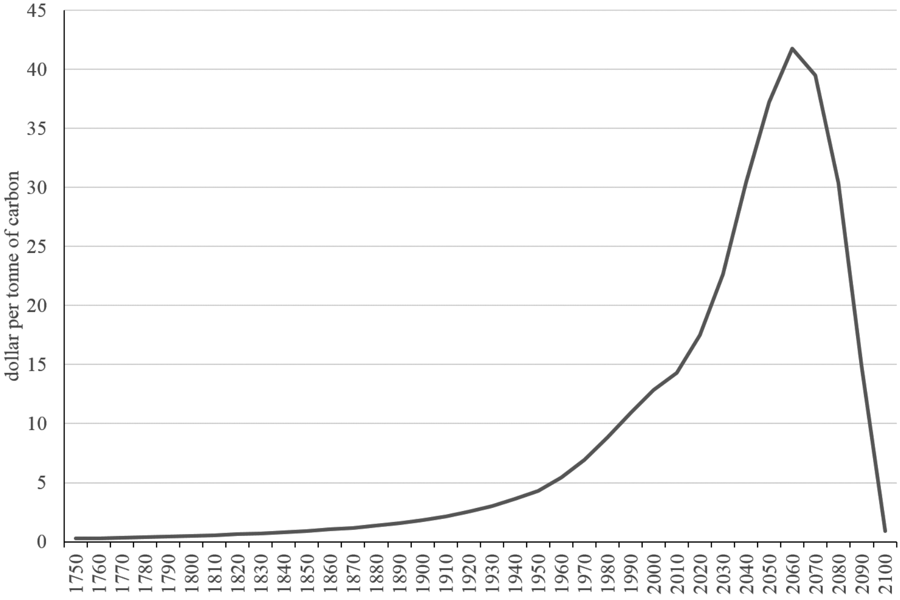

Figure 16.6 The evolution of the social cost of carbon over time

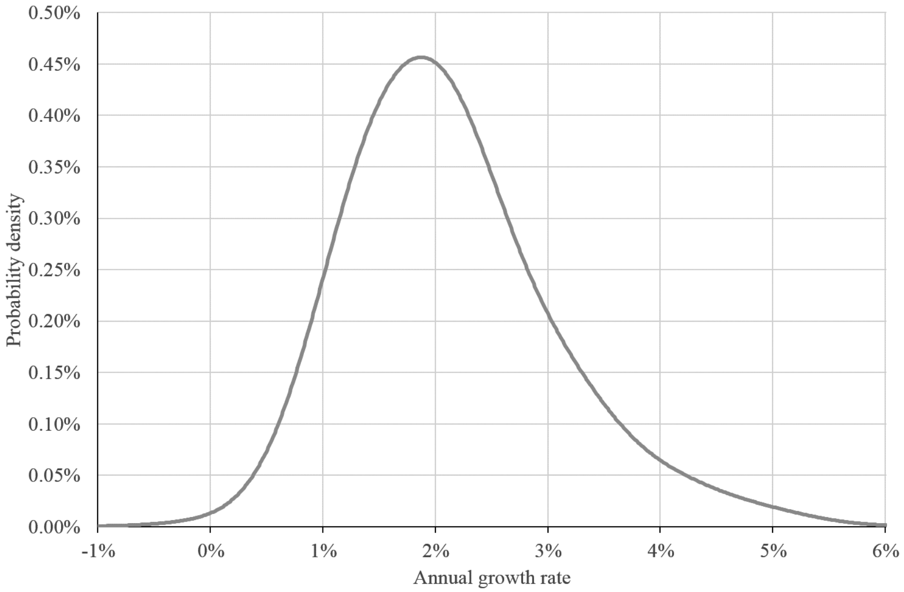

Figure 16.7 Probability density function of the growth rate of the social cost of carbon

at two or more points in time; if more than two time periods are reported, I used the earliest data and the latest at which the social cost of carbon was still rising.[3] The modal growth rate is 1.9% per year and the mean growth rate is 2.1%. The distribution is right-skewed. The probability that the social cost of carbon should fall over time is 0.6%. In other words, if you pick a carbon tax of $100/tC in 2018, you should pick a carbon tax of $102/tC in 2019.

4 Discussion and conclusion

Contrary to popular belief, the total economic impacts of climate change are modest. The best guess is that a century of climate is about as bad as losing a year of economic growth. The uncertainty is rather large, and negative surprises are more likely than positive ones. Poorer countries are more vulnerable. Taken that into account, a century of climate change is about as bad as losing a decade of growth.

There are many caveats. Valuing impacts is hard, and extrapolating values harder. Impact assessments are incomplete, but incompleteness only implies bias if the missing impacts are predominantly negative. Impacts are contingent on adaptation and development, but current models of adaptation are overly simplistic and typical estimates reflect the impact of a future climate on a society of the recent past. Impact estimates are comparative static, ignoring the dynamic effects. Impact assessments focus on the most likely outcomes at the expense of more salient but hard to quantify tail-risks.

As the economic impact of climate change is negative, there is a benefit to reducing greenhouse gas emissions. Indeed, a meta-analysis reveals that the vast majority of published estimates of the social cost of carbon is positive. That is, at the margin, emission reduction is beneficial. Greenhouse gas emissions should be taxed, at a rate that gradually increases over time. Estimates vary widely, because the social cost of carbon depends on many parameters that reasonable people can reasonably disagree about, including scenarios about how the future might unfold, the response of the climate system to emissions, and the impact of climate change and its valuation.

Estimates of the social cost of carbon are also determined by ethical parameters such as the rates of pure time preference, risk aversion, and inequality aversion (Anthoff et al., 2009). These parameters can be set with reference to the guidance provided by religious leaders (Augustine, Muhammad), philosophers (Socrates, Rawls), or other thought leaders (Johnny Rotten, Lady Gaga). But as the social cost of carbon is meant to guide the government in its choice of the ambition of climate policy in the near term, this is tantamount to paternalism. Alternatively, the government may decide to follow the will of the people. Unfortunately, measuring preferences is difficult (see e.g. Frederick et al., 2002) and preferences revealed through private transactions need not reflect preferences for public policy (for instance when that private transaction involves a public good; see Bergstrom et al., 1986).

Future research should lead to a better understanding of the social cost of carbon. Estimates for understudied impacts – transport, energy supply, tourism, ocean acidification, water, and air pollution – and the interactions between climate and development would complete the analysis, while further study of other impacts may narrow the uncertainties. Such research requires an understanding not only of economics, both for valuation and adaptation, but also of relevant academic discipline, be it ecology, hydrology, physiology, or agronomy. Part of the current uncertainty is irreducible, as the social cost of carbon measures the impact of future emissions on future societies. With regard to ethical parameters, the best we can do is a careful mapping of assumptions to conclusions, as it is not for us to decide what the right numbers or approaches are. We should nevertheless seek to estimate the relevant parameters, if only to highlight that certain ethical choices appear to have little support among the electorate.

Notes

1 This study was done at a time when no one could reasonably claim expertise on the economic impacts of climate change.

2 Linearization at the margin is the appropriate way to apportion liability for past emissions.

3 In the long run, the social cost of carbon may start falling as emissions approach zero and the climate starts to cool.

References

Ackerman, F. and C. Munitz. A critique of climate damage modeling: Carbon fertilization, adaptation, and the limits of fund. *Energy Research Social Science*, 12:62–67, 2016. URL www.sciencedirect.com/science/article/pii/S2214629615300773.

Adger, W. N. Vulnerability. *Global Environmental Change*, 16(3):268–281, 2006. ISSN 0959–3780. URL www.sciencedirect.com/science/article/pii/S0959378006000422. Resilience, Vulnerability, and Adaptation: A Cross-Cutting Theme of the International Human Dimensions Programme on Global Environmental Change.

Adler, M., D. Anthoff, V. Bosetti, G. Garner, K. Keller, and N. Treich. Priority for the worse-off and the social cost of carbon. *Nature Climate Change*, 7:443–449, 2017.

Anthoff, D. and R.S.J. Tol. Climate policy under fat-tailed risk: an application of FUND. *Annals of Operations Research*, 220(1):223–237, September 2014. URL https://ideas.repec.org/a/spr/annopr/v220y2014i1p223–23710.1007-s10479-013-1343-2.html.

Anthoff, D. and R.S.J. Tol. On international equity weights and national decision making on climate change. *Journal of Environmental Economics and Management*, 60(1):14–20, 2010. ISSN 0095-0696. doi: https://doi.org/10.1016/j.jeem.2010.04.002. URL www.sciencedirect.com/science/article/pii/S0095069610000422.

Anthoff, D., R.S.J. Tol and G. W. Yohe. Risk aversion, time preference, and the social cost of carbon. *Environmental Research Letters*, 4(2–2):1–7, 2009.

Arrow, K. A note on uncertainty and discounting in models of economic growth. *Journal of Risk and Uncertainty*, 38(2):87–94, April 2009. URL https://ideas.repec.org/a/kap/jrisku/v38y2009i2p87–94.html.

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. Determining benefits and costs for future generations. *Science*, 341(6144):349–350, 2013. ISSN 0036-8075. doi: 10.1126/science.1235665. URL http://science.sciencemag.org/content/341/6144/349.

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. Should governments use a declining discount rate in project analysis? *Review of Environmental Economics and Policy*, 8(2):145–163, 2014. URL http://dx.doi.org/10.1093/reep/reu008.

Atkinson, A. B. On the measurement of inequality. *Journal of Economic Theory*, 2:244–263, 1970.

Bergstrom, T., L. Blume and H. Varian. On the private provision of public goods. *Journal of Public Economics*, 29(1):25–49, 1986.

Berz, G. Insuring against catastrophe. *Disasters*, 1996. URL www.ourplanet.com/imgversn/113/berz.html.

Bosello, F., F. Eboli and R. Pierfederici. Assessing the economic impacts of climate change. *Review of Environment Energy and Economics*: 1–9, 2012.

Budolfson, M., F. Dennig, M. Fleurbaey, A. Siebert and R. H. Socolow. The comparative importance for optimal climate policy of discounting, inequalities and catastrophes. *Climatic Change*, 145(3):481–494, December 2017. URL https://doi.org/10.1007/s10584-017-2094-x.

Burke, M., W. M. Davis and N. S. Diffenbaugh. Large potential reduction in economic damages under UN mitigation targets. *Nature*, 557(7706):549–553, 2018. URL https://doi.org/10.1038/s41586-018-0071-9.

Burke, M., S. M. Hsiang and E. Miguel. Global non-linear effect of temperature on economic production. *Nature*, 527(7577):235–239, 2015. doi: 10.1038/nature15725.

Cai, Y., T. M. Lenton and T. S. Lontzek. Risk of multiple interacting tipping points should encourage rapid co2 emission reduction. *Nature Climate Change*, 6:520–525, 2016.

Cameron, T. Updating subjective risks in the presence of conflicting information: An application to climate change. *Journal of Risk and Uncertainty*, 30(1):63–97, 2005. doi: 10.1007/s11166-005-5833-8.

Cohen, A. and L. Einav. Estimating risk preferences from deductible choice. *American Economic Review*, 97(3):745–788, 2007. doi: 10.1257/aer.97.3.745.

d'Arge, R. *Climate and economic activity*, pages 652–681. World Meteorological Organization, Geneva, 1979.

Dayaratna, K., R. McKitrick and D. Kreutzer. Empirically constrained climate sensitivity and the social cost of carbon. *Climate Change Economics*, 08(02):1750006, 2017. URL www.worldscientific.com/doi/abs/10.1142/S2010007817500063.

Dell, M., B. F. Jones and B. A. Olken. What do we learn from the weather? the new climate-economy Literature. *Journal of Economic Literature*, 52(3):740–798, 2014.

Dennig, F., M. B. Budolfson, M. Fleurbaey, A. Siebert and R. H. Socolow. Inequality, climate impacts on the future poor, and carbon prices. *Proceedings of the National Academy of Sciences*, 112(52):15827–15832, 2015. doi: 10.1073/pnas.1513967112. URL www.pnas.org/content/112/52/15827.

Deryugina, T. and S. Hsiang. The marginal product of climate. Working Paper 24072, National Bureau of Economic Research, November 2017. URL www.nber.org/papers/w24072.

Deschenes, O. and M. Greenstone. The economic impacts of climate change: Evidence from agricultural output and random fluctuations in weather. *American Economic Review*, 97(1):354–385, 2007.

Dietz, S. and G. B. Asheim. Climate policy under sustainable discounted utilitarianism. *Journal of Environmental Economics and Management*, 63(3):321–335, 2012. ISSN 0095-0696. https://doi.org/10.1016/j.jeem.2012.01.003. URL www.sciencedirect.com/science/article/pii/S0095069612000058.

Donkers, B., B. Melenberg and A. Van Soest. Estimating risk attitudes using lotteries: A large sample approach. *Journal of Risk and Uncertainty*, 22(2):165–195, 2001. doi: 10.1023/A:1011109625844.

Eismont, O. and H. Welsch. Optimal greenhouse gas emissions under various assessments of climate change ambiguity. *Environmental and Resource Economics*, 8(2):129–140, 1996. doi: 10.1007/BF00357360.

Fankhauser, S. *Valuing Climate Change: The Economics of the Greenhouse*, volume 1. EarthScan, London, 1995. ISBN 1-85383-237-5.

Frederick, S., G. Loewenstein and T. O'Donoghue. Time discounting and time preference: A critical review. *Journal of Economic Literature*, 40(2):351–401, 2002.

Freeman, M. C. and B. Groom. How certain are we about the certainty-equivalent long term social discount rate? *Journal of Environmental Economics and Management*, 79:152–168, 2016. URL www.sciencedirect.com/science/article/pii/S0095069616300845.

Freeman, M. C. and B. Groom. Positively gamma discounting: Combining the opinions of experts on the social discount rate. *The Economic Journal*, 125(585):1015–1024, 2014. URL https://onlinelibrary.wiley.com/doi/abs/10.1111/ecoj.12129.

Freeman, M. C., B. Groom, E. Panopoulou and T. Pantelidis. Declining discount rates and the fisher effect: Inflated past, discounted future? *Journal of Environmental Economics and Management*, 73:32–49, 2015. URL www.sciencedirect.com/science/article/pii/S0095069615000492.

Golosov, M., J. Hassler, P. Krusell and A. Tsyvinski. Optimal taxes on fossil fuel in general equilibrium. *Econometrica*, 82(1):41–88, 2014. URL https://onlinelibrary.wiley.com/doi/abs/10.3982/ECTA10217.

Greenstone, M., E. Kopits, and A. Wolverton. Developing a social cost of carbon for us regulatory analysis: A methodology and interpretation. *Review of Environmental Economics and Policy*, 7(1):23–46, 2013.

Guivarch, C., A. Mjean, A. Pottier and M. Fleurbaey. Social cost of carbon: Global duty. *Science*, 351(6278):1160, 2016.

Hahn, R. W. and R. A. Ritz. Does the social cost of carbon matter? Evidence from us policy. *Journal of Legal Studies*, 44(1):229–248, 2015.

Hartog, J., A. Ferrer-i Carbonell, and N. Jonker. Linking measured risk aversion to individual characteristics. *Kyklos*, 55(1):3–26, 2002. doi: 10.1111/1467-6435.00175.

Hatase, K. and S. Managi. Increase in carbon prices: Analysis of energy-economy modeling. *Environmental Economics and Policy Studies*, 17(2):241–262, April 2015. URL https://doi.org/10.1007/s10018-014-0101-2.

Havranek, T., Z. Irsova, K. Janda and D. Zilberman. Selective reporting and the social cost of carbon. *Energy Economics*, 51:394–406, 2015. URL www.sciencedirect.com/science/article/pii/S0140988315002327.

Heal, G. The economics of the climate. *Journal of Economic Literature*, 55(3):1046–1063, 2017. doi: 10.1257/jel.20151335.

Heyes, A., D. Morgan and N. Rivers. The use of a social cost of carbon in Canadian cost-benefit analysis. *Canadian Public Policy*, 39(Suppl.2):S67–S79, 2013.

Hope, C. W. The marginal impact of co2 from page2002: An integrated assessment model incorporating the IPCC's five reasons for concern. *Integrated Assessment Journal*, 6(1):19–56, 2006.

Horowitz, J. and A. Lange. Cost benefit analysis under uncertainty a note on Weitzman's dismal theorem. *Energy Economics*, 42:201–203, 2014. URL www.sciencedirect.com/science/article/pii/S014098831300296X.

Howard, P. H. and T. Sterner. Few and not so far between: A meta-analysis of climate damage estimates. *Environmental and Resource Economics*, 68(1):197–225, September 2017. URL https://doi.org/10.1007/s10640–017–0166-z.

Hsiang, S., R. Kopp, A. Jina, J. Rising, M. Delgado, S. Mohan, D. J. Rasmussen, R. Muir-Wood, P. Wilson, M. Oppenheimer, K. Larsen, and T. Houser. Estimating economic damage from climate change in the united states. *Science*, 356(6345):1362, 2017.

Keller, K., B. M. Bolker, and D. F. Bradford. Uncertain climate thresholds and optimal economic growth. *Journal of Environmental Economics and Management*, 48:723–741, 2004.

Koopmans, T. C. Stationary ordinal utility and impatience. *Econometrica*, 28(2):287–309, 1960. ISSN 00129682, 14680262. URL www.jstor.org/stable/1907722.

Lemoine, D. and C. P. Traeger. Ambiguous tipping points. *Journal of Economic Behavior Organization*, 132:5–18, 2016. URL www.sciencedirect.com/science/article/pii/S0167268116300221. Thresholds, Tipping Points, and Random Events in Dynamic Economic Systems.

Llavador, H., J. E. Roemer and J. Silvestre. A dynamic analysis of human welfare in a warming planet. *Journal of Public Economics*, 95(11):1607–1620, 2011. ISSN 0047-2727. https://doi.org/10.1016/j.jpubeco.2011.05.017. URL www.sciencedirect.com/science/article/pii/S0047272711000922. Special Issue: International Seminar for Public Economics on Normative Tax Theory.

Maddison, D. J. The amenity value of the climate: The household production function approach. *Resource and Energy Economics*, 25(2):155–175, 2003.

Maddison, D. J. and K. Rehdanz. The impact of climate on life satisfaction. *Ecological Economics*, 70(12): 2437–2445, 2011. URL www.sciencedirect.com/science/article/pii/S0921800911003028.

Maier-Reimer, E. and K. Hasselmann. Transport and storage of co2 in the ocean: An inorganic ocean-circulation carbon cycle model. *Climate Dynamics*, 2(2):63–90, August 1987. URL https://doi.org/10.1007/BF01054491.

Mendelsohn, R. O., M. E. Schlesinger and L. J. Williams. Comparing impacts across climate models. *Integrated Assessment*, 1(1):37–48, 2000.

Metcalf, G. E. and J. H. Stock. Integrated assessment models and the social cost of carbon: A review and assessment of U.S. experience. *Review of Environmental Economics and Policy*, 11(1):80–99, 2017.

Millner, A. On welfare frameworks and catastrophic climate risks. *Journal of Environmental Economics and Management*, 65(2):310–325, 2013. URL www.sciencedirect.com/science/article/pii/S0095069612001209.

Nakicenovic, N. and R. Swart, editors. *Special Report on Emissions Scenarios: A special Report of Working Group III of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, 2000.

Nordhaus, W. D. Expert opinion on climate change. *American Scientist*, 82(1):45–51, 1994b.

Nordhaus, W. D. Geography and macroeconomics: New data and new findings. *Proceedings of the National Academy of Science*, 103(10):3510–3517, 2006. URL www.pnas.org/cgi/doi/10.1073/pnas.0509842103.

Nordhaus, W. D. How fast should we graze the global commons? *American Economic Review*, 72(2):242–246, 1982.

Nordhaus, W. D. *Managing the Global Commons: The Economics of Climate Change*. The MIT Press, Cambridge, 1994a.

Nordhaus, W. D. *A Question of Balance: Weighing the Options on Global Warming Policies*. Yale University Press, New Haven, 2008.

Nordhaus, W. D. Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, 114(7):1518–1523, 2017. URL www.pnas.org/content/114/7/1518.

Nordhaus, W. D. To slow or not to slow: The economics of the greenhouse effect. *Economic Journal*, 101(444):920–937, 1991.

Nordhaus, W. D. and J. G. Boyer. *Warming the World: Economic Models of Global Warming*. The MIT Press, Cambridge, MA and London, England, 2000. ISBN 0-262-14071-3.

Nordhaus, W. D. and A. Moffat. A survey of global impacts of climate change: Replication, survey methods, and a statistical analysis. Working Paper 23646, National Bureau of Economic Research, August 2017. URL www.nber.org/papers/w23646.

Nordhaus, W. D. and Z. Yang. Rice: A regional dynamic general equilibrium model of optimal climate-change policy. *American Economic Review*, 86(4):741–765, 1996.

Pigou, A. *The Economics of Welfare*. Macmillan, London, 1920.

Pindyck, R. S. Coase lecturetaxes, targets and the social cost of carbon. *Economica*, 84(335):345–364, 2017a.

Pindyck, R. S. The use and misuse of models for climate policy. *Review of Environmental Economics and Policy*, 11(1):110–114, 2017b. ISSN 21097.

Pizer, W., M. Adler, J. Aldy, D. Anthoff, M. Cropper, K. Gillingham, M. Greenstone, B. Murray, R. Newell, R. Richels, A. Rowell, S. Waldhoff and J. Wiener. Using and improving the social cost of carbon. *Science*, 346(6214):1189–1190, 2014.

Plambeck, E. L. and C. W. Hope. Page95: An updated valuation of the impacts of global warming. *Energy Policy*, 24(9):783–793, 1996.

Ramsey, F. P. A mathematical theory of saving. *The Economic Journal*, 38(152):543–559, 1928. URL www.jstor.org/stable/2224098.

Rehdanz, K. and D. J. Maddison. Climate and happiness. *Ecological Economics*, 52(1):111–125, 2005.

Revesz, R., M. Greenstone, M. Hanemann, M. Livermore, T. Sterner, D. Grab, P. Howard and J. Schwartz. Best cost estimate of greenhouse gases. *Science*, 357(6352):655, 2017. URL http://science.sciencemag.org/content/357/6352/655.abstracthttp://science.sciencemag.org/content/sci/357/6352/655.full.pdf.

Riahi, K., D. P. van Vuuren, E. Kriegler, J. Edmonds, B. C. ONeill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, W. Lutz, A. Popp, J. C. Cuaresma, S. KC, M. Leimbach, L. Jiang, T. Kram, S. Rao, J. Emmerling, K. Ebi, T. Hasegawa, P. Havlik, F. Humpender, L.A.D. Silva, S. Smith, E. Stehfest, V. Bosetti, J. Eom, D. Gernaat, T. Masui, J. Rogelj, J. Strefler, L. Drouet, V. Krey, G. Luderer, M. Harmsen, K. Takahashi, L. Baumstark, J. C. Doelman, M. Kainuma, Z. Klimont, G. Marangoni, H. Lotze-Campen, M. Obersteiner, A. Tabeau and M. Tavoni. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, 42:153–168, 2017. ISSN 0959-3780. https://doi.org/10.1016/j.gloenvcha.2016.05.009. URL www.sciencedirect.com/science/article/pii/S0959378016300681.

Ricardo, D. *On the Principles of Political Economy and Taxation.* John Murray, London, 1817.

Roe, G. H. and M. B. Baker. Why is climate sensitivity so unpredictable? *Science*, 318(5850):629–632, 2007. doi: 10.1126/science.1144735. URL http://science.sciencemag.org/content/318/5850/629.

Rose, S. K. The role of the social cost of carbon in policy. *WIREs Climate Change*, 3:195–212, 2012.

Rose, S. K., D. B. Diaz and G. J. Blanford. Understanding the social cost of carbon: A model diagnostic and inter-comparison study. *Climate Change Economics*, 08(02):1750009, 2017. URL www.worldscientific.com/doi/abs/10.1142/S2010007817500099.

Roson, R. and D. van der Mensbrugghe. Climate change and economic growth: Impacts and interactions. *International Journal of Sustainable Economy*, 4(3):270–285, 2012.

Saelen, H., S. Dietz, C. Hepburn, J. Helgeson and G. Atkinson. Siblings, not triplets: Social preferences for risk, inequality and time in discounting climate change. *Economics: The Open-Access, Open-Assessment E-Journal*, 3(26):1–28, 2009.

Schneider, S. H. and S. L. Thompson. Atmospheric co2 and climate: Importance of the transient response. *Journal of Geophysical Research*, 86(C4):3135–3147, 1981.

Silverman, B. *Density Estimation for Statistics and Data Analysis*. Chapman Hall, London, 1986.

Sunstein, C. R. On not revisiting official discount rates: Institutional inertia and the social cost of carbon. *American Economic Review*, 104(5):547–551, 2014.

Tol, R.S.J. Bootstraps for meta-analysis with an application to the impact of climate change. *Computational Economics*, 46(2):287–303, 2015. doi: 10.1007/s10614-014-9448-5.

Tol, R.S.J. The damage costs of climate change toward more comprehensive calculations. *Environmental and Resource Economics*, 5(4):353–374, 1995.

Tol, R.S.J. The economic impacts of climate change. *Review of Environmental Economics and Policy*, 12(1):4–25, 2018. URL http://dx.doi.org/10.1093/reep/rex027.

Tol, R.S.J. Estimates of the damage costs of climate change, part i: Benchmark estimates. *Environmental and Resource Economics*, 21(1):47–73, 2002.

Tol, R.S.J. International inequity aversion and the social cost of carbon. *Climate Change Economics*, 01(01): 21–32, 2010. URL www.worldscientific.com/doi/abs/10.1142/S2010007810000029.

Tol, R.S.J. The marginal damage costs of carbon dioxide emissions: An assessment of the uncertainties. *Energy Policy*, 33:2064–2074, 2005.

Tol, R.S.J. The social cost of carbon. *Annual Review of Resource Economics*, 3:419–443, 2011.

Tol, R.S.J. Targets for global climate policy: An overview. *Journal of Economic Dynamics Control*, 37(5):911–928, 2013.

Tol, R.S.J. and G. W. Yohe. The stern review: A deconstruction. *Energy Policy*, 37(3):1032–1040, 2009. ISSN 0301-4215. https://doi.org/10.1016/j.enpol.2008.11.008. URL www.sciencedirect.com/science/article/pii/S0301421508007076.

Traeger, C. Why uncertainty matters: Discounting under intertemporal risk aversion and ambiguity. *Economic Theory*, 56(3):627–664, 2014. doi: 10.1007/s00199-014-0800-8.

van den Bergh, J.C.J.M. and W.J.W. Botzen. A lower bound to the social cost of co2 emissions. *Nature Climate Change*, 4(4):253–258, 2014. URL http://dx.doi.org/10.1038/nclimate2135.

van der Ploeg, F. Untapped fossil fuel and the green paradox: A classroom calibration of the optimal carbon tax. *Environmental Economics and Policy Studies*, 17(2):185–210, April 2015. URL https://doi.org/10.1007/s10018-014-0097-7.

Weitzman, M. L. Fat-tailed uncertainty in the economics of catastrophic climate change. *Review of Environmental Economics and Policy*, 5(2):275–292, 2011.

Welsch, H. Greenhouse gas abatement under ambiguity. *Energy Economics*, 17(2):91–100, 1995. doi: 10.1016/0140-9883(95)00010-R.

WorldBank and Ecofys. State and trends of carbon pricing 2018. Technical report, World Bank, Washington, DC, 2018. URL https://openknowledge.worldbank.org/handle/10986/29687.

Yohe, G. W. and R.S.J. Tol. Indicators for social and economic coping capacity: Moving towards a working definition of adaptive capacity. *Global Environmental Change*, 12(1):25–40, 2002.