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Economic impacts of climate change

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Abstract: Climate change will probably have a limited impact on the economy and human welfare in the 21st century. The initial impacts of climate change may well be positive. In the long run, the negative impacts dominate the positive ones. Negative impacts will be substantially greater in poorer, hotter, and lower-lying countries. Poverty reduction complements greenhouse gas emissions reduction as a means to reduce climate change impacts. Climate change may affect the growth rate of the economy and may trap more people in poverty but quantification is difficult. The optimal carbon tax in the near term is somewhere between a few tens and a few hundreds of dollars per tonne of carbon.

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1. Introduction

For such a fractious discipline, there has been remarkable agreement amongst economists on first-best climate policy. Ever since the writings of Nordhaus (1977), d'Arge (1979) and Schelling (1992), it has been widely accepted that climate change is, on balance, a negative externality and that greenhouse gas emissions should be priced, preferably taxed. There is a vigorous debate about the eventual climate targets (Nordhaus, 2013; Stern et al., 2006), but few dispute that a sensible climate policy starts gradually before accelerating (Goulder & Mathai, 2000; Wigley, Richels, & Edmonds, 1996). Estimates of the marginal impact of climate change range so widely (see below) that the initial carbon price is a matter of politics rather than economics.

Despite the agreement, the debate about the economics of climate change is unusually bitter, perhaps because there is so little to disagree about, or as a reflection of the wider polarization of climate research and climate policy. Young economists should think twice before entering the climate research but the paper nonetheless ends (Section 7) with a research agenda for the economic impacts of climate change.

Prior to that, I explore estimates of the total economic impact of climate change (Section 2), the distribution of those impacts across the world (Section 3), the impact of economic development on vulnerability to climate change (Section 4), the impact of climate change on economic development (Section 5), and the social cost of carbon (Section 6). In each section, I discuss the state of play while emphasizing recent developments.

2. The total impact of climate change

The impacts of climate change are many and diverse. The question whether climate change is beneficial or detrimental, big or large, depends on sector, location and time. Reading through the literature on the impacts of climate change (Field & Canziani, 2014) would leave one confused. There as so many, so different effects: crops hit by worsening drought, crops growing faster because of carbon dioxide fertilization, heat stress increasing, cold stress decreasing, sea levels rising, cooling energy demand going up, heating energy demand going down, infectious disease spreading, species going extinct. It is hard to make sense of this. Therefore, aggregate indicators are needed to assess whether climate change is, on balance, a good thing or a bad thing, and whether the climate problem is small or large relative to the many other problems that we have. Smith et al. (2001) introduced alternative high-level indicators. I here focus on two of their four reasons for concern: the impact of climate change on total economic welfare, and the distribution of those welfare impacts.

Figure 1 shows the 27 published estimates of the total economic impact of climate change, taken from 22 studies listed in Table 1. The numbers should be read as follows: A global warming of 2.5ºC would make the average person feels as if she had lost 1.3% of her income. (1.3% is the average of the 11 estimates at 2.5ºC.)

These estimates were derived as follows. Field experts used models – of every sort – to estimate the impacts of climate change for all parts of the world. Economists took these impact estimates, estimated the values of these impacts, multiplied the quantities and prices, and added everything up. This is the so-called enumerative method (Berz; d'Arge, 1979; Fankhauser, 1995; Hope, 2006; Nordhaus, 1982, 1991, 1994b, 2008, 2013; Nordhaus & Boyer, 2000; Nordhaus & Yang, 1996; Plambeck & Hope, 1996; Tol, 1995, 2002).

Other estimates involve regressions of some sort of variations of economic quantity over space on climate variations over space (Maddison & Rehdanz, 2011; Maddison, 2003;

Mendelsohn, Schlesinger, & Williams, 2000; Nordhaus, 2006; Rehdanz & Maddison, 2005). Agricultural land prices, for instance, reflect the productivity of the land and hence the value of the climate that allows plants to grow. Expenditure patterns, income and self-reported happiness each in their own way reflect how climate constrains or enables economic activity. The main advantage of the statistical method is that is based on actual behaviour (rather than modelled behaviour as in the enumerative method). 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 differs much more strongly over space than over time.

Yet other estimates elicit the views of, supposed, experts (Nordhaus, 1994a), or use the physical impact estimates also used in the enumerative studies to shock a computable general equilibrium model and derive a welfare estimate that takes all market interactions into account (Bosello, Eboli, & Pierfederici, 2012; Roson & van der Mensbrugghe, 2012).

Pindyck (2013) argues that the estimates of the economic impact of climate change have no foundation in economic theory. While no estimate is perfect, the existing estimates use well-established and well-accepted methods. Moreover, the estimates in Figure 1 are based on different methods, yet corroborate each other. External validity is a problem, but this is true for any prediction of the future. Pindyck (2015) tones down the rhetoric, arguing instead for simplicity and transparency. One may counter that Pindyck's contributions to climate policy suffer from oversimplification.

Figure 1 contains many messages. First of all, there are only 27 estimates, a thin basis for any conclusion.

The 11 estimates for 2.5ºC show that researchers disagree on the sign of the net impact: 3 are positive, and 8 negative. Climate change may lead to a welfare gain or loss. At the same time, researchers agree on the order of magnitude – despite the variety of methods used to estimate these numbers. The welfare change caused by climate change is equivalent to the welfare change caused by an income change of a few percent. That is, a century of climate change is about as good/bad for welfare as a year of economic growth.

Statements that climate change is the biggest (environmental) problem of humankind are unfounded: We can readily think of bigger problems. For example, the people of Greece lost a third of their income in five years' time, arguably because monetary policy was unfit for purpose. The people of Syria lost more in a shorter period.

Considering all 27 estimates, it is suggested that initial warming is positive on net, while further warming would lead to net damages (d'Arge, Schulze, & Brookshire, 1982). This is illustrated by the solid line in Figure 1, which depicts a piecewise linear model. See Table 2 for alternative specifications and how they fare when fitted to the data of Table 1, an exercise not done often enough in climate economics. The piecewise linear model of Figure 1 is by far the best fit, followed by the parabola of (Tol, 2009). Other impact functions do not fit the data at all. Weitzman (2011), for instance, argues that the climate change impact function is very non-linear, with a sharp turn towards large damages at more profound global warming. This claim is not supported by the empirical evidence shown in Figure 1.

The initially positive impacts do not imply that greenhouse gas emissions should be subsidized. In Figure 1, the total impacts turn negative just below 1.7ºC warming above pre-industrial. More importantly, the *incremental* impacts turn negative before that, around 1.1ºC global warming. Because of the slow workings of the climate system and the large inertia in the energy sector, a warming of 2ºC can probably not be avoided and a warming of 1ºC can certainly not be avoided. 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.

The uncertainty is rather large, however. The error bars in Figure 1, derived from the few standard errors report in Table 1, depict the 95% 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 well. Taking the confidence interval at face value, the impact of climate change does not significantly deviate from zero until 3.5°C warming.

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 (Clarke et al., 2014; Nakicenovic & Swart, 2001; van Vuuren et al., 2011). It is true for climate itself: Feedbacks that accelerate climate change are likely to be stronger than feedbacks that dampen warming (Knutti & Hegerl, 2008; Lewis, 2013; Roe & Baker, 2007). The impacts of climate change are typically found to be more than linear: If climate change doubles, its impacts more than double (cf. Figure 1). Many have painted dismal scenarios of climate change (Myers, 1993; Oppenheimer et al., 2014; Potsdam Institute for Climate Impact & Climate, 2012; Stern et al., 2006), but no one has credibly suggested that climate change will make us all blissfully happy. In the light of these uncertainties and asymmetries, the above conclusion needs to be rephrased: A century of climate change is no worse than losing a decade of economic growth.

The right-hand side of Figure 1 is interesting too. At 3.0ºC of warming, impacts are negative and deteriorating, and its uncertainty is widening. It is likely that the world will warm beyond 3.0ºC. Yet, beyond that point, there are few estimates only. Instead, there is extrapolation and speculation.

3. Regional impacts

Thirteen of the 22 studies listed in Table 1 report not only an estimate of the global economic impact of climate change but also regional impact estimates or even, in the case of the Maddison papers, national impact estimates.

These estimates show that poorer and hotter countries are notably more vulnerable to climate change than richer ones. Regressing the estimated regional impact on per capita income and average annual temperature, with dummies for the studies, I find that

$$(1) \qquad I_c = -13.4\ (8.7) + 1.70(0.79)\ ln\, y_c - 0.46(0.14) T_c$$

where I_c is the impact in country *c* (in percent GDP), y_c is its average income, and T_c is the average annual temperature. The equation and the estimated parameters match the findings above, which is no surprise as the source of information is the same. Hotter countries have more negative impacts. Richer countries have more positive impacts. As an illustration, Canada and Japan have a similar income but Japan is much warmer; the impact of 2.5˚C warming is +7.5% GDP in Canada but -0.1% GDP in Japan. Japan and Turkey have a similar climate but Turkey is much poorer; its impact is -2.7% GDP.

Figure 2 shows the expected impacts by country for a global warming of 2.5˚C. In the top panel, countries are ranked from low to high per capita income (in 2005); in the bottom panel, the ranking is by average annual temperature. In Figure 1, the global total impact is -1.4% of GDP for 2.5˚C warming. In Figure 2, the majority of countries shows a more negative impact. This is because the world economy is concentrated in a few, rich countries. The world average in Figure 2 counts dollars, rather than countries, let alone people.

Figure 2 also shows that, by and large, the negative impacts of climate change will fall on developing economies. Some have argued that the proportional impacts of climate change increase with per capita income (Hoel & Sterner, 2007; Sterner & Persson, 2008). The empirical evidence shows the opposite.[1]

There are three reasons for the disproportional vulnerability of developing countries. 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) from the vagaries of weather and hence climate change. Agriculture and water resources are far more important, relative to the size of the economy, in poorer countries.

Second, poorer countries tend to be in hotter places. This means that ecosystems are closer to their biophysical upper limits, and that there are no analogues for human behaviour and technology. Great Britain's future climate may become like Spain's current climate. The people of Britain would therefore adopt some of the habits of the people of Spain, and build their houses like the Spaniards do. If the hottest climate on the planet gets hotter still, there are no examples to copy from; new technologies will have to be invented, behaviour will have to be adjusted by trial and error.

Third, poorer countries often lack access to modern technology and institutions that can help protect against the weather, such as air conditioning, malaria medicine, crop insurance. Poorer countries may lack the ability, and sometimes the political will, to mobilize the resources for large-scale infrastructure—irrigation and coastal protection, for example. In other words, poorer countries tend to have a limited adaptive capacity (Adger, 2006; Yohe & 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. Adaptive capacity also depends on human and social capital. An ounce of prevention is worth a pound of cure, but prevention requires that you are able to recognize problems before they manifest themselves and that you are able to act on that knowledge. 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, the elite may chose to ignore the impacts.

For these reasons, poorer countries are more vulnerable to climate change, as reflected in Equation (1). Of course, that simple equation does not capture the special vulnerability of delta and island nations, some of which would disappear altogether unless they spend a large fraction of their income on coastal protection (Hinkel et al., 2014; Nicholls & Tol, 2006).

4. Development and climate policy

The disproportionate exposure to climate change of those most vulnerable is a good reason to be cautious about greenhouse gas emissions. The case has been exaggerated, however. It is peculiar to express great concern about the plight of the poor when it comes to climate but not in other policy domains (Schelling, 1992, 2000). Levels of charitable giving and official

[1] Note that Equation (1) implies an income elasticity of impacts, but since the impact can be both positive and negative, the elasticity is not readily interpreted or, around zero impact, meaningful.

development aid suggest a low level of inequity aversion between countries (Tol, 2010). Our trade and migration policies suggest a greater disregard for the extra-jurisdictional poor. More importantly, there are two ways to mitigate the excessive impact of climate change on the poor: Reduce climate change, and reduce poverty.

Bangladesh and the Netherlands are two densely populated, low-lying countries at risk from flooding by river and sea. Bangladesh is generally seen to be very vulnerable to climate change whereas most think that the Netherlands will be able to cope. After all, the Netherlands is famous for thriving below sea level. The Netherlands started its modern, large-scale dike building program only in 1850 (Tol & Langen, 2000). Before that, dike building was local, primitive, and not very effective: The country was regularly plagued by devastating floods. In 1850, the Netherlands was somewhat richer than Bangladesh is now ($\$^{PPP}$2400 v $\$^{PPP}$1400), but Bangladesh now of course has access to much better technology than the Netherlands did then.

However, the main difference between the Netherlands in 1850 and Bangladesh in 2014 is political. In response to the European Spring of 1848, the Netherlands adopted a new constitution in 1849 that introduced a powerful central government broadly representative of the population (or rather, the male Protestant part of the population). The new government promptly prioritised flood protection.

Bangladesh is one of the most corrupt and poorly governed countries in the world. Floods primarily hurt the poor, who live in the river and coastal flats where land is cheap (Brouwer, Akter, Brander, & Haque, 2007). There is no political reason to protect them; after all, floods are thought to be an act of Allah rather than a consequence of decisions (not) made or not made by incompetent and indifferent politicians. As long as this is the case, Bangladesh will be vulnerable to climate change.

In the worst projections, climate change could cut crop yields in Africa by half (Porter et al., 2014). At present, subsistence farmers often get no more from their land than one-tenth what is achieved at model farms working the same soil in the same climate (Mueller et al., 2012). The immediate reason for the so-called yield gap is a lack of access to irrigation, high-quality seeds, pesticides, fertilizers, tools, and things like that. The underlying causes include a lack of access to capital and product markets due to poor roads and insecure land tenure (Dorward, Kydd, Morrison, & Urey, 2004; Foley et al., 2011). Closing the yield gap would do more good sooner than climate change would do harm later. If one really wants to spend money to help farmers in Africa, one should invest in the land registry rather than in solar power.

Indeed, modernizing agriculture in Africa would also make it less vulnerable to climate change (Howden et al., 2007; Mendelsohn & Dinar, 1999). African farming is particularly vulnerable, because isolated, undercapitalized farmers struggle to cope with any change, climatic or otherwise.

The same point can be illustrated with infectious diseases and its spread over time (Hay, Guerra, Tatem, Noor, & Snow, 2004). Malaria used to be endemic in large parts of Europe and North America, and outbreaks were reported as far north as Murmansk. However, habitat reduction, mosquito control, and medicine long ago tamed malaria. Nowadays, malaria only occasionally returns to these places by plane (Phillips-Howard, Radalowicz, Mitchell, & Bradley, 1990). Malaria has thus become a tropical disease.

Climate change would spread malaria because the parasite is more vigorous in hot weather and mosquitoes thrive in hotter and wetter places (Martens, Jetten, & Focks, 1997; van Lieshout, Kovats, Livermore, & Martens, 2004). However, malaria is first and foremost a disease of poverty (Tol & Dowlatabadi, 2001; Tol, Ebi, & Yohe, 2007). Investment in greenhouse gas emission abatement can alternatively be spent on insecticides and bed nets, reducing malaria risks today, or invested in vaccine development, with the prospect of a malaria-free world, regardless of climate (Cotter et al., 2013; Seder et al., 2013).

These three examples—of coastal protection, agriculture, and malaria—show that development and vulnerability to climate change are closely intertwined. Slowing economic growth to reduce climate change may therefore do more harm than good (Anthoff & Tol, 2012; Tol, 2005a). Concentrating the reduction of greenhouse gas emissions in rich countries will not solve the climate problem, and slower growth in rich countries means less export from and investment in poor countries.

There is also a direct link between climate policy and development. A fifth of official development aid is now diverted to climate policy (Michaelowa & Michaelowa, 2007; Tol, 2014). Some donors no longer support the use of coal, by far the cheapest way to generate electricity, or indeed any other fossil fuel. Cheap and abundant energy fuelled the industrial revolution (Stern & Kander, 2012). Sudden increases in the price of oil caused many of the economic recessions since World War II (Barsky & Kilian, 2004; Hamilton, 1996; Kilian, 2009). Lack of (reliable) electricity retards growth in poor countries (Chontanawat, Hunt, & Pierse, 2008; Steinbuks & Foster, 2010).

5. Development and climate change

Fankhauser and Tol (2005) show that, besides the comparative static impact estimates of Figure 1, climate change also affect the growth rate of the economy. Hallegatte (2005), Eboli, Parrado, and Roson (2010), and Bretschger and Valente (2011) find the same. Climate change may well affect the size of the labour force and the capital stock, as well as productivity. If so, investment and hence future output would be affected too. Dietz and Stern (2014), Moyer, Woolley, Matteson, Glotter, and Weisbach (2014) and Moore and Diaz (2015) conjecture, without offering any justification or evidence, that climate change would also affect technological progress. As foreseen by Solow (1956), this has a large effect on economic growth.

Dell, Jones, and Olken (2014) survey the econometric literature on the impact of weather on economic activity. Although they argue that weather impacts cannot be interpreted as climate impacts, they do so nonetheless. Dell, Jones, and Olken (2009) and Horowitz (2009) find that higher temperatures would reduce income, although the effect may be limited to poor countries (Dell, Jones, & Olken, 2012). Barrios, Bertinelli, and Strobl (2010) and Brown, Meeks, Hunu, and Yu (2011) find a large impact of anomalous rainfall on economic growth, albeit only in Sub-Saharan Africa. Some argue that geography is the main cause of (under)development (Diamond, 1999; Olsson & Hibbs, 2005). Gallup, Sachs, and Mellinger (1999) emphasize the link between climate, disease, and poverty. Masters and McMillan (2001) focus on climate, agricultural pests, and poverty, finding that winter cold kills pests and thus enhances productivity. Other studies (Acemoglu, Johnson, & Robinson, 2001, 2002; Easterly & Levine, 2003) argue that climatic influence on development disappears if differences in human institutions (the rule of law, education, etc) are accounted for. Bhattacharyya (2009) attempts to reconcile the two schools of thought, arguing that the geography of diseases is more important for the least developed economies, while institutions matter more elsewhere. van der Vliert (2008) and Van de Vliert and Tol (2014) demonstrate that climate affects human culture, at least in poor countries, and thus institutions.

Bloom, Canning, and Sevilla (2003) find limited support for an impact of climate on past growth when assuming a single-equilibrium model, but strong support in a multipleequilibrium model: hot and wet conditions and large variability in rainfall reduce long-term growth in poor countries (but not in hot ones) and increase the probability of being poor. Bonds, Keenan, Rohani, and Sachs (2010) offer further evidence. There are two equilibria in the models of Galor and Weil (1996), Galor and Weil (1999), Galor and Weil (2000) and Strulik (2008). The 'Malthusian' equilibrium is characterized by high population growth and low capital intensity, the 'Solowian' equilibrium by low population growth and high capital intensity. Physical labour is more important for setting wages, output, and savings in the Malthusian equilibrium than in the Solowian equilibrium. Capital intensity separates the two equilibria. A drop in labour productivity would reduce savings, locking the economy deeper in the poverty trap. Climate change would negatively affect labour productivity via morbidity and crop yields. Childhood malnutrition and disease lead to long-term cognitive impairment. Furthermore, high infant mortality may induce parents to have many children so that investment in education and health care is spread thin. Climate may thus help to explain poverty traps.

The literature on the impact of climate (change) on development has yet to reach firm conclusions. Climate change could moderate the rate of economic growth, but estimates range from high to low. More people may be trapped in poverty because of climate, but this effect could be large or small.

6. The social cost of carbon

There have been a number of developments since my last surveys of the social cost of carbon (Tol, 2011, 2013b). The volume of papers and estimates has increased rapidly – see Table 2 and Appendix B – partly, I believe, in response to the US government adopting an official social cost of carbon.

Some have argued that current estimates of the social cost of carbon are lower bounds to the true social cost of carbon. By implication, US climate policy is not ambitious enough. These claims rest on three grounds. First, estimates of the social cost of carbon are said to underestimate the true risks (Botzen & van den Bergh, 2012; van den Bergh & Botzen, 2014, 2015), although both primary estimates (Anthoff & Tol, 2013, 2014; Anthoff, Tol, & Yohe, 2009c) and meta-analyses (Arent et al., 2014; Tol, 2009) pay considerable attention to risks. Second, estimates of the social cost of carbon rely on incomplete impact assessment (Revesz et al., 2014). However, incompleteness only implies bias if the missing impacts are all negative (Arent et al., 2014; Tol, 2009). Third, estimates of the social cost of carbon are partly determined by ethical parameters such as the rates of pure time preference, risk aversion, and inequality aversion (Anthoff, Hepburn, & Tol, 2009a; Anthoff & Tol, 2010; Anthoff, Tol, & Yohe, 2009b; Guo, Hepburn, Tol, & Anthoff, 2006; Tol, 2010, 2013a). Some have argued in favour of particular parameter values (Stern, 2010, 2013; Stern, 2008; van den Bergh & Botzen, 2014, 2015), thus putting bounds on the social cost of carbon. However, there is a wide range of estimates of parameters that describe attitudes towards time (Frederick, Loewenstein, & O'Donoghue, 2002) and risk, and it is not obvious under what conditions democratically elected governments could or should overrule the preferences of the electorate.

Anyway, the relationship between these ethical parameters and the social cost of carbon is not as simple as some might think. For instance, the impact of inequality aversion is ambiguous since, although poorer countries are more vulnerable to climate change than richer ones, carbon dioxide fertilization disproportionality benefits poorer countries (Anthoff et al., 2009c). The curvature of the utility function governs trade-offs between risks, between present and future, and between rich and poor. Models often assume this curvature to be the same in the three dimensions (Atkinson, Dietz, Helgeson, Hepburn, & Saelen, 2009) and, as economic growth is typically assumed to continue, this implies an ambiguous effect on the social cost of carbon. Some recent papers separate risk and time (Crost & Traeger, 2014; Jensen & Traeger, 2014; Lemoine & Traeger, 2014), but disregard distributional issues within and between countries.

Golosov, Hassler, Krusell, and Tsyvinski (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 (1) that utility is logarithmic in consumption, (2) that time discounting is exponential, (3) that the carbon cycle follows a linear difference equation, (4) that climate change impacts are proportional to total output, (5) that climate change impacts are proportional to the exponent of the atmospheric concentration of carbon dioxide, and (6) that there are no catastrophic risks. Unfortunately, none of these assumptions is realistic. The first two are discussed elsewhere in this paper. Maier-Reimer and Hasselmann (1987) show that the removal of carbon dioxide from the atmosphere cannot be approximated by a linear difference equation. As argued above, poverty implies vulnerability to climate change, so that impacts are less than proportional to output. The equilibrium temperature is logarithmic in the atmospheric concentration, so Golosov et al. (2014) assume that impact is proportional to the double exponent of temperature. Figure 1 suggests that the relationship is close to linear; see also Table 2. A series of papers (Keller, Bolker, & Bradford, 2004; Lemoine & Traeger, 2014; van den Bijgaart, Gerlagh, Korsten, & Liski, 2013; Van der Ploeg, 2014) show that catastrophes break the smoothness assumed by Golosov et al. (2014), and thus their simple function for the social cost of carbon. Particularly, these studies show that the Pigou tax does not follow a simple Hotelling-like path – but they offer little new insight into the optimal carbon tax in the near term.

Table 3 shows the number of studies of the social cost of carbon by year of publication and the number of estimates as well. As noted above, there has been a marked increase in recent years, with 7 new studies and 72 new estimates in the first few months of 2015 alone. Table 3 also shows the pure rate of time preference averaged across these estimates. There is a slight upward, but insignificant trend (0.0005±0.0179 per cent per year). Table 3 further shows the average social cost of carbon and its standard error. There is a slight downward but insignificant trend (-3.09±4.91 dollar per tonne of carbon per year).

Finally, Table 3 shows the social cost of carbon and its standard error averaged over all previously published estimates, and the results of a t-test for the difference between the average of the estimates published in a year and the average of earlier years. In 9 out of 24 years, estimates deviate significantly from earlier ones. This literature does not suffer from confirmation bias. Instead, the received wisdom is regularly challenged. A consensus has yet to be reached. Tables A1-A6 repeat Table 3 for estimates based on the six most frequently used pure rates of time preference (0, 0.1, 1, 1.5, 2, and 3%). Similar patterns are found. The results of Table 3 are therefore not due to differences in discounting.

The year 2014 stands out. The average is much higher than in previous years. The difference is not significant, because the standard error increases even more. This is due to three studies (Howarth, Gerst, & Borsuk, 2014; Marten, 2014; Moyer et al., 2014) with high estimates of the social cost of carbon. Howarth and colleagues report an estimate as high as $105,000/tC. The social cost of carbon may be interpreted as how much we should be willing to pay to reduce carbon dioxide emissions, or as the tax that we should impose on such emissions. We should expect to pay such a tax over many years, so we cannot pay more than our annual income. One may argue that a carbon tax should offset other taxes, but not increase the total tax burden (Tol, 2012). In 2010, global average carbon efficiency was around $7,600/tC. If applied globally, as a carbon tax should, Howarth's tax would thus take 14 times total world income. In recent years, world average tax revenue was about 15% of GDP, so a tax of $1,150/tC or larger would increase the size of the public sector.

Figure 3 shows the kernel density of the social cost of carbon. The method is as in Tol (2013b). The kernel function is a Fisher-Tippett distribution, a fat-tailed, right-skewed PDF defined on the real line. The mode is set equal to the estimate, the bandwidth to the sample standard deviation. Only Hope and Tol admit to the possibility that the impacts of modest climate change may be positive. The kernel function for estimates by other authors are therefore knotted at zero. Estimates are weighted by study characteristics, as in Tol (2005b). In addition, estimates in excess of $7,600/tC are excluded. 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.

Figure 3 shows the kernel density for the entire sample, and for those estimates based on a pure rate of time preference of 0%, 1% or 3% per year. The higher the discount rate, the lower the concern for the future, and the lower the social cost of carbon: The mode is $220/tC for a 0% PRTP, $93/tC for 1%, and $28/tC for 3%. Furthermore, as the uncertainty grows as we look further into the future, a lower discount rate implies a more diffuse estimate. The standard deviation is $669/tC for a 0% PRTP, $468/tC for 1% and $35/tC for 3%. The two effects come together in the mean social cost of carbon, which is $677/tC for a 0% PRTP, $360/tC for 1%, and $44/tC for 3%.

The PDFs in Figure 3 jump at $0/tC. This is by construction. Figure A1 shows the PDF for all estimates if we do not knot the kernel function at 0. In that case, there is a substantial probability mass for carbon subsidies, which is at odds with the underlying literature: with knotting, there is 9% chance of a negative social costs of carbon; without knotting, there is 26% chance. Figure A1 also shows the implications of the decision to discount estimates that would lead to an expansion of the public sectors, and to discard estimates in excess of annual income. Because there are such large estimates in the database, the bandwidth is large and the PDF is diffuse.

Figure 4 returns to the above discussion on confirmation bias. It shows the median and the 90% confidence interval for estimates published in a particular year and for estimates published in previous years. Whereas Table 3 show frequent challenges to the received wisdom, Figure 4 does not. Besides the discounting of high estimates, the key difference between Table 3 and Figure 4 is proper reflection of uncertainty by means of the kernel density estimation: The standard error of the mean in Table 3 is rather low. The bandwidths underlying Figures 3 and 4 are chosen to avoid overconfidence, a choice that seems appropriate in the light of the great uncertainties and controversies in climate change. Based on these assumptions, Figure 4 reveals a gradual decline of the central estimate of the social cost of carbon and a modest tightening of its confidence interval.

7. Conclusion and further research

The impact of climate change on the economy and human welfare is likely to be limited, at least in the 21st century. In the short to medium run, climate change may well bring gains, particularly to those who depend on rainfed agriculture (as carbon dioxide fertilization makes plants more drought resistant) and those who spend substantial money on heating (as warming is faster in winter). In the long run, the negative impacts of climate change are likely to outweigh the positive ones. These negative impacts will be substantially greater in poorer, hotter, and lower-lying countries. As poverty causes vulnerability, development is a complementary strategy to greenhouse gas emissions reduction; any trade-off between slower economic growth and lower emissions needs to be carefully considered. At the same time, climate change may affect the growth rate of the economy, and may trap more people in poverty – although estimates of the size of these effects vary from negligible to substantial. Although recent research has made substantial progress on the rich dynamics of the Pigou tax, our best estimate of the optimal carbon tax in the near term is still a few tens to a few hundreds of dollars per tonne of carbon.

While the qualitative insights above are probably robust, the quantitative assessment is uncertain and incomplete. The uncertainty is partly irreducible. We are, after all, estimating and valuing the impact of future climate change on future society.

There are also open questions, however, where further research should shed light. The impact of climate change on water resources, transport, migration, violent conflict, energy supply, space cooling, and tourism and recreation have not received sufficient attention – there is either very little solid evidence or no conclusive evidence. Estimates of the impact of climate change are thus incomplete. We do not know whether the bias is upwards or downwards, but the uncertainty is enhanced which, of course, strengthens the case for greenhouse gas emission reduction.

While important details may be refined, and confidence in the numbers may be enhanced, future research is unlikely to overturn the basic finding that it is the poor who will suffer most from climate change, and that reducing poverty is a key part of alleviating the impact of climate change. Quantification remains problematic.

The impact of climate and climate change on economic growth and development is not well understood – or rather, different studies have reached opposite conclusions. New data and the latest econometric techniques should shed new, perhaps decisive light on these issues.

The policy advice derived from all this is channelled through estimates of the social cost of carbon. But the social cost of carbon also aggregates – between impacts, across species, within societies, between societies, across alternative futures, and over time. The importance of the discount rates has long been recognized. Recent papers make some progress in illustrating that the other parameters of the welfare function are very important too, but a comprehensive analysis is still some way off. There is also a disconnect between the assumptions made in integrated assessment models and the insights from behavioural and experimental economics.

Climate policy is one of the defining issues of our times. The research agenda above is rich enough to keep us occupied for years to come – and touches on fundamental issues in economics, such as trade-offs between risky prospects for different people and why some are rich and others poor. Together, this makes for intellectually fascinating and immediately relevant research – but also for an environment where the truth is better whispered.

Table 1. Estimates of the welfare impact of climate change[a, b, c]

Study	Warming	Impact (%GDP)			
	(°C)	Best	SD	Low	High
d'Arge 1979	-1.0	-0.6			
Nordhaus 1982	2.5	-3.0		-12.0	5.0
Nordhaus 1991	3.0	-1.0			
Nordhaus 1994b	3.0	-1.3			
Nordhaus 1994a	3.0	-3.6		-21.0	0.0
	6.0	-6.7			
Fankhauser 1995	2.5	-1.4			
Berz undated	2.5	-1.5			
Tol 1995	2.5	-1.9			
Nordhaus and Yang 1996	2.5	-1.4			
Plambeck and Hope 1996	2.5	-2.9		-13.1	-0.5
Mendelsohn et al. 2000	2.5	0.0			
	2.5	0.1			
Nordhaus and Boyer 2000	2.5	-1.5			
Tol 2002	1.0	2.3	1.0		
Maddison 2003	2.5	0.0			
Rehdanz and Maddison 2005	0.6	-0.2			
	1.0	-0.3			
Hope 2006	2.5	-1.0		-3.0	0.0
Nordhaus 2006	3.0	-0.9	0.1		
	3.0	-1.1	0.1		
Nordhaus 2008	3.0	-2.5			
Maddison and Rehdanz 2011	3.2	-5.1			
Bosello et al. 2012	1.9	-0.5			
Roson and van der Mensbrugghe 2012	2.9	-2.1			
	5.4	-6.1			
Nordhaus 2013	2.9	-2.0			

[a] Impact is measured as welfare-equivalent income loss, and expressed as percentage of income. Climate change is characterised by the increase in the global annual mean surface air temperature. Estimates are best guesses. Where available, either the standard deviation (SD) of the estimate or an indication of lower (low) and upper (high) bound of its confidence interval are given.

[b] There are three differences between this table and the IPCC one. First, the table here includes the estimates by d'Arge, Berz and Nordhaus 1982. Second, the Mendelsohn estimates are shown against the area-average temperature change, rather than the population-average, just like the other estimates in the current table. Third, the Maddison and Rehdanz estimate is shown in market exchange rate dollars, rather than in purchasing power parity dollars, just like the other estimates in the current table.

[c] Data are at http://users.sussex.ac.uk/~rt220/totalimpactreep.xlsx

Table 2. Alternative impact functions and their best fit to the data in Table 1.[a]

Specification	Proposer	Standard error of regression	Relative likelihood
$0.74\ T\ I_{T<1.14} + (0.83 - 1.60\ T)\ I_{T\geq 1.14}$	This paper	1.10	$84\ 10^{-2}$
$-0.060\ T - 0.19\ T^2$	Tol (2009)	1.16	$14\ 10^{-2}$
$-0.21\ T^2$	Nordhaus	1.23	$18\ 10^{-3}$
$-0.75\ T$	Hope	1.40	$54\ 10^{-5}$
$0.02 - 0.02\ \exp(T)$	Karp; Van der Ploeg	1.74	$13\ 10^{-7}$
$1.1\ 10^{-174} - 4.2\ 10^{-175}\ \exp(\exp(T))$	Golosov	2.25	$14\ 10^{-10}$
$-0.23\ T^2 + 5.8\ 10^{-6}\ T^7$	Weitzman	2.36	$63\ 10^{-11}$
$-0.23\ T^2 + 3.5\ 10^{-5}\ T^6$	Weitzman	2.37	$57\ 10^{-11}$

[a] Data are at http://users.sussex.ac.uk/~rt220/totalimpactreep.xlsx

Table 3. The social cost of carbon[a,b]

Year	#S	#E	PRTP	Estimates		Previous estimates		Sign.
1982	1	2	1.00	609	(323)			
1991	2	10	0.57	146	(55)	609	(323)	
1992	5	7	2.00	575	(491)	223	(87)	
1993	4	96	0.98	154	(74)	353	(193)	
1994	3	5	0.75	350	(187)	187	(70)	
1995	2	3	3.00	101	(62)	194	(67)	
1996	7	34	1.66	253	(68)	191	(66)	
1997	2	3	3.00	64	(38)	205	(54)	**
1999	4	35	1.93	177	(29)	202	(53)	
2000	1	1	-	12	-	198	(44)	***
2001	2	4	1.00	36	(15)	197	(43)	***
2002	1	1	1.00	149	-	193	(42)	
2003	3	11	1.00	45	(19)	193	(42)	***
2004	5	26	1.35	205	(56)	186	(40)	
2005	5	58	1.59	208	(81)	188	(36)	
2006	5	27	1.80	79	(20)	192	(33)	***
2007	1	2	0.00	148	(10)	182	(31)	
2008	3	19	1.89	148	(61)	182	(30)	
2009	5	57	1.33	56	(11)	180	(29)	***
2010	6	25	1.33	58	(14)	162	(25)	***
2011	7	131	1.28	333	(77)	156	(23)	**
2012	10	230	2.69	107	(11)	198	(26)	***
2013	11	110	1.41	293	(73)	171	(19)	
2014	12	244	1.00	842	(441)	186	(19)	
2015	7	72	1.36	171	(35)	326	(96)	
2016						317	(90)	

[a] Year: Year of publication; #S: Number of studies published in that year; #E: Number of estimates published in that year; PRTP: Average of the pure rate of time preference for estimates published in that year; Estimates: Mean and standard error of the mean for estimates published in that year; Previous estimates: Mean and standard error of the mean for estimates published before that year; Sign: Denotes significant difference between estimates and previous estimates.

[b] Data are at http://users.sussex.ac.uk/~rt220/socialcostofcarbon.xlsx

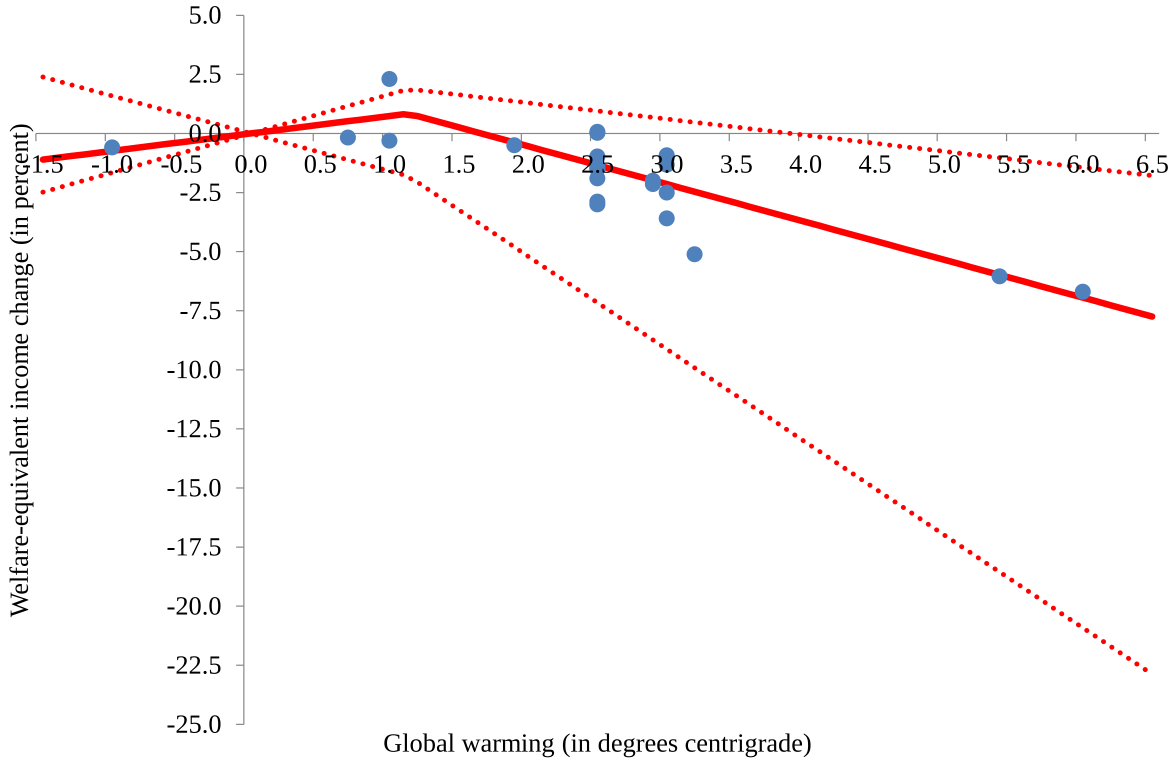

Figure 1. The global total annual impact of climate change expressed in welfare-equivalent income change as a function of the rise in the global annual mean surface air temperature since pre-industrial times; the dots are the primary estimates reported in Table 1, the solid line the best-fit piecewise linear function, and the dotted lines denote the 95% confidence interval.

Data are at http://users.sussex.ac.uk/~rt220/totalimpactreep.xlsx

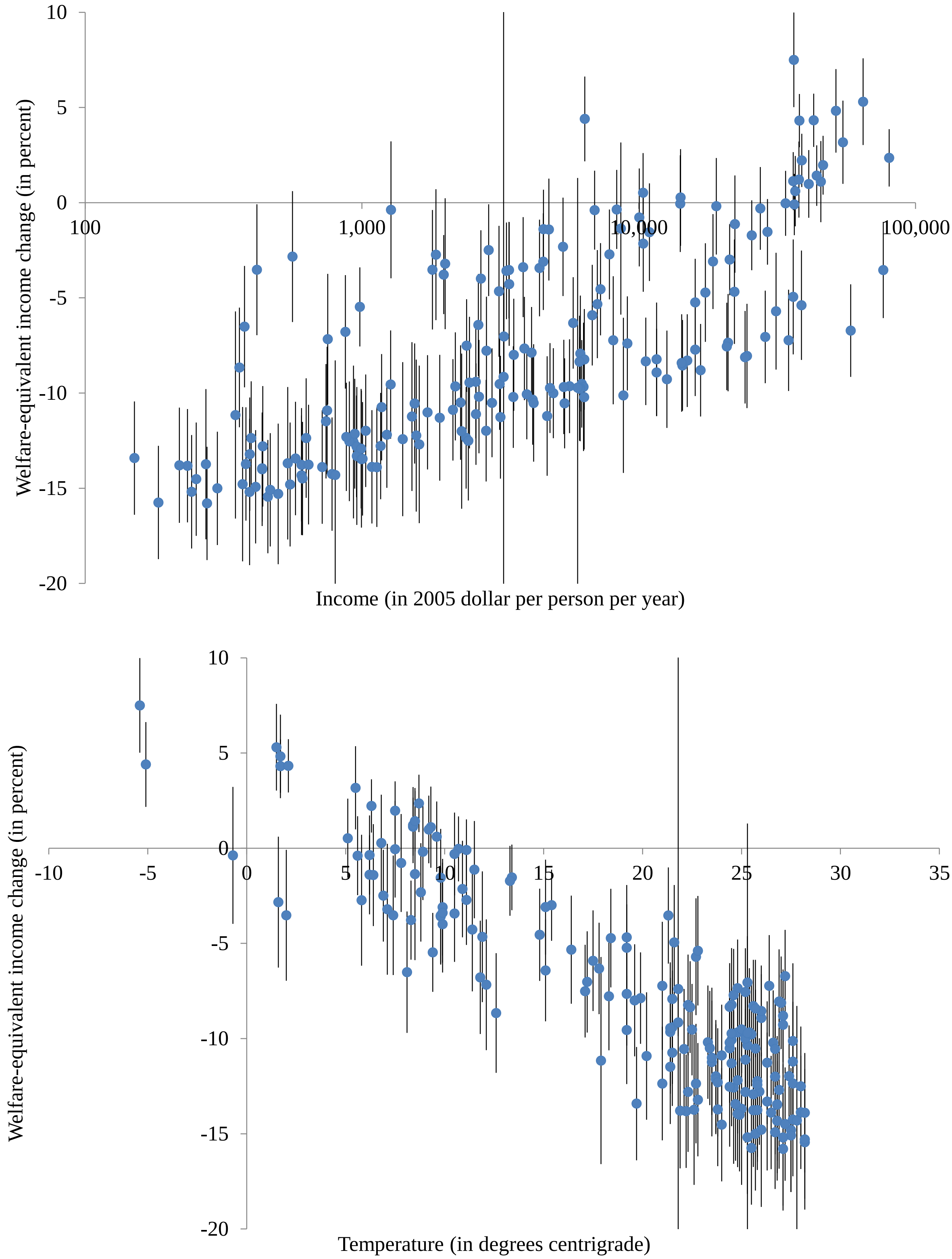

Figure 2. The national total annual impact of climate change expressed in welfare-equivalent income change for a 2.5˚C global warming (relative to pre-industrial times) as a function of per capita income (top panel) and temperature (bottom panel).

Data are at http://users.sussex.ac.uk/~rt220/totalimpactreep.xlsx

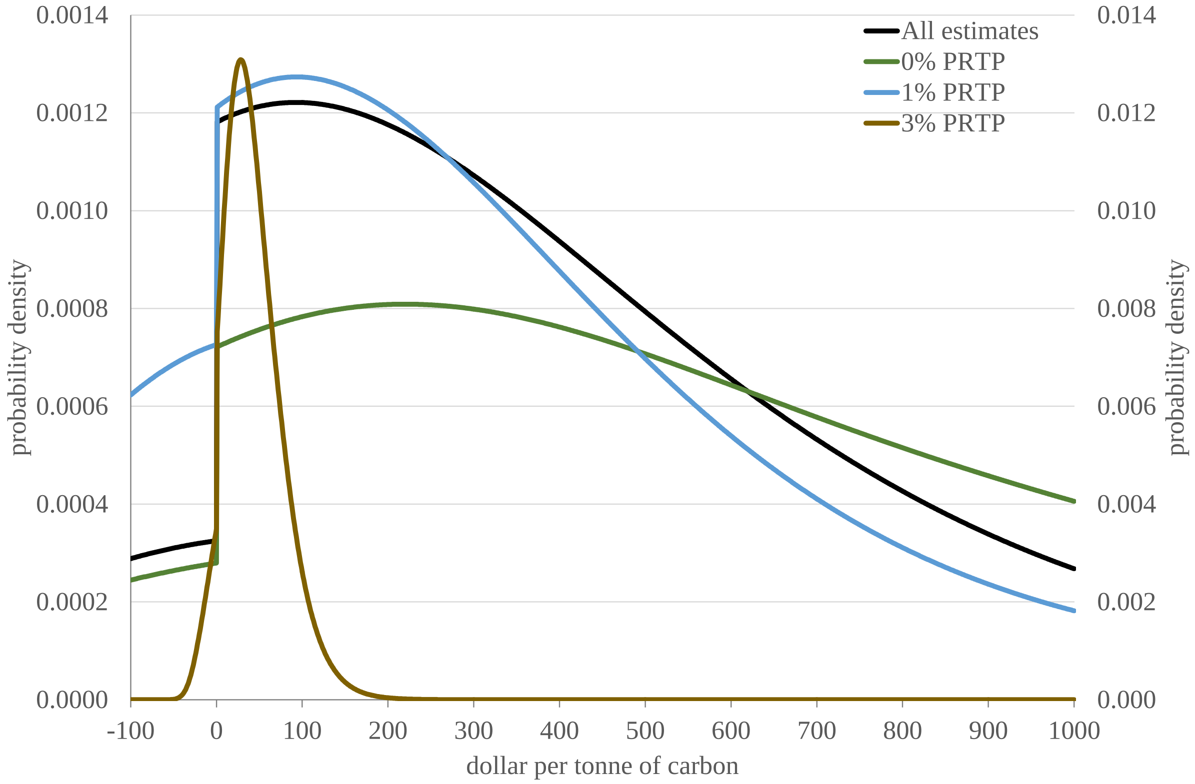

Figure 3. The kernel density of the social cost of carbon (in 2010 dollars per metric tonne of carbon, for emissions in 2015) for all estimates, and for estimates based on a 0%, 1% or 3% pure rate of time preference.

Data are at http://users.sussex.ac.uk/~rt220/results-REEP.xlsx. Code is at http://users.sussex.ac.uk/~rt220/MetaSCC.zip.

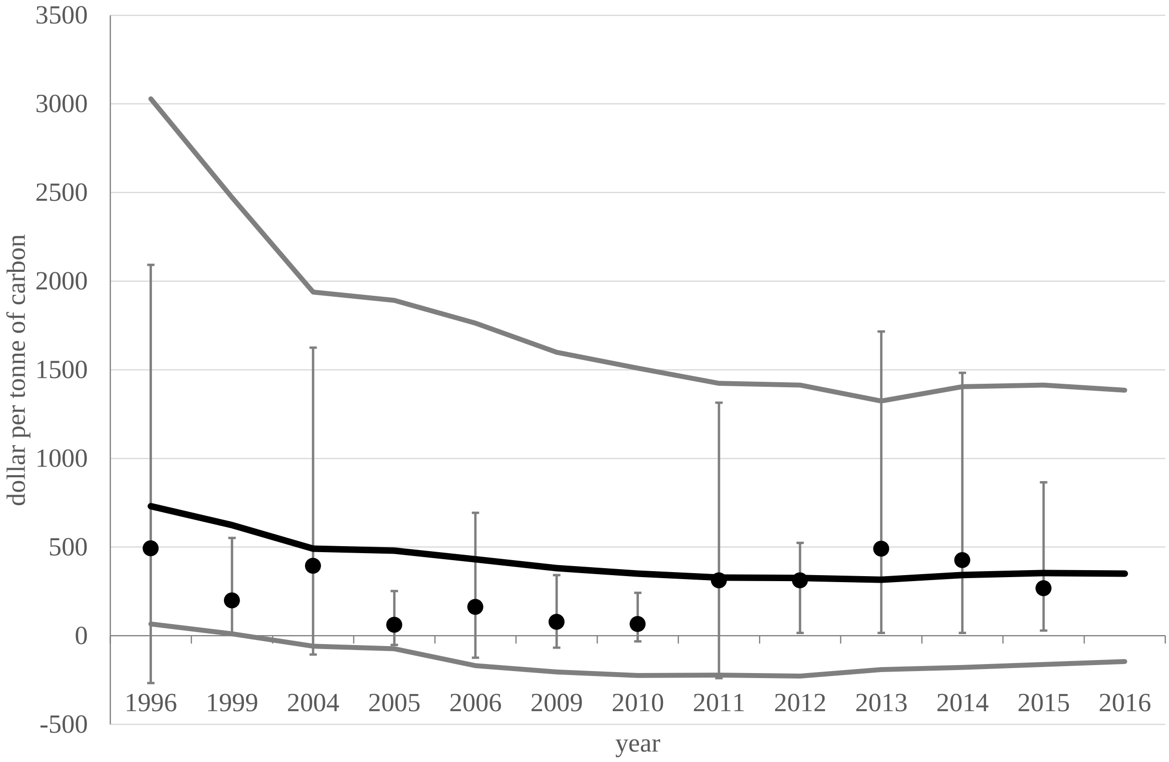

Figure 4. The kernel median and 90% confidence interval of estimates published in a particular year (dots and bars) and in previous years (lines).

Data are at http://users.sussex.ac.uk/~rt220/results-REEP.xlsx. Code is at http://users.sussex.ac.uk/~rt220/MetaSCC.zip.

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APPENDIX A: ADDITIONAL RESULTS

Table A1. The social cost of carbon for a pure rate of time preference of 0%*

Year	N	Estimates		Previous estimates		Sign.
1991	3	311	119			
1993	62	221	114	311	119	
1994	3	563	243	226	108	
1996	5	709	180	240	105	**
2003	3	54	6	273	99	**
2004	9	414	129	264	95	
2005	13	609	324	280	87	
2006	4	252	72	323	87	
2007	2	148	10	321	84	**
2008	2	153	84	317	82	
2009	12	88	15	314	81	***
2010	3	189	30	291	73	
2011	20	1194	419	289	71	**
2013	4	1606	1195	417	89	
2014	6	5630	2060	450	94	**
2015				656	147	

* Year: Year of publication; N: Number of estimates published in that year; Estimates: Mean and standard error of the mean for estimates published in that year; Previous estimates: Mean and standard error of the mean for estimates published before that year; Sign: Denotes significant difference between estimates and previous estimates.

Table A2. The social cost of carbon for a pure rate of time preference of 0.1%*

Year	N	Estimates		Previous estimates		Sign.
1996	4	481	142			
2011	10	575	270	481	142	
2013	9	540	187	548	197	
2014	52	152	19	545	140	***
2015	8	60	6	273	50	***
2016				252	45	

* Year: Year of publication; N: Number of estimates published in that year; Estimates: Mean and standard error of the mean for estimates published in that year; Previous estimates: Mean and standard error of the mean for estimates published before that year; Sign: Denotes significant difference between estimates and previous estimates.

Table A3. The social cost of carbon for a pure rate of time preference of 1.0%*

Year	N	Estimates		Previous estimates		Sign.
1982	2	609	323			
1991	4	123	50	609	323	
1996	4	145	36	285	146	
1999	8	101	9	229	92	
2001	4	36	15	172	53	**
2002	1	149	0	147	45	
2003	1	38	0	147	43	**
2004	7	148	50	143	42	
2005	13	146	78	144	34	
2006	5	88	34	145	33	
2008	6	316	164	139	30	
2009	12	15	4	158	33	***
2010	13	34	8	133	28	***
2011	49	123	28	117	24	
2012	8	112	24	119	18	
2013	12	307	119	119	17	
2014	36	700	414	134	19	
2015				244	84	

* Year: Year of publication; N: Number of estimates published in that year; Estimates: Mean and standard error of the mean for estimates published in that year; Previous estimates: Mean and standard error of the mean for estimates published before that year; Sign: Denotes significant difference between estimates and previous estimates.

Table A4. The social cost of carbon for a pure rate of time preference of 1.5%*

Year	N	Estimates		Previous estimates		Sign.
2011	8	144	68			
2013	24	423	214	144	68	
2014	73	1578	1433	353	163	
2015	48	203	52	1205	999	
2016				890	687	

* Year: Year of publication; N: Number of estimates published in that year; Estimates: Mean and standard error of the mean for estimates published in that year; Previous estimates: Mean and standard error of the mean for estimates published before that year; Sign: Denotes significant difference between estimates and previous estimates.

Table A5. The social cost of carbon for a pure rate of time preference of 2.0%*

Year	N	Estimates		Previous estimates		Sign.
1992	5	23.4	7.3			
1996	7	44.7	11.6	23.4	7.3	
2003	3	15.5	2.4	35.8	8.0	**
2004	2	122.6	44.3	31.8	6.7	**
2006	2	56.6	8.8	42.4	10.6	
2008	3	141.7	64.8	43.9	9.6	
2013	5	59.9	15.4	57.3	14.1	
2014				57.8	11.8	

* Year: Year of publication; N: Number of estimates published in that year; Estimates: Mean and standard error of the mean for estimates published in that year; Previous estimates: Mean and standard error of the mean for estimates published before that year; Sign: Denotes significant difference between estimates and previous estimates.

Table A6. The social cost of carbon for a pure rate of time preference of 3.0%*

Year	N	Estimates		Previous estimates		Sign.
1993	30	31.7	2.8			
1994	1	11.7	0.0	31.7	2.8	***
1995	1	31.9	0.0	31.0	2.8	
1996	11	38.1	8.9	31.0	2.7	
1997	2	17.3	3.7	32.9	3.1	***
1999	7	45.8	7.1	32.2	3.0	*
2004	8	39.7	12.1	34.0	2.8	
2005	20	33.9	11.5	34.8	2.9	
2006	9	18.7	5.5	34.6	3.6	**
2008	8	23.2	2.1	33.0	3.3	**
2009	12	-5.3	0.6	32.1	3.1	***
2010	5	13.5	6.4	28.0	3.0	**
2011	29	17.5	5.7	27.4	2.9	
2012	44	38.4	1.7	25.4	2.6	***
2013	11	25.9	5.5	28.5	2.1	
2014	8	57.4	9.4	28.3	2.0	***
2015	2	55.5	8.0	29.4	2.0	***
2016				29.7	2.0	

* Year: Year of publication; N: Number of estimates published in that year; Estimates: Mean and standard error of the mean for estimates published in that year; Previous estimates: Mean and standard error of the mean for estimates published before that year; Sign: Denotes significant difference between estimates and previous estimates.

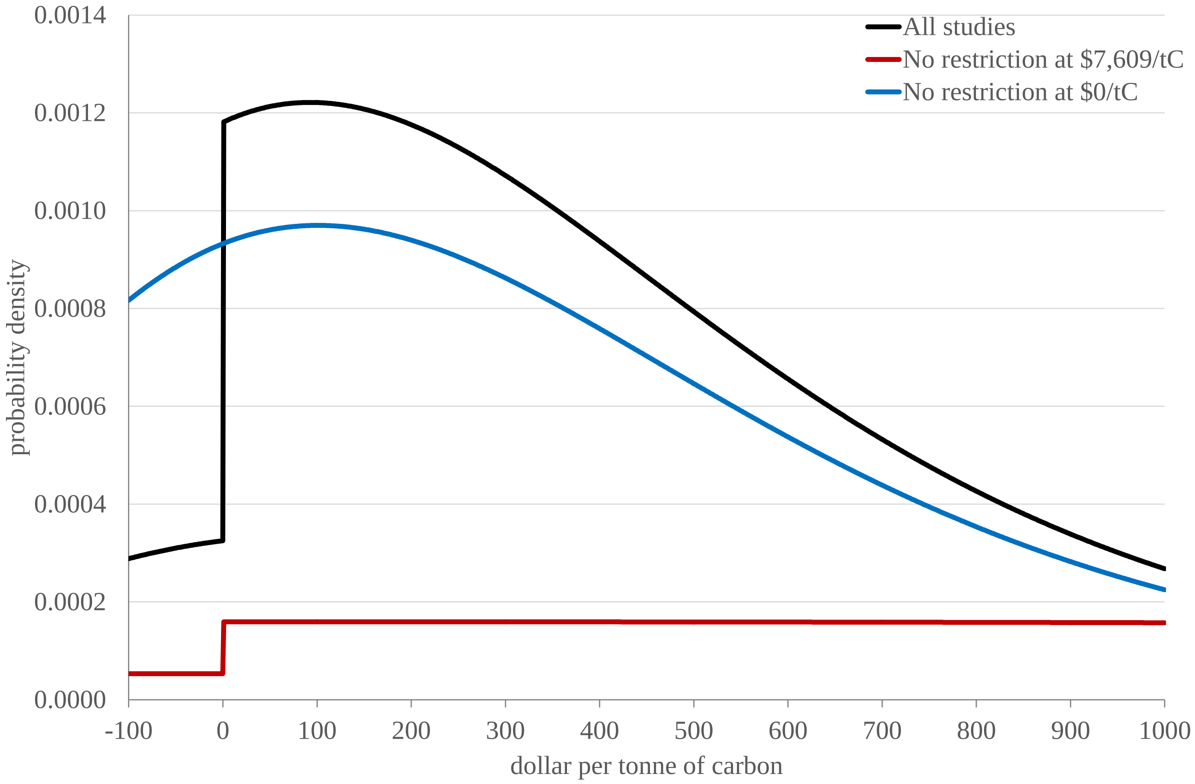

Figure A1. The kernel density of the social cost of carbon (in 2010 dollars per metric tonne of carbon, for emissions in 2015) for all estimates as in Figure 3, without knotting at zero, and without discounting high estimates.

Appendix B Studies that estimate the social cost of carbon

(Ackerman & Munitz, 2012; Ackerman & Stanton, 2012; Anthoff, Hepburn, & Tol, 2009; Anthoff, Rose, Tol, & Waldhoff, 2011; Anthoff & Tol, 2010, 2011, 2013; Anthoff, Tol, & Yohe, 2009a, b; Ayres & Walter, 1991; Azar, 1994; Azar & Sterner, 1996; Botzen & van den Bergh, 2012; Cai, Judd, & Lontzek, 2012; Ceronsky, Anthoff, Hepburn, & Tol, 2006, 2011; Clarkson & Deyes, 2002; Cline, 1992, 1997, 2004; Crost & Traeger, 2014; Dietz & Stern, 2015; Downing et al., 2005; Downing, Eyre, Greener, & Blackwell, 1996; Epa & Nhtsa, 2009; Eyre, Downing, Rennings, & Tol, 1999; Fankhauser, 1994; Foley, Rezai, & Taylor, 2013; Guo, Hepburn, Tol, & Anthoff, 2006; Haraden, 1992, 1993; Heal & Millner, 2014; Hohmeyer, 1996, 2004; Hohmeyer & Gaertner, 1992; Hope, 2005a, b, 2006a, b, 2008a, b, 2011, 2013; Hope & Hope, 2013; Hope & Maul, 1996; Howarth, Gerst, & Borsuk, 2014; Interagency Working Group on the Social Cost of, 2013; Jensen & Traeger, 2014; Johnson & Hope, 2012; Kemfert & Schill, 2010; Kopp, Golub, Keohane, & Onda, 2012; Lemoine & Traeger, 2014; Link & Tol, 2004; Lontzek, Cai, Judd, & Lenton, 2015; Maddison, 1995; Manne, 2004; Marten, 2014; Marten & Newbold, 2012; Marten & Newbold, 2013; Mendelsohn, 2004; Moore & Diaz, 2015; Moyer, Woolley, Matteson, Glotter, & Weisbach, 2014; Narita, Anthoff, & Tol, 2009, 2010; Newbold, Griffiths, Moore, Wolverton, & Kopits, 2013; Newell & Pizer, 2003; Nordhaus, 2013, 2014; Nordhaus, 1982, 1991, 1993, 1994, 2008; Nordhaus, 2010; Nordhaus, 2011; Nordhaus & Boyer, 2000; Nordhaus & Popp, 1997; Nordhaus & Yang, 1996; Parry, 1993; Pearce, 2003; Peck & Teisberg, 1993; Penner, Haraden, & Mates, 1992; Perrissin Fabert, Dumas, & Hourcade, 2012; Plambeck & Hope, 1996; Pottier, Espagne, Perrissin Fabert, & Dumas, 2015; Pycroft, Vergano, & Hope, 2014; Pycroft, Vergano, Hope, Paci, & Ciscar, 2011; Reilly & Richards, 1993; Rezai & Van der Ploeg, 2014; Rezai, Van der Ploeg, & Withagen, 2012; Roughgarden & Schneider, 1999; Schauer, 1995; Shindell, 2015; Sohngen, 2010; Stern et al., 2006; Stern & Taylor, 2007; Tol, 1999, 2005, 2010, 2012; Traeger, 2006; Uzawa, 2003; van den Bijgaart, Gerlagh, Korsten, & Liski, 2013; Van der Ploeg, 2014; Van der Ploeg & De Zeeuw, 2013, 2015; Wahba & Hope, 2006; Waldhoff, Anthoff, Rose, & Tol, 2014; Waldhoff, Anthoff, Rose, & Tol, 2011; Weitzman, 2013)

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