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The Economic Impacts of Climate Change

Richard S. J. Tol*

Introduction

For such a fractious discipline, there has been remarkable agreement among economists concerning the 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 (GHG) emissions should be priced, preferably taxed. Although there continues to be a vigorous debate about climate targets in the long-term (Stern et al. 2006; Nordhaus 2013), most economists agree that a sensible climate policy starts modestly and then accelerates (Wigley, Richels, and Edmonds 1996' Goulder and Mathai 2000). Despite this general agreement on the need to reduce GHG emissions, the debate among economists about climate change has been unusually bitter, perhaps as a reflection of the wider polarization of climate research and climate policy. In particular, estimates of the marginal impact of climate change vary so widely that the initial carbon price is more a matter of politics than economics.

The purpose of this article is to examine the economic impacts of climate change. More specifically, I review estimates of the total economic impact of climate change and the distribution of those impacts around the world, discuss the interactions between economic development and climate change, and review and analyze estimates of the social cost of carbon (i.e., the Pigou tax). For each of these topics I discuss the state of the art with an emphasis on key recent developments. I present a summary of my findings and a proposed research agenda in the final section. I find that the total economic impacts of climate change are negative, but modest on average, and that the severe impacts on less developed countries are caused primarily by poverty. The impact of climate and climate change on economic growth is poorly understood but could imply that current estimates are too optimistic. Estimates of the social cost of carbon are very uncertain but are typically above observed carbon prices.

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The Total Economic Impact of Climate Change

The impacts of climate change are many and diverse. Determining whether these impacts are beneficial or detrimental, small or large, depends on the sector, location, and time being considered. Unfortunately, a reading of the literature on the impacts of climate change (Field and Canziani 2014) is likely to leave a lay reader confused. It is very difficult to make sense of the many and different effects: crops hit by worsening drought, crops growing faster because of carbon dioxide fertilization, heat stress increasing, cold stress decreasing, sea levels rising, increasing energy demand for cooling, decreasing energy demand for heating, infectious disease spreading, species going extinct. Thus we need aggregate indicators 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 society faces. I focus in this and the next section on two aggregate indicators (Smith et al. 2001): the impact of climate change on total economic welfare and the distribution of those welfare impacts.

Estimates of Impacts on Total Economic Welfare

There are currently 27 published estimates of the total economic impact of climate change (measured in terms of welfare-equivalent income loss) contained in 22 studies (see table 1 and figure 1).[1] To put these estimates in context, they indicate that a global mean temperature increase of 2.5°C would make the average person feel as if she had lost 1.3 percent of her income (1.3 percent is the average of the 11 impact estimates for warming of 2.5°C).

Pindyck (2013) argues that these estimates of the economic impact of climate change have no foundation in economic theory. No estimate is perfect, but the existing estimates use well-established and well-accepted methods.[2] Moreover, although the estimates in table 1 and figure 1 are based on different methods, the results are consistent with each other. We do not know the accuracy of these estimates, but this is true for any prediction of the future. In a later paper, Pindyck (2017) argues for transparency and simplicity, extrapolating into the far future, and deep tails without any detail on the processes involved. Heal (2017) writes that current models are "not accurate enough to provide quantitative insights" and, like Pindyck, calls for a more intuitive approach to climate policy advice.

Clearly, 27 estimates are a thin basis for drawing definitive conclusions about the total welfare impacts of climate change. Moreover, the 11 estimates for warming of 2.5°C indicate that researchers disagree on the sign of the *net* impact: 3 estimates are positive and 8 are

[1]A number of papers estimate the impact of weather on a range of economic indicators (Deschênes and Greenstone 2007; Barreca 2012; Hsiang and Meng 2015; Hsiang et al. 2017). The key advantage of considering weather impacts is that weather is, from an economic perspective, random. The economic impact of weather is therefore properly identified. Although some of these papers may suggest otherwise, the impact of a weather shock is not the same as the impact of climate change. Climate is what you expect, while 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. In contrast, 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, but what we are interested in is the *long-run* elasticity. Thus, extrapolating the impact of weather shocks to the impact of climate change is unlikely to lead to credible results.

[2]See appendix A in the online supplementary materials for a discussion of the methods used to estimate the total welfare impacts of climate change presented in table 1.

Table 1 Estimates of the welfare impact of climate change

Study	Warming (°C)	Impact (% GDP)			
		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			

Notes: Impact is measured as welfare-equivalent income loss and expressed as a percentage of income. Climate change is characterized by the increase in the global annual mean surface air temperature. Estimates are best guesses (Best). Where available, either the standard deviation (SD) of the estimate or an indication of the lower (low) and upper (high) bound of its confidence interval is given. There are three differences between this table and the IPCC table (Arent et al. 2014). First, this table includes the estimates by d'Arge, (1979). Second, to be consistent with the other estimates in the table, the Mendelsohn estimates are shown against the area average temperature change rather than the population average. Third, to be consistent with the other estimates in the table, the Maddison and Rehdanz estimate is shown in market exchange rate dollars rather than in purchasing power parity dollars.
Source: Data are available at http://users.sussex.ac.uk/~rt220/totalimpactreep.xlsx.

negative. Thus it is unclear whether climate change will lead to a net welfare gain or loss. At the same time, however, despite the variety of methods used to estimate welfare impacts, researchers agree on the order of magnitude, with the welfare change caused by climate change being equivalent to the welfare change caused by an income change of a few percent. That is, these estimates suggest that a century of climate change is about as good/bad for welfare as a year of economic growth.[3]

[3]This suggests that there are bigger problems facing humankind than climate change. For example, the people of Greece lost a third of their income in five years' time, arguably due to poor monetary policy. The people of Syria lost even more in a shorter period. Climate change may not even be our biggest environmental problem, as many people are killed by indoor and urban air pollution (WHO 2014).

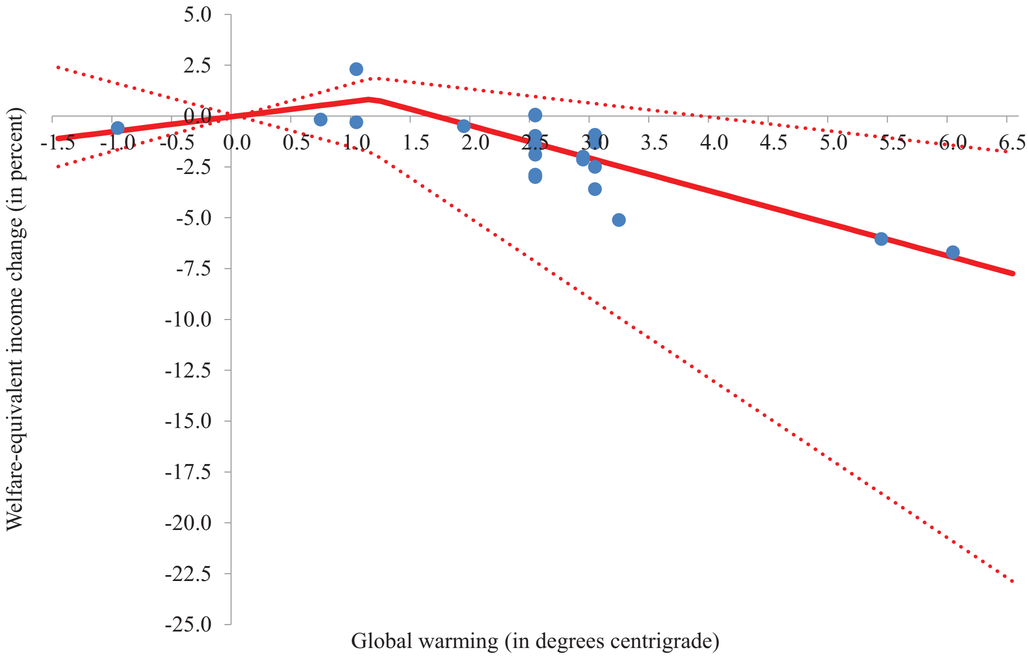


Figure 1 The global total annual impact of climate change

Notes: Impact is expressed in welfare-equivalent income change as a function of the increase in the global annual mean surface air temperature since preindustrial times. The dots represent the estimates reported in table 1, the solid line indicates the best-fit piecewise linear function, and the dotted lines indicate the 95 percent confidence interval.

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

Considered together, the 27 estimates suggest that the welfare impacts of *initial* warming are positive on net, while further warming will lead to net damages (d'Arge, Schulze, and Brookshire 1982). This is illustrated by the solid line in figure 1. Alternative specifications of the impact function are possible, but the piecewise linear model of figure 1 is by far the best fit.[4] Some popular impact functions do not fit the data at all.[5]

The initially positive impacts do not imply that GHG emissions should be subsidized. As shown in figure 1, the total impacts turn negative just below 1.7°C warming above preindustrial levels. More importantly, the *incremental* impacts turn negative before that, around 1.1°C global warming. Because of the slow workings of the climate system and the long-lived capital in the energy sector, it is likely that a warming of 2°C cannot be avoided; a warming of 1°C can certainly not be avoided. Thus the initial net benefits of climate change are sunk benefits—that is, we will reap these benefits no matter what we do to our emissions. This means that GHG emissions should be taxed, not subsidized.

[4]Table B1 in the online supplementary materials presents alternative specifications and how they fare when fitted to the data of table 1, an exercise that should be done more often in climate economics. Note that the parabolic function of Tol (2009) provides the second-best fit.

[5]For example, although Weitzman (2011) argues that the climate change impact function is very nonlinear, with a sharp turn towards large damages at higher temperatures, this is not supported by the estimates shown in table 1 and figure 1.

Impact of Uncertainty

The uncertainty about the estimates of the impact of climate change on total economic welfare is rather large. The dotted lines in figure 1, which are derived from the few standard errors reported in table 1, depict the 95 percent confidence interval. However, given that experts tend to be overconfident (Lichtenstein and Fischhoff 1977) and the 27 estimates were derived by a group of researchers who know each other well, this is probably an underestimate of the true uncertainty. If we take the confidence interval at face value, the impact of climate change does not significantly deviate from zero until 3.5 °C warming.

It is important to note, however, that the uncertainty indicated in figure 1 is right-skewed. That is, negative surprises are more likely than positive surprises of similar magnitude. This is true for both GHG emissions and the climate itself. For example, it is easier to imagine a world that burns a lot of coal than a world that rapidly switches to wind and solar power (Nakicenovic and Swart 2001; van Vuuren et al. 2011; Clarke et al. 2014). Feedbacks that accelerate climate change are likely to be stronger than feedbacks that dampen warming (Roe and Baker 2007; Knutti and Hegerl 2008; Lewis 2013). Furthermore, the impacts of climate change are typically found to be more than linear. That is, if climate change doubles, its impacts more than double (see figure 1). Many researchers have painted dismal scenarios of climate change (Myers 1993; Chalko 2001; Stern et al. 2006; Potsdam Institute for Climate Impact Research and Climate Analytics 2012; Oppenheimer et al. 2014). However, no one has credibly suggested that climate change will make us all blissfully happy. In light of these uncertainties and asymmetries, the earlier conclusion that a century of climate change is about as good/bad for welfare as a year of economic growth needs to be rephrased: A century of climate change is likely to be no worse than losing a *decade* of economic growth.

Distribution of Impacts

Thirteen of the twenty-two studies listed in table 1 include estimates of the regional impacts of climate change and, in the case of the Maddison (2003), Rehdanz and Maddison (2005), and Maddison and Rehdanz (2011), national impact estimates. These estimates indicate that poorer and hotter countries are notably more vulnerable to climate change than richer ones.[6]

As shown in figure 2, for global warming of 2.5°C, the expected impacts for the majority of countries are more negative than in figure 1, where the global total impact is −1.4 percent of gross domestic product. This is because the world economy is concentrated in a few rich countries.[7]

Figure 2 also shows that, by and large, the negative impacts of climate change will be borne by developing economies. Contrary to what is assumed in some studies (Hoel and Sterner 2007; Sterner and Persson 2008), the relative impacts of climate change decline as per capita income rises.

Developing countries are more vulnerable to the impacts of climate change for three reasons. First, poorer countries are more exposed to the weather because of the important role of agriculture and water resources in the economy. In contrast, richer countries have a larger share of their economic activities in manufacturing and services, which are typically shielded (to some extent) from the vagaries of weather and hence climate change.

[6]See appendix C in the online supplementary materials for a description of the methods used.
[7]Note also that the world average in figure 1 counts dollars, rather than countries, let alone people.

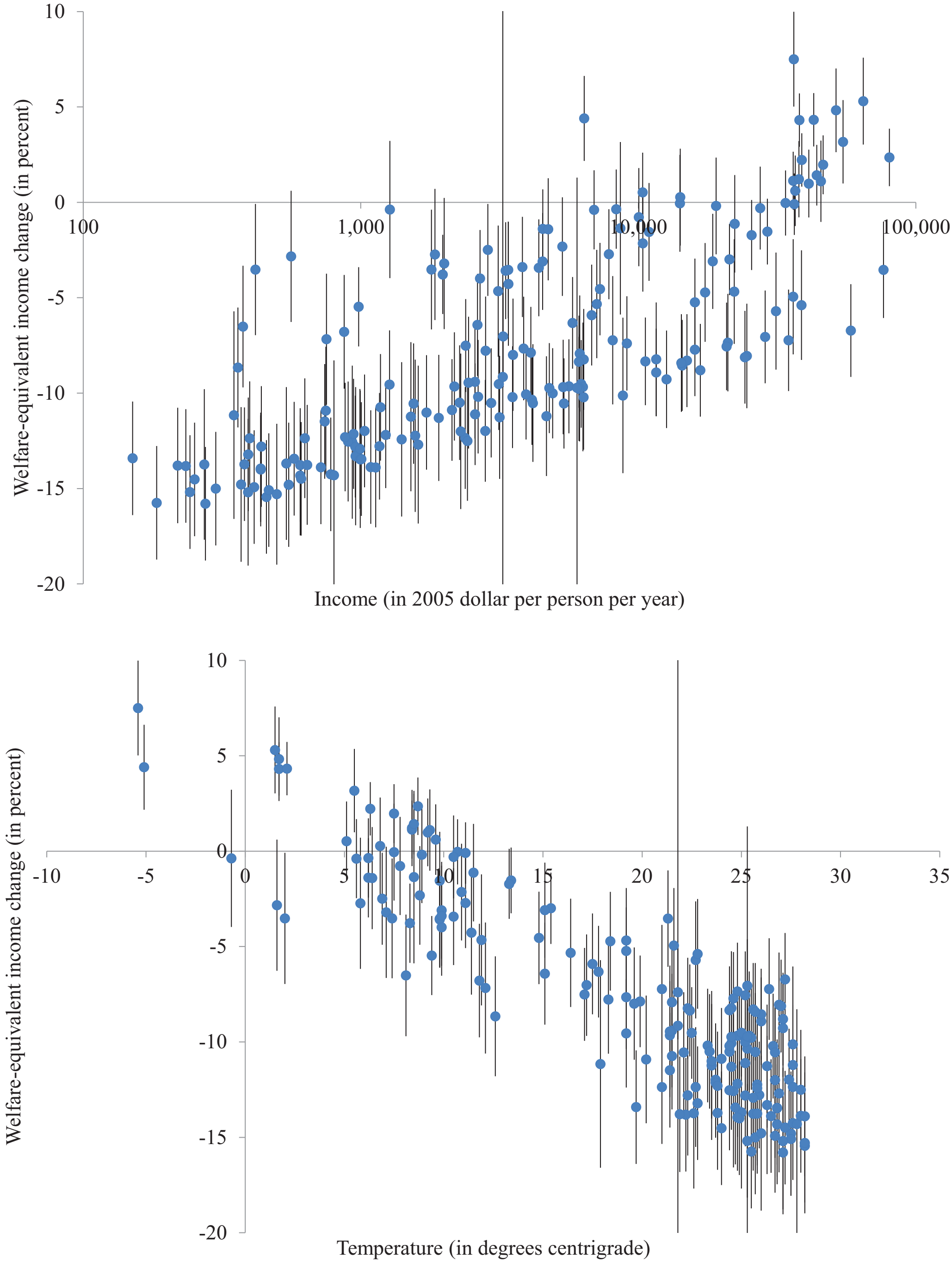


Figure 2 The national total annual impact of climate change

Notes: Impact is expressed in welfare-equivalent income change for a 2.5 °C global warming (relative to preindustrial times) as a function of per capita income (top panel) and temperature (bottom panel). 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.

Source: Data are available at http://users.sussex.ac.uk/∼rt220/totalimpactreep.xlsx.

Second, poorer countries tend to be in hotter places. This means both that ecosystems are closer to their biophysical upper limits and that there are no analogues for human behavior and technology. That is, if the hottest places on the planet become even hotter, there are no existing examples to learn from; new technologies will have to be developed and behavior will have to be adjusted by trial and error. In contrast, Great Britain's future climate may become like Spain's current climate, and the people of Britain would likely adopt some of the behaviors and technologies of the people of Spain.

Third, poorer countries tend to have a limited adaptive capacity (Adger 2006; Yohe and Tol 2002), which depends on a range of factors, such as the availability of technology and the ability to pay for those technologies. Poorer countries often lack access to modern technology and institutions that can help protect against the weather (e.g., air conditioning, malaria medicine, crop insurance). They may also lack the ability, and sometimes the political will, to mobilize the resources for large-scale infrastructure—irrigation and coastal protection, for example.

Development and Climate Policy

There are two options for mitigating the excessive impact of climate change on the poor: reduce climate change and/or reduce poverty. However, the relationship between poverty and vulnerability to climate change is not simple, as I illustrate with some examples below.

Coastal Protection

Bangladesh and the Netherlands are both densely populated, low-lying countries at risk from flooding by river and sea. However, Bangladesh is much more vulnerable to climate change. The Netherlands started its modern, large-scale dike building program in 1850 (Tol and Langen 2000). Before that, dike building was local and primitive and the country was regularly plagued by floods. In 1850, the Netherlands was somewhat richer than Bangladesh is now (purchasing power parity $2400 versus $1400 per person per year), but dike-building technology has improved since then. The main difference between the Netherlands in 1850 and Bangladesh in 2014 is political. In 1849, the Netherlands had a powerful central government broadly representative of the population, which prioritized flood protection. In contrast, Bangladesh is one of the most corrupt and poorly governed countries in the world.[8] Floods primarily affect the poor, who live in the river and coastal flats where land is cheap (Brouwer et al. 2007). There is no political reason to protect the poor because votes can be bought[9] and floods are seen as an act of Allah (Alam 1990). This makes Bangladesh more vulnerable to climate change than the Netherlands.

Agriculture

Climate change could reduce crop yields in Africa by up to 50 percent (Porter et al. 2014). Yields from subsistence farms are often only one-tenth of what is achieved at model farms that have the same soil and climate (Mueller et al. 2012). This so-called yield gap is caused by

[8]See https://www.transparency.org/news/feature/corruption_perceptions_index_2016.
[9]See http://bdnews24.com/economy/2015/04/27/bangladesh-bank-suspends-mobile-banking-to-prevent-vote-buying-in-city-polls.

factors such as a lack of access to irrigation, high-quality seeds, and pesticides, but the underlying causes include a lack of access to capital and product markets due to poor roads and insecure land tenure (Dorward et al. 2004; Foley et al. 2011). Modernizing agriculture would close this yield gap and make African agriculture less vulnerable to climate change (Mendelsohn and Dinar 1999; Howden et al. 2007).

Malaria

Malaria was endemic in large parts of Europe and North America (Hay et al. 2004). Habitat reduction, mosquito control, and medicine turned malaria into a tropical disease. Climate change would spread malaria since the parasite is more vigorous in hot weather and mosquitoes thrive in hotter and wetter places (Martens, Jetten, and Focks 1997; van Lieshout et al. 2004). However, malaria is first and foremost a disease of poverty (Tol and Dowlatabadi 2001; Tol, Ebi, and Yohe 2007). Investments in insecticides, bed nets, and vaccine development have the potential to ensure a malaria-free world, regardless of climate (Cotter et al. 2013; Seder et al. 2013).

Implications for Research and Policy

These three examples—coastal protection, agriculture, and malaria—illustrate that development and vulnerability to climate change are closely intertwined. Although this was first discussed by Schelling (1992), many studies have ignored this relationship, assuming that vulnerability is constant (Burke et al. 2016).

Concentrating GHG emissions reductions in rich countries will not solve the climate problem, while slowing economic growth in poor countries to reduce climate change may do more harm than good (Tol 2005a; Anthoff and Tol 2012). One-fifth of official development aid is now aimed at climate policy (Michaelowa and Michaelowa 2007; Tol 2014), although there has been some relabeling of conventional aid as climate aid (Michaelowa and Michaelowa 2011). Cheap and abundant energy fuelled the industrial revolution (Stern and Kander 2012), and a lack of (reliable) electricity retards growth in poor countries (Chontanawat, Hunt, and Pierse 2008; Steinbuks and Foster 2010). Yet some donors no longer support the use of coal, the cheapest way to generate electricity, or indeed any other fossil fuel. Energy poverty alleviation and carbon dioxide emission reduction may be contradictory goals (Chakravarty and Tavoni 2013). Climate policy could thus increase the impacts of climate change in poor countries.

The disproportionate impacts of climate change on the most vulnerable is a good reason to reduce GHG emissions. However, it is odd 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 development aid suggest a low level of inequity aversion between countries (Tol 2010). Barriers to international trade (Winters, McCulloch, and McKay 2004; Hertel et al. 2009; Winters and Martuscelli 2014) and labor migration (Lipton 1980; Adams and Page 2005) suggest a disregard for the poor in other countries. The disconnect between climate and other policies and the implied concern for people in poor countries may be interpreted in one of two ways: concern about the impact of climate change on the global poor is exaggerated, or our aid, trade, and migration policies need reform.[10]

Development and Climate Change

In addition to its comparative static impacts (see figure 1), climate change affects the *growth rate* of the economy (Fankhauser and Tol 2005; Hallegatte 2005; Eboli, Parrado, and Roson 2010; Bretschger and Valente 2011; Lemoine and Kapnick 2016). Climate change may affect the size and productivity of the labor force and the capital stock, which would affect investment and hence future output. Dietz and Stern (2015), Moyer et al. (2014), and Moore and Diaz (2015) conjecture, without evidence, that climate change would also affect technological progress, which would have a large effect on economic growth (Solow 1956).[11] If true, the dynamic impacts of climate change would dominate the static ones.

There is empirical evidence that climate change has an impact on economic growth. Dell, Jones, and Olken (2009) and Horowitz (2009) find that higher temperatures would reduce income, particularly in poor countries (Dell, Jones, and Olken 2012). Barrios, Bertinelli, and Strobl (2010) and Brown et al. (2011) find a large impact of anomalous rainfall on economic growth in sub-Saharan Africa. Bloom, Canning, and Sevilla (2003) find that 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. With the exception of Burke, Hsiang, and Miguel (2015), these studies find relatively small effects.

The impact of climate (rather than climate change) on development is a subject of active debate and research (Bhattacharyya 2009; Dell, Jones, and Olken 2014). The implications for climate change are unclear, as the findings are mixed. Some argue that geography is the main cause of (under)development in the past (Diamond 1999; Olsson and Hibbs 2005), and presumably in the future. Others emphasize the links between climate and disease (Gallup, Sachs, and Mellinger 1999) and climate and agriculture (Masters and McMillan 2001). If differences in human institutions are accounted for, the apparent influence of climate on development disappears in some studies (Acemoglu, Johnson, and Robinson 2001, 2002; Easterly and Levine 2003)[12] but not in others (Alsan 2015). Some argue that the reported impact of climate on development is actually an impact of ultraviolet radiation (Andersen, Dalgaard, and Selaya 2016).

In sum, the literature on the impact of climate (change) on development has yet to reach firm conclusions. Climate change could reduce the rate of economic growth and even trap people in poverty. If this occurs, then the dynamic impacts could be larger than the static ones reviewed earlier, which means the social cost of carbon would be (much) higher.

[10]Alternatively one may argue, as one referee does, that GHG emissions are categorically different from other actions and inactions that cause harm to others and therefore the observed indifference in other policy domains does not apply to climate policy.

[11]See Bell and Gersbach (2013) for an analysis of an alternative mechanism through which disease and human capital formation affect economic growth.

[12]Climate affects human culture, at least in poor countries, and thus institutions (van de Vliert 2008; van de Vliert and Tol 2014).

The Social Cost of Carbon

The social cost of carbon is the incremental impact of emitting an additional ton 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 GHG emissions should be taxed in order to maximize welfare.

There have been a number of developments concerning the social cost of carbon since my earlier surveys (Tol 2011, 2013b). The volume of papers and estimates has increased rapidly,[13] partly, I believe, in response to the U.S. government adopting an official social cost of carbon (IAWGSCC 2010, 2013, 2015). After a discussion of conceptual issues, I review these new estimates.

New Insights into the Social Cost of Carbon

Some researchers have argued that current estimates of the social cost of carbon are lower bounds on the true social cost of carbon and that, by implication, climate policy is not ambitious enough. Three arguments are put forward. First, estimates of the social cost of carbon are said to underestimate the true risks of climate change (Botzen and van den Bergh 2012; van den Bergh and Botzen 2014, 2015), although both primary estimates (Anthoff, Tol, and Yohe 2009b; Anthoff and Tol 2013, 2014) and meta-analyses (Tol 2009; Arent et al. 2014) pay considerable attention to risks. Second, estimates of the social cost of carbon rely on incomplete impact assessments (Revesz et al. 2014). However, incompleteness only implies bias if the missing impacts are all negative (Tol 2009; Arent et al. 2014). 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 (Guo et al. 2006; Anthoff, Hepburn, and Tol 2009; Anthoff, Tol, and Yohe 2009a; Anthoff and Tol 2010; Tol 2010, 2013a). Some have argued in favor of particular parameter values (Stern 2008, 2010, 2013; van den Bergh and 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, and 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. In any case, 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, because although poorer countries are more vulnerable to climate change than richer ones, carbon dioxide fertilization[14] disproportionately benefits poorer countries (Anthoff, Tol, and Yohe 2009b).

The social welfare function governs trade-offs between risks, between present and future, and between rich and poor. Models often assume that the social welfare function is identically curved in the three dimensions of time, risk, and regard for others (Atkinson et al. 2009). 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 and Traeger 2014;

[13]For example, there were 7 new studies and 72 new estimates in the first few months of 2015 alone. See appendix D in the online supplementary materials for more details.

[14]Carbon dioxide is a key ingredient in photosynthesis. If there is more carbon dioxide in the atmosphere, plants grow faster and become more resistant to drought as less water is lost through evapotranspiration.

Jensen and Traeger 2014; Lemoine and Traeger 2014) but disregard distributional issues within and between countries.

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 following 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 assumptions are discussed elsewhere in this article. 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 earlier, poverty implies vulnerability to climate change; that is, 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 exponent of the exponent of temperature. Figure 1 suggests that the relationship between temperature and impact is close to linear. A series of papers (Keller, Bolker, and Bradford 2004; van den Bijgaart et al. 2013; Lemoine and Traeger 2014; van der Ploeg 2014) show that catastrophes break the smoothness assumed by Golosov et al. (2014), and hence their simple function for the social cost of carbon. Note that these studies offer little new insight into the optimal carbon tax in the near term.[15]

New Estimates of the Social Cost of Carbon

I next examine the probability density of the social cost of carbon for all published estimates (see appendix figure 1). The method follows Tol (2013b),[16] with the estimates weighted by study characteristics as in Tol (2005b). In addition, estimates in excess of $7,600 per ton of carbon are excluded.[17] Estimates between $1,150 and $7,600 per ton of carbon are discounted by a linear function that equals 1 for $1,150 per ton of carbon and 0 for $7,600 per ton of

[15]These studies show that the optimal carbon price does not follow a Hotelling-like path. Lemoine and Rudik (2017) show the same for the cost-effective carbon price.

[16]The probability density function (PDF) is a kernel density. 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 the models developed by Hope and Tol acknowledge the possibility that the impacts of modest climate change may be positive. The kernel functions for estimates by other authors are therefore knotted at zero.

[17]This assumes that the social cost of carbon is a tax that should be paid. Howarth, Gerst, and Borsuk (2014) report an estimate as high as $105,000 per ton of carbon. 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. In 2010, global average carbon efficiency was around $7,600 per ton of carbon; this is an upper bound for a carbon tax. Howarth's tax would thus take fourteen times total world income. One could argue that a carbon tax should offset other taxes, but not increase the total tax burden (Tol 2012). In recent years, world average tax revenue was about 15 percent of gross domestic product, so a tax of $1,150 per ton of carbon or larger would increase the total tax take. This would be an alternative upper bound. If, on the other hand, the social cost of carbon is interpreted as a marginal welfare loss, then there is no upper bound.

carbon. I next discuss the new estimates and their policy implications, deep uncertainty, and publication bias.

Policy implications

Appendix figure 1 presents the probability density of the social cost of carbon for the entire sample and for those estimates based on a pure rate of time preference (PRTP) of 0, 1 or 3 percent per year.[18] The higher the discount rate, the lower the concern for the future and the lower the social cost of carbon: The mode is $220 per ton of carbon for a 0 percent PRTP, $93 per ton of carbon for a 1 percent PRTP, and $28 per ton of carbon for a 3 percent 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 $669 per ton of carbon for a 0 percent PRTP, $468 per ton of carbon for a 1 percent PRTP, and $35 per ton of carbon for a 3 percent PRTP. The higher mode and standard deviation come together in the mean social cost of carbon, which is $677 per ton of carbon for a 0 percent PRTP, $360 per ton of carbon for a 1 percent PRTP, and $44 per ton of carbon for a 3 percent PRTP. To provide some context, burning a barrel of oil emits 0.43 metric ton of carbon dioxide. A $28 per ton of carbon tax is thus equivalent to $3 per barrel, while a $677 per ton of carbon tax is equivalent to $79 per barrel. The former carbon tax is small relative to today's price of oil, while the latter tax is on the same order as price changes on the world market over the last few years. In January 2016, the price of carbon permits in the European Union Emission Trading System (EU ETS) was $28 per ton of carbon.[19] In November 2015, permits were auctioned by the California Air Resources Board at $47 per ton of carbon.[20] The U.S. government uses a social cost of carbon for regulatory benefit–cost analysis that is between $12 and $58 per ton of carbon (Revesz et al. 2017), although the current administration may seek to lower that (EPA 2017). This suggests that current climate policy can readily be justified by benefit–cost analysis and may indeed need to be tightened.

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. However, the evidence in appendix figure 1 challenges this assertion. Moreover, Weitzman's result only holds in partial 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).

[18]The PDFs in appendix figure 1 jump at $0 per ton of carbon. This is by construction. Figure D1 in the online supplementary materials shows the PDF for all estimates if we do not knot the kernel function at zero. In this case there is a substantial probability mass for carbon subsidies, which is at odds with the underlying literature: with knotting, there is a 9 percent chance of a negative social cost of carbon; without knotting, there is a 26 percent chance. Figure D1 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 in figure D1 is large and the PDF is diffuse.

[19]https://www.eex.com/en/market-data/environmental-markets/auction-market/european-emission-allowances-auction#!/2017/01/09.

[20]http://calcarbondash.org/.

Publication bias

Havranek et al. (2015) show that low 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.[21] Indeed, in 9 of 24 years, estimates of the social cost of carbon deviate significantly from earlier ones;[22] the patterns are similar if the sample is split by the PRTP.[23] This indicates that the differences in estimates of the social cost of carbon are not due to differences in discounting and thus that a consensus on the social cost of carbon has yet to be reached.

However, the median and the 90 percent confidence interval for estimates of the social cost of carbon published in a particular year and published in previous years do *not* show frequent challenges to the received wisdom (see figure 3).[24] Figure 3 suggests a gradual decline in the central estimate of the social cost of carbon and a modest tightening of its confidence interval. Thus figure 3 indicates that neither upward revisions nor downward revisions (because the trends are statistically insignificant) of the social cost of carbon are supported.

Conclusions and Research Priorities

This review of estimates in the literature indicates that the impact of climate change on the economy and human welfare is likely to be limited, at least in the twenty-first century. In the short to medium run, climate change may well bring gains, particularly to those who depend on rain-fed agriculture (as carbon dioxide fertilization makes plants more drought resistant) and those who spend substantial money on heating (as warming is faster in winter). However, 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. Because poverty causes vulnerability to climate change, development is a complementary strategy to GHG 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. Thus climate change would appear to be an important issue primarily for those who are concerned about the distant future, faraway lands, and remote probabilities. Moreover, although recent research has substantially improved our understanding of the dynamics of the Pigou tax, our

[21]See table D1 in the online supplementary materials, which lists the number of studies by year of publication, the number of estimates, and the average PRTP. There is a slight downward but insignificant trend (−3.09 ± 4.91 dollars per ton of carbon per year) in the estimated social cost of carbon. There is a slight upward but insignificant trend (0.0005 ± 0.0179 percent per year) in the PRTP.

[22]See table D1 in the online supplementary materials for 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.

[23]See tables D2–D7 in the online supplementary materials for estimates of the social cost of carbon based on the six most frequently used PRTP values (0, 0.1, 1, 1.5, 2, and 3 percent).

[24]Besides the discounting of high estimates that exceed income, the key difference between table D1 in the online supplementary materials and figure 3 is the proper reflection of uncertainty through the probability density estimation: although the standard error of the mean in table D1 is rather low, having estimated the mean with confidence does not imply that the uncertainty is small. The bandwidths underlying appendix figure 1 and figure 3 were chosen to avoid overconfidence, a choice that seems appropriate in light of the great uncertainties and controversies concerning climate change.

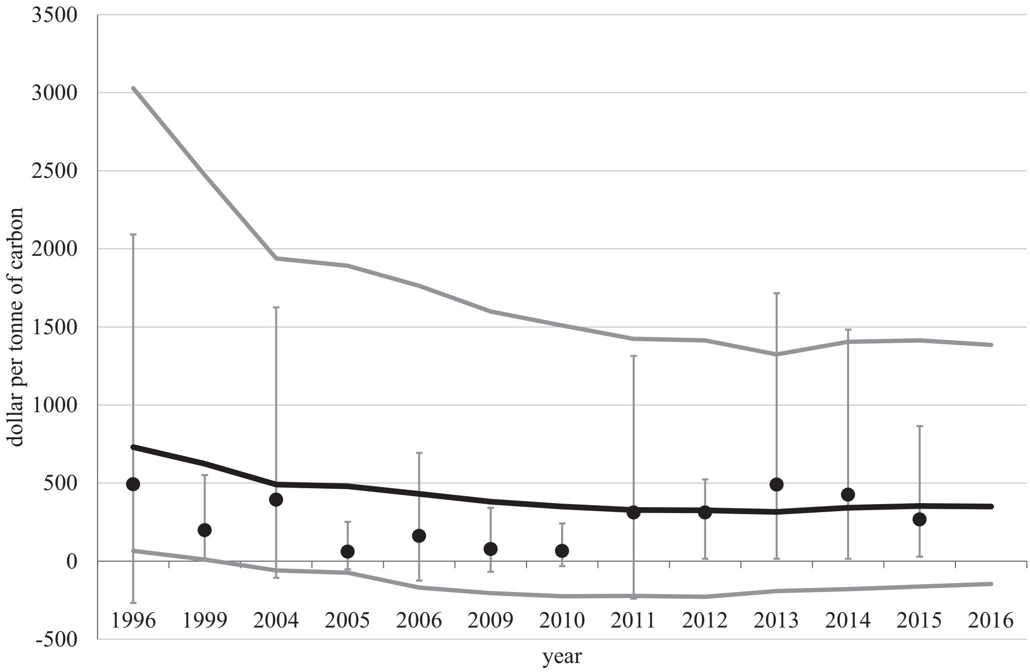


Figure 3 The median and 90 percent confidence interval of estimates of the social cost of carbon published in a particular year (dots and bars) and in previous years (lines)

Notes: The median here indicates the kernel median.

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

best estimate of the optimal carbon tax in the near term still ranges from a few tens to a few hundreds of dollars per ton of carbon, leaving ample room for political maneuvering.

These qualitative insights are robust, but the quantitative assessment of the impacts of climate change is uncertain and incomplete. This uncertainty is partly irreducible. We are, after all, estimating and valuing the impact of future climate change on future society.

Further research is needed concerning several unresolved issues. First, natural scientists and economists tend to disagree about the seriousness of climate change, and have done so for many years (Nordhaus 1994a). However, the reasons for this discrepancy, and indeed whether it is real, are not well understood and thus require further study to determine who is closer to the truth.

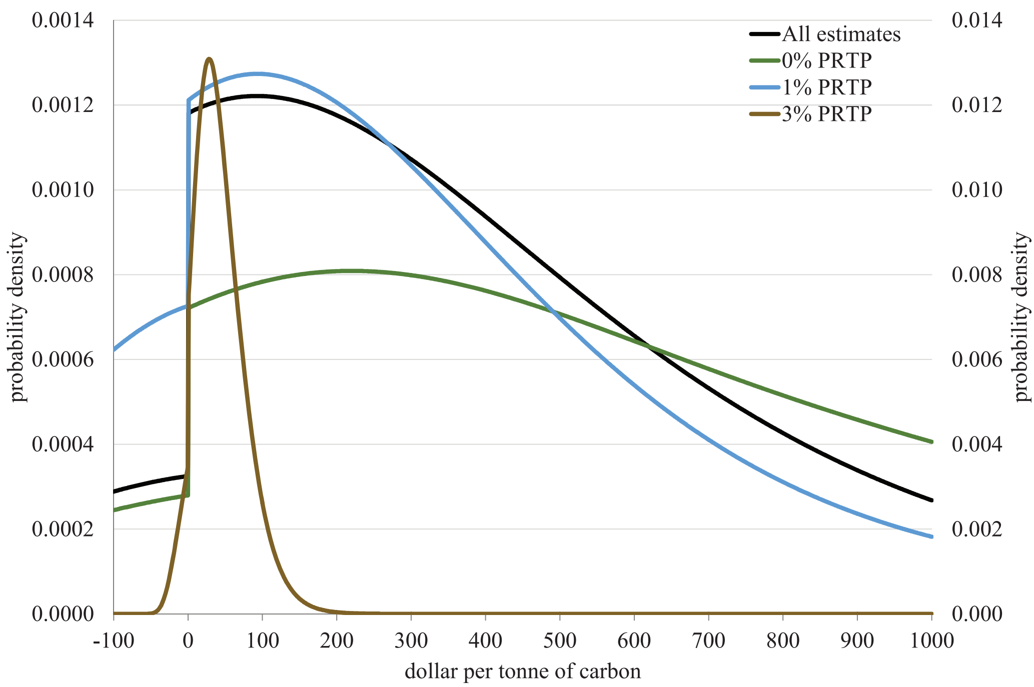
Second, the impact of climate change on numerous important issues—water resources, transport, migration, violent conflict, energy supply, space cooling, labor productivity, and tourism and recreation—has not received sufficient attention; there is either very little solid evidence, no conclusive evidence, or no quantification of welfare impacts. This means that the estimates of the impact of climate change are incomplete and we cannot know whether the bias is upwards or downwards until more research is conducted. However, this also increases the uncertainty about the impact of climate change, which strengthens the case for GHG emissions reductions.

It is unlikely that future research will overturn the fundamental finding that it is the poor who will suffer most from climate change and reducing poverty should be a key priority for policies aimed at alleviating the impact of climate change. That being said, the quantification remains problematic and should be researched in greater detail.

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

Climate policy advice is channeled through estimates of the social cost of carbon, which is very sensitive to the discount rate. However, the social cost of carbon aggregates not only over time, but also between impacts, across species, within and between societies, and across alternative futures. Although recent studies have made some progress in illustrating the importance of other parameters in the welfare function for the social cost of carbon, 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 behavioral and experimental economics. Future meta-analyses may be able to determine whether there is a systematic relationship between model structure and the social cost of carbon.

Climate policy is one of the defining issues of our time. The research agenda I have outlined here is rich enough to keep economists occupied for years to come. Moreover, this agenda 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 proposed agenda makes for research that is both intellectually fascinating and policy relevant.



Appendix Figure 1 The probability density function of the social cost of carbon
Notes: This is shown 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.
Source: 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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