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A meta-analysis of the total economic impact of climate change

Richard S.J. Tol [*,1]

Department of Economics, University of Sussex, Falmer, United Kingdom
Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands
Department of Spatial Economics, Vrije Universiteit, Amsterdam, The Netherlands
Tinbergen Institute, Amsterdam, The Netherlands
CESifo, Munich, Germany
Payne Institute for Public Policy, Colorado School of Mines, Golden, CO, USA
College of Business, Abu Dhabi University, United Arab Emirates

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ABSTRACT

Earlier meta-analyses of the economic impact of climate change are updated with more data, with three new results: (1) The central estimate of the economic impact of global warming is always negative. (2) The confidence interval about the estimates is much wider. (3) Elicitation methods are most pessimistic, econometric studies most optimistic. Two previous results remain: (4) The uncertainty about the impact is skewed towards negative surprises. (5) Poorer countries are much more vulnerable than richer ones. A meta-analysis of the impact of weather shocks reveals that studies, which relate economic growth to temperature levels, cannot agree on the sign of the impact whereas studies, which make economic growth a function of temperature change do agree on the sign but differ an order of magnitude in effect size. The former studies posit that climate change has a permanent effect on economic growth, the latter that the effect is transient. The impact on economic growth implied by studies of the impact of climate change is close to the growth impact estimated as a function of weather shocks. The social cost of carbon shows a similar pattern to the total impact estimates, but with more emphasis on the impacts of moderate warming in the near and medium term.

1. Introduction

Estimates of the total economic impact of climate change underpin the social cost of carbon, which determines the optimal rate of greenhouse gas emission reduction. The number of estimates of the total impact has risen rapidly in recent years, so that previous meta-analyses (Howard and Sterner, 2017; Nordhaus and Moffat, 2017; Tol, 2018) are now out of date. The literature comprises a wide range and seemingly incommensurate estimates of the effects of climate change and weather shocks. This paper reconciles different estimates and updates previous meta-analyses.

Studies of the economic impact of climate change use a range of methods—enumeration, elicitation, computable general equilibrium, econometrics—each with its pros and cons. Studies of the economic impact of weather are exclusively econometric but use two alternative specifications, one in which *temperature* affects economic growth and one in which *temperature change* affects growth. As shown below, the former is inconsistent with the climate literature. The latter is consistent in principle, conditional on a scenario and model.

This paper makes three contributions. First, I update my earlier meta-analysis of the economic impact of climate change (Tol, 2009, 2014, 2018), using the same methods as before. This confirms some earlier findings but overturns others.

Piontek et al. (2021) and Rising et al. (2022b,a) discuss much the same literature but do not reconcile the different estimates using meta-analysis. In contrast to Howard and Sterner (2017), I separately analyse weather and climate estimates. I use more estimates than they do, but skip some of their numbers. They appear to have misread some papers, included some estimates twice, and added estimates that are not. See Appendix A for details. Compared to Nordhaus and Moffat (2017), I add more estimates, avoid arbitrary weights,[2] and include estimates of the impact of weather shocks. I use more estimates than Rose et al. (2022, see also Tol (2016)), and separate the impacts of climate change and weather shocks.

* Correspondence to: Jubilee Building, BN1 9SL, UK.
E-mail address: r.tol@sussex.ac.uk.
URL: http://www.ae-info.org/ae/Member/Tol_Richard.

[1] I am grateful to Roula Inglesi-Lotz and two anonymous referees. I apologize to Mel & Kim.

[2] Nordhaus and Moffat discount older studies, studies that republish earlier estimates, and studies that use methods deemed uninformative.

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As a second contribution, I present the first meta-analyses of the two literatures on the economic impact of weather shocks. Auffhammer (2018) and Kolstad and Moore (2020) discuss this literature but do not combine estimates.

Third, I propose a method to reconcile one of the weather literatures with the climate literature.

The paper proceeds as follows. Section 2 discusses the literature on the estimated impacts of climate change. This section follows Tol (2021), but with new numbers. Section 3 turns to the impacts of weather shocks. Section 4 reconciles these estimates where possible. Section 5 shows the implications for the social cost of carbon. Section 6 concludes.

2. Impacts of climate change

Table 1 shows 69 estimates, from all 39 studies known to the present author, of the total economic impact of climate change. The 39 papers are taken from the previous meta-analysis listed in the introduction, supplemented with papers unearthed in an extensive literature survey on the social cost of carbon (Tol, 2023), papers that came to the attention of the author as a referee, and papers found in a search on Scopus.[3] These estimates are comparative static, comparing economies of the recent past with and without some future climate change. Fig. 1 plots 58 of the estimates; Figure B6 plots them all, including 3 estimates for very large warming. The horizontal axis is the increase in the global annual mean surface air temperature. The vertical axis is the welfare-equivalent income change, some approximation of the Hicksian Equivalent Variation. These numbers should be read as follows: A global warming of 2.5 °C would make the average person feel as if she had lost 1.7% of her income. 1.7% is the average of the 13 dots at this level of warming.

2.1. Methods

As indicated in Fig. 1 and Table 1, these estimates use a range of methods. Older studies tend to rely on the enumerative method.[4] Estimates of the impacts (after assumed adaptation) of climate change in their natural units are multiplied with estimates of their values and added up. This is a direct cost, a poor approximation of the change in welfare. The enumerative approach omits price changes and interactions between sectors, such as changes in water resources affecting agriculture.

Price changes and market interactions between sectors are included in estimates that use a computable general equilibrium model (CGE). This method has become more popular over the years. These studies report the Hicksian Equivalent Variation but, as they are based on the national accounts, omit direct welfare impacts on health and nature.[5] CGE models allow for adaptation in the production function—for example, a drop in the productivity of land would be partially compensated by an increase in the application of fertilizer and labour—and through shifts in supply and demand.[6]

Econometric studies have also become more numerous over time. Differences in prices, expenditures, self-reported happiness, or total output are ascribed to variations in climate. A key advantage of this method, in contrast to the other methods, is that no assumptions are made on how people, companies and governments adapt to climate change; observed impacts include actual adaptation. However, identification of the climate impact comes from the cross-sectional variation of climate over space. Projected impacts assume that climate differences between locations are valid analogs for climate changes over time.

Four studies elicit expert views. Two of these studies were done before anyone could reasonably claim expertise on the economic impacts of climate change, the later ones use a mix of people who have and have not published on the subject. Views were expressed about the impact of climate change on global output, which can be interpreted as a measure of economic activity (but not welfare) as well as a measure of income (and thus welfare).

2.2. Combining estimates

Fig. 1 shows a curve, based on the method of Tol (2019b). Seven alternative impact functions, all but one proposed in the literature—linear, piecewise linear, quadratic, parabolic, exponential, catastrophic—were fitted to the data. These models were all proposed because of their mathematical convenience, except the piecewise linear one, which best fitted the data (Tol, 2018). I dropped the double-exponential model of Golosov et al. (2014), as its fit to the data is so poor, and replaced it with the hyperbolic sine, which does much better. Table 2 gives the equations and their fit to the data. I calibrated the parameters by minimizing the weighted sum of squared differences between the model and the primary estimate, weighting all estimates from a single study equally and attaching a total weight of one per study. The curve shown is the Bayesian model average, that is, the seven impact functions are weighted according to their fit to the primary estimates. Assuming normality of the residuals implies a loglikelihood of the estimated model. The fit equals the exponent of that loglikelihood, rescaled so that the sum of the likelihoods is one.

The method is eclectic. I treat the universe of 69 published estimates as if they were a sample of observations from a population of estimates that could have been published so as to fit the seven alternative curves with least squares, assuming the residuals to be normally distributed. Howard and Sterner (2017) do the same thing. Nordhaus and Moffat (2017) instead create a sample by drawing from the universe of model results. I then switch gears and treat the impact functions as if they were alternative models in the Bayesian sense of those words and take their weighted average. The mixing of classical and Bayesian methods can be avoided by pretending that the OLS results really are posteriors from uninformative priors. Tol (2012) extensively discusses the various ways this can be done; the method used here seems to be most faithful to the actual information contained in the published literature.

The curve in Fig. 1 is roughly linear. This implies that it does not really matter whether we estimate the impact of climate change relative to pre-industrial times or relative to today. The authors of the studies listed in Table 1 are not always clear about the assumed baseline climate. In almost all cases, however, vulnerability is assumed to be constant. That is, climate change would have the same, relative effect on the current economy as it would on the pre-industrial one. The near-linearity in temperature and the invariance in development allows me to shift the origin of the meta-function in Fig. 1 to pre-industrial times.

The 95% "confidence interval"[7] shown in Fig. 1 is based on the uncertainty reported in 14 of the primary estimates, following Tol (2018, see also Tol (2012, 2015)). The lower and upper bound, see Table 1 is estimated separately as a linear function of the temperature

[3] There are many more studies that cover part of the economy, limiting the attention to a particular country or region. These studies have been omitted here because of the difficulties in making these estimates comparable and correcting for the overrepresentation of certain countries (USA) and sectors (agriculture).

[4] Rennert et al. (2022) use the enumerative method but do not show estimates of the total impact of climate change.

[5] One CGE study (Takakura et al., 2019) uses the value of a statistical life to assess health impacts.

[6] If adaptation is implied in the assumed shock, then there is no adaptation in production. For example, many CGEs take their impact of climate change on labour productivity, one of the largest impacts, from Kjellstrom et al. (2009), but as temperature is not an input factor, air conditioning is kept constant just as it is in Kjellstrom.

[7] The term *confidence interval* is here used in the loosest of meanings.

Table 1
Estimates of the comparative static impact on global economic welfare.

Study	Warming	Impact	st.dev.	min	max	Method	scc
d'Arge (1979)	−1.0	−0.6				enum	92
Nordhaus (1982)	2.5	−3.0		−12.0	5.0	enum	74
Nordhaus (1991)	3.0	−1.0				enum	17
Nordhaus (1994a)[a]	3.0	−1.3				enum	23
Nordhaus (1994b)	3.0	−3.6		−21.0	0.0	elicit	62
	6.0	−6.7					29
Fankhauser (1995)[b]	2.5	−1.4				enum	35
Berz (2001)[b]	2.5	−1.5				enum	37
Schauer (1995)	2.5	−5.22	8.44			elicit	129
Tol (1995)[b]	2.5	−1.9				enum	47
Nordhause and Yang (1996)[a]	2.5	−1.4				enum	35
Plambeck and Hope (1996)[b]	2.5	−2.9		−13.1	−0.5	enum	71
Mendelsohn et al. (2000)	2.5	0.03	0.05			ectric	−0.7
	2.5	0.10	0.01				−2.5
	4.0	−0.01					0.1
	4.0	−0.04					0.4
	5.2	−0.01					0.1
	5.2	−0.13					0.7
Nordhause and Boyer (2000)[a]	2.5	−1.5				enum	37
Tol (2002)	1.0	2.3	1.0			enum	−355
Maddison (2003)	2.5	0.0				ectric	−0.8
Rehdanz and Maddison (2005)	0.6	−0.2				ectric	77
	1.0	−0.3					48
Hope (2006)	2.5	−1.0		−3.0	0.0	enum	24
Nordhaus (2006)	3.0	−0.9	0.1			ectric	16
	3.0	−1.1	0.1				18
Nordhaus (2008)[a]	3.0	−2.5				enum	43
Horowitz (2009)	1.0	3.8		−4.2	−2.7	ectric	587
Eboli et al. (2010)[c]	3.0	−1.35				CGE	23
Hope (2011)	3.0	−0.7		−1.8	−0.3	enum	12
Maddison and Rehdanz (2011)	3.2	−5.1				ectric	77
Ng and Zhao (2011)	1.0	−1.35				ectric	209
	1.0	−1.61					249
Bosello et al. (2012)[c]	1.9	−0.5				CGE	21
Roson and van der Mensbrugghe (2012)[c]	2.9	−1.8				CGE	33
	5.4	−4.6					24
McCallum et al. (2013)[c]	2	−0.7				CGE	27
	4	−1.8					17
Nordhaus (2013)[a]	2.9	−2.0				enum	37
Desmet and Rossi-Hansberg (2015)[e]	4.6	5.1				ectric	−37
	9.3	−4.9					9
	13.6	−24.1					20
	16.7	−78.9					44
Sartori and Roson (2016)[d]	3.0	−0.7				CGE	12
Kompas et al. (2018)[d]	1.0	−0.5				CGE	72
	2.0	−1.1					41
	3.0	−1.8					32
	4.0	−2.8					27
Dellink et al. (2019)	2.5	−2.0				CGE	49
Takakura et al. (2019)	2.0	−1.1	0.6			CGE	41
	4.0	−4.7	0.7				45
	6.0	−9.5	1.2				41
Howard and Sylvan (2020)	3.0	−9.2	10.3	−20	−2	elicit	158
Kalkuhl and Wenz (2020)	1.0	−2.3	1.32			ectric	355
Conte et al. (2021)	3.7	−3.7				ectric	42
Cruz and Rossi-Hansberg (2021)	7.2	−5.0				ectric	15

(*continued on next page*)

Table 1 (*continued*).

Study	Warming	Impact	st.dev.	min	max	Method	scc
Howard and Sylvan (2021)	1.2	−2.2	2.9			elicit	236
	3.0	−8.5	6.7				146
	5.0	−16.1	13.3				100
	7.0	−25.0	20.7				79
Newell et al. (2021)	4.3	5.63				ectric	−47
	4.3	3.61					−30
	4.3	−1.71					14
	4.3	−1.63					14
	4.3	−2.17					18
	4.3	−0.64					5
	4.3	−1.82					15
	4.3	−1.75					15
	4.3	−2.16					18

Valuation methods are **enum**erative, **elicit**ation, **ec**onome**tric**, and **c**omputable **g**eneral **e**quilibrium. The social cost of carbon, in 2010 US dollar per metric tonne of carbon, is for emissions in the year 2015, the SSP2 scenario, a pure rate of time preference of 1% and a rate of risk aversion of 1; impacts are proportional to temperature squared.

[a] These six studies are assumed to form one independent estimate.

[b] Plambeck takes the average of Fankhauser and Tol. Berz is a minor update of Fankhauser.

[c] These four studies are assumed to form one independent estimate.

[d] These two studies are assumed to form one independent estimate.

[e] Temperature: Fig. 5; impact: Fig. 7; structure: Fig. 8. Read with Matlab's GRABIT.

Table 2
Impact functions.

Name	Function	Likelihood	Proponent	scc
Parabolic	$-0.45T - 0.082T^2$	20.78%	Tol (2009)	29
Hyperbolic sine	$\frac{1-e^{2 \cdot 0.41T}}{2e^{0.41T}}$	18.36%	this study	22
Quadratic	$-0.17T^2$	17.36%	Nordhaus (1992)	27
Weitzman 6	$-0.19T^2 + 1.10 \cdot 10^{-5}T^6$	11.76%	Weitzman (2012)	29
Weitzman 7	$-0.18T^2 + 9.85 \cdot 10^{-7}T^7$	11.61%	Weitzman (2012)[a]	28
Linear	$-0.79T$	13.91%	Hope (2006)[b]	30
Piecewise linear	$-0.79T$ if $T \leq 12.8$ $-0.79 \cdot 12.8 - 17.8(T - 12.8)$ if $T > 12.8$	13.18%	Tol (2018)	30
Exponential	$0.0078 - 0.0078e^T$	0.10%	Van der Ploeg (2014)	3

The social cost of carbon, in 2010 US dollar per metric tonne of carbon, is for emissions in the year 2015, the SSP2 scenario, a pure rate of time preference of 1%, and a rate of risk aversion of 1.

[a] Weitzman actually raises temperature to the power 6.754, which excludes cooling.

[b] Hope is actually piecewise linear, with zero impacts below one temperature threshold, linear damages above that threshold, and shifted linear damages above another temperature threshold.

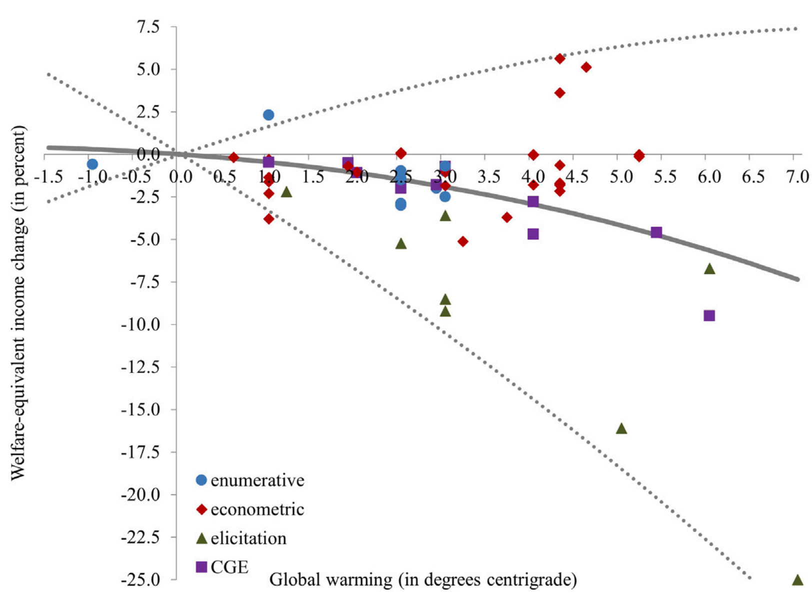

Fig. 1. The impact of climate change since pre-industrial times on global welfare according to comparative static studies.
Primary estimates are shown as dots. The central, solid line is the Bayesian model average, the dashed lines the central estimate plus or minus twice the estimated standard deviation.

increase, using weighted least squares as above. The positive standard deviation is $1.05(0.25)T$, the negative one $1.45(0.25)T$, where the number in brackets is the standard error of the estimated coefficient.

The confidence interval in Fig. 1 has the desirable property that there is no uncertainty about the lack of impact from a lack of climate change. The confidence interval widens as climate change gets more pronounced. Figure B7 instead shows the confidence interval based on the standard error of regression, which is unduly wide around zero warming and independent of warming.

2.3. Results

Compared to my previous meta-analysis based on the same methods (Tol, 2019b), Fig. 1 shows a very different picture—see Figure B3. The number of estimates has more than doubled. The number of estimates beyond 3.2 °C of warming has increased tenfold. As there is a non-negligible chance of large warming, the previous paucity of evidence allowed for speculation about the expected impact of climate change (Weitzman, 2009; Anthoff and Tol, 2022).

The central estimate of the impact of global warming is always negative, but the confidence interval is too wide to put much confidence in that. The wider confidence interval, compared to Tol (2019b), is mostly due to the range of uncertainties reported by Howard and Sylvan (2020, 2021). The central estimate is higher because of the positive impacts reported by Desmet and Rossi-Hansberg (2015) and Newell et al. (2021)[8] for substantial global warming. Enumerative studies report positive impacts of climate change due to reduced costs of heating in winter, lower cold-related mortality, and carbon dioxide fertilization. In Desmet and Rossi-Hansberg (2015), the positive impacts are in manufacturing.[9] There is no sectoral breakdown in Newell et al. (2021); the positive impacts are in specifications that relate economic growth to the temperature level (see below).

Researchers disagree on the sign of the net impact, but agree on the order of magnitude: The welfare loss (or gain) caused by climate change is equivalent to the welfare loss caused by an income drop of at most ten percent—a century of climate change is not worse than losing a decade of economic growth.

This is a key finding from published estimates. These estimates are incomplete and probably underestimate the true impact (Arent et al., 2014). Some argue that the real impacts are *much* larger than the published estimates (e.g., Rising et al., 2022b,a). This assumes, first, that the missing impacts are negative and, second, that over 40 years of impact research has somehow missed the most important effects of climate change.

Figure B4 dispels two common misconceptions. First, many estimates have been published in recent years. Second, positive impact estimates are not confined to the earlier years. Figure B4 shows a weighted regression on publication year. Estimates have become more pessimistic over the years, but this trend is not statistically significant. There are two outliers, one positive (Tol, 2002) and one negative (Horowitz, 2009).

The uncertainty is large and right-skewed. For every degree warming, the positive standard deviation increases by 1.02% GDP while the negative standard deviation increases by 1.43% GDP. That is, negative surprises are larger than positive surprises of equal probability.

Fig. 1 suggests that different methods yield different results. Figure B5 shows the curve fitted separately by method used for the primary impact estimates. Instead of using the Bayesian model average, the curve with the best fit is shown because there are not enough observations to estimate so many parameters if the sample is split into four. The elicitation studies are most pessimistic, the econometric studies most optimistic about the impacts of climate change. The enumerative and general equilibrium papers lie in between, with the former more pessimistic for moderate warming and less pessimistic for more profound warming. Although the central estimates are different, the uncertainty is so large that differences do not become statistically significant from zero before 4 °C of warming.

2.4. Sensitivity analyses

‘ Figure B7, introduced above to illustrate the construction of the confidence interval, also shows an alternative result for the central estimate. In the main analysis, each study is given equal weight. Some studies, however, update previous ones.[10] The studies are marked in Table 1.[11] As a robustness check, I gave these sets of studies equal weight. Figure B7 shows that this makes very little difference for the Bayesian model average. The confidence interval, however, is much wider because there are fewer observations.

In Table 1, estimates are presented as the impact of global warming relative to pre-industrial times. This is the relevant information, as global climate policy targets use the same metric. However, the impact studies listed in Table 1 use different baselines. Some use warming relative to the recent past, some relative to pre-industrial times, and some papers are not explicit about the definition of warming and may even use different definitions between sectors. In order to test the sensitivity of the results to this, I assume for all estimates that the reported impact is the impact relative to “today” and the assumed warming is the warming since “today”. I thus add to the reported warming the global surface air temperature anomaly, relative to pre-industrial times, averaged over the 30 years prior to the data of publication. I use the central line in Fig. 1 to rescale the reported impact. I then re-estimate the impact functions. Figure B1 shows the result and compares it to the base case. Re-basing the estimates in this way does not really matter because the Bayesian model average is approximately linear.

Some studies, however, report impacts at various levels of warming. For those studies, I fitted a power function, if all reported impacts have the same sign, or otherwise a second-order polynomial to the minimum and maximum impact; and used the fitted function to rescale the reported impact to warming relative to preindustrial times. Furthermore, some studies assume linearity whereas other researchers, William Nordhaus in particular, assume that impacts are quadratic. I use those assumptions. Figure B1 shows the result and compares it to the base case and the first alternative above. Again, re-basing the impact estimates to pre-industrial temperature does not materially affect the results. Since the two extreme assumptions—warming is relative to preindustrial versus warming is relative to today—lead to essentially the same outcome, so will an attempt to recover what the original authors meant by “warming”.

Newell et al. (2021) study the impact of weather shocks but only report the implied impact of climate change. Figure B2 re-estimates the Bayesian model average without their results. This does not meaningfully affect the estimated impact function.

Figure B2 shows an alternative sensitivity analysis, where the two most extreme estimates are omitted, Desmet and Rossi-Hansberg (2015) on the optimistic side and Howard and Sylvan (2020) on the pessimistic side. The central estimate shifts down for warming over 3 °C. The lower bound hardly moves, but the upper bound falls considerably, skewing the distribution further towards negative surprises.

[8] Newell et al. (2021) is included in the set of studies on the impact of climate change, rather than in the set of studies on the impact of weather shocks, because they do not report their parameter estimates.

[9] The “into Siberia” series of papers (Desmet and Rossi-Hansberg, 2015; Conte et al., 2021; Cruz and Rossi-Hansberg, 2021) assume unfettered mobility of capital and labour.

[10] Studies that *republish* earlier studies are excluded. There are many such studies; see Tol (2023) for a subset.

[11] Note that my assessment of which studies depends on which is markedly different from that in Howard and Sterner (2017). See appendix.

Table 3
Sectoral impacts of 2.5 °C global warming. Impacts are expressed as a percentage of gross global income. Imputed impacts are in *italics*.

	Fankhauser	Berz	Tol	Nordhaus	Bosello	Dellink	Sartori	Kompas	Takakura	Average
Agriculture	−0.20	−0.19	−0.13	−0.13	−0.39	−0.75	−0.10	−0.22	0.00	−0.23
Forestry	−0.01	−0.02	*−0.01*	0.00	−0.01	*−0.01*	*−0.01*	−0.02	*−0.01*	−0.01
Energy	−0.12	−0.11	*−0.12*	−0.02	−0.02	−0.06	*−0.12*	−0.06	−0.43	−0.12
Water	−0.24	−0.23	*−0.10*	−0.03	−0.01	*−0.10*	*−0.10*	−0.01	*−0.10*	−0.10
Tourism	*−0.09*	*−0.09*	*−0.09*	*−0.09*	−0.17	−0.14	0.04	−0.10	*−0.09*	−0.09
Other markets	*−0.64*	*−0.64*	*−0.64*	*−0.64*	*−0.64*	*−0.64*	−0.30	−0.99	*−0.64*	−0.64
Coastal defence	0.00	−0.01	−0.08	−0.04	−0.03	−0.04	0.00	−0.02	*−0.03*	−0.03
Dryland	−0.07	−0.07	−0.09	−0.09	−0.08	−0.10	0.00	−0.07	−0.02	−0.07
Wetland	−0.16	−0.16	−0.17	−0.19	*−0.17*	*−0.17*	*−0.17*	*−0.17*	*−0.17*	−0.17
Ecosystem	−0.21	−0.20	−0.19	−0.20	*−0.20*	*−0.20*	*−0.20*	*−0.20*	*−0.20*	−0.20
Health	−0.26	−0.40	−0.77	−0.10	−0.01	−0.90	−0.20	−0.48	−1.21	−0.48
Air pollution	−0.08	−0.08	*−0.08*	*−0.08*	*−0.08*	*−0.08*	*−0.08*	*−0.08*	*−0.08*	−0.08
Time use	*0.29*	*0.29*	*0.29*	0.29	*0.29*	*0.29*	*0.29*	*0.29*	*0.29*	0.29
Settlements	*−0.17*	*−0.17*	*−0.17*	−0.17	*−0.17*	*−0.17*	*−0.17*	*−0.17*	*−0.17*	−0.17
Catastrophe	*−0.01*	*−0.01*	*−0.01*	*−1.02*	−0.21	−0.21	−0.21	−0.21	*0.00*	−0.21
Migration	−0.02	−0.02	−0.12	*−0.06*	*−0.06*	*−0.06*	*−0.06*	*−0.06*	*−0.06*	−0.06
Amenity	*−0.33*	*−0.33*	−0.33	*−0.33*	*−0.33*	*−0.33*	*−0.33*	*−0.33*	*−0.33*	−0.33
Total	−2.35	−2.45	−2.83	−2.91	−2.29	−3.69	−1.72	−2.90	−3.27	−2.71
Original	−1.40	−1.50	−1.90	−1.50	−0.50	−2.00	−0.56	−1.42	−1.67	−1.58
Ratio	1.68	1.63	1.49	1.94	3.20	1.84	3.10	2.04	1.96	1.72

Figure B2 also shows a third sensitivity analysis, one that does matter. In Table 1, I show the estimated impact of 1 °C global warming according to Ng and Zhao (2011), Horowitz and Lange (2014) and Kalkuhl and Wenz (2020). The impact immediately follows from the estimated coefficients. These coefficients were estimated on a sample that showed far less than 1 °C warming, so Table 1 extrapolates, perhaps unduly so. However, Newell et al. (2021) use roughly the same sample but show estimates of the impact of 4.3 °C warming, which goes well beyond the conventional limits of extrapolation. I therefore rescale the impact estimates of Ng and Zhao (2011), Horowitz and Lange (2014) and Kalkuhl and Wenz (2020) to 4.3 °C and re-estimate the impact functions. Figure B2 shows the results and compare them to the base case. The central estimate is more pessimistic. For 2.5 °C warming, the impact falls from −1.4% to −1.9% of income; for 5.0 °C, from −4.2% to −5.6%. The largest impact, however, is on the upper bound of the confidence interval. Instead of increasing linearly with temperature, it stabilizes around 2.3% of income.

2.5. Sectoral impacts and omission bias

Nine studies show sectoral impacts in tabular format. The results are shown in Table 3 for 2.5 °C global warming. The estimates by Sartori and Roson (2016) and Kompas et al. (2018) are scaled using the function shown in Fig. 1. Recall that there are many sector-specific impact studies that are not reviewed here.

The different studies cover different sectors. I mapped the reported results to the sectors shown in Table 3; the mapping was obvious for all nine papers since later papers adopted the sectoral classification of earlier ones.[12] Sectoral coverage is incomplete for all studies. Following Tol (2019a), I impute missing values with the average of the studies that do include this impact. Imputed values are in *italics*.

The following results emerge. “Other markets” is the biggest impact. Although recorded in an obscure way, this is primarily the impact of heat on labour productivity. Health impacts come second, followed by amenity, extreme weather, and agriculture. Only the impact of climate change on time use is positive. Overall, market impacts make up 54% of the total, while the remaining 46% directly affect welfare.

On average, imputation of missing impacts increases the total impact estimate by 72%. See Table 3. The study by Tol (1995) is most complete, Sartori and Roson (2016) least. The estimates in Fig. 1 therefore appear to be underestimates of the true impact.

[12] The exact mapping can be found in the sheet “Sectors”, in file “Totalimpactenpol.xlsx” at GitHub.

2.6. Distribution of impacts

Fig. 1 shows the global average impact of climate change. 19 of the 39 studies include estimates of the *regional* impacts of climate change or *national* impact estimates. Recall that there are many country-specific impact studies that are not reviewed here.

Following Tol (2021), I regress the published regional impact, in percent of GDP, on per capita income in 2010 and average annual temperature 1980–2010, with dummies α_s for the 19 studies. This yields

$$I_c = \alpha_s + 1.82(0.44)\ln y_c - 0.37(0.06)T_c \quad (1)$$

where I_c is the impact in region c (in %GDP), y_c is its average income (in 2010 market exchange dollars per person per year), and T_c is the population-weighted average annual temperature (in degrees Celsius); the bracketed numbers are standard errors. The regression is a weighted regression; the weights equal one over the number of regions per study. Hotter countries face more negative impacts, as one would expect. Richer countries have relatively less negative impacts, as first predicted by Schelling (1984).[13] For each of the studies, this equation is used to impute national impacts, making sure that the regional or global totals match those in the original estimates. The function shown in Fig. 1 is then used to shift all impacts to 2.5 °C warming.[14] For each country, the average and standard deviation across studies is taken.

Fig. 5 shows results for individual countries for 2.5 °C warming. Hotter countries, poorer countries see more negative impacts. In fact, the majority of countries show a larger damage than the global average of 1.7%. This is because the world economy is concentrated in a few, rich countries. The world average economic impact counts dollars, rather than countries, let alone people.

Poorer countries are more vulnerable to climate change for three reasons. First, poorer countries have a higher share of their economic activity in sectors, such as agriculture, that are directly exposed to the vagaries of weather. Second, poorer countries tend to be in hotter places. This makes adaptation more difficult as there are no analogues for human behaviour and technology. Cities in temperate climates need to look at subtropical cities to discover how to cope in a warmer

[13] Sterner and Persson (2008) and Van den Bremer and Van der Ploeg (2021) assume the opposite, empirical support to the contrary notwithstanding (e.g. Botzen et al., 2021; Gandhi et al., 2022).

[14] Note that I use the *global* function to shift the imputed *national* impacts. Tol (2019b) shows that this is more robust than estimating *national* impact functions.

climate, and subtropical cities at tropical ones. The hottest cities will need to invent, from scratch, how to deal with greater heat. Third, poorer countries tend to have a limited *adaptive capacity* (Adger, 2006; Yohe and Tol, 2002). Adaptive capacity depends on a range of factors, such as the availability of technology, the ability to pay for those technologies, the political will to mobilize resources for the public good, and the government's competence in raising funds and delivering projects. All these factors are worse in developing countries.

3. Impacts of weather shocks

Climate, the thirty-year average of weather, varies only slowly over time and has not varied much over the period for which data are good. In the econometric studies discussed above, the impact of climate is identified from cross-sectional variation. Many other things vary over space too. Panel data help, but some confounders do not change much over time. Therefore, some researchers have estimated the impacts of *weather* on a range of economic activities. From an economic perspective, weather is random and its impact therefore properly identified. Unfortunately, the impact of a weather shock is not the same as the impact of climate change (Dell et al., 2014). Particularly, weather studies estimate the short-run response of the economy, whereas the interest is in the long-run response, with adjustments in capital, behaviour and technology. Deryugina and Hsiang (2017) derive the rather restrictive conditions under which weather variability is informative about climate change. These conditions are roughly the same as for a market equilibrium to be a Pareto optimum. These conditions are not met. Food markets are distorted by subsidies and import tariffs. Coastal protection is a public good. Infectious disease is an externality. Irrigation is a lumpy investment. Lemoine (2018) notes that economic agents would need to have rational expectations of future weather for investments in adaptation to be optimal. There is little evidence to support that. Extrapolating the impact of weather shocks therefore does not lead to credible estimates of the impact of climate change.

Kolstad and Moore (2020) note that the impact of climate is unidentified if the impact of weather is estimated with panel data in a *linear* model; but that the impact of climate can be partially recovered if a *non-linear* model is estimated, an approach pioneered by Bigano et al. (2006) and Auffhammer (2022). Although a model that is non-linear in weather can be interpreted as a model with an interaction between weather and climate, it can also be seen as a model that is non-linear in weather. I use the latter, direct interpretation below.

These caveats notwithstanding, there are a number of papers that estimate the economic impact of weather shocks. I restrict the attention to studies of the impact of temperature shocks on economic growth.[15] Different studies use different specifications, but there are two broad clusters. The first, older cluster regresses the growth rate of economic output on temperature *levels*. The second, younger cluster regresses the economic growth rate on the *change* in temperature.[16] I separately discuss these clusters.

3.1. Temperature levels and economic growth

Seven studies estimate the impact of weather shocks using temperature *levels* on economic growth: Dell et al. (2012), Burke et al. (2015), Pretis et al. (2018), Henseler and Schumacher (2019), Acevedo et al. (2020), Damania et al. (2020) and Kikstra et al. (2021).[17] The impact of temperature levels on economic growth numerically dominates the impact of temperature changes in Kalkuhl and Wenz (2020).[18]

Note that all these papers use country-fixed effects, nullifying a systematic effect of climate on economic growth rates in-sample. However, in this specification, the impact of climate change on economic growth will last forever. Economic growth rates would return to their base level not if climate stops changing, but only if climate returns to the climate of the recent past.

Temperature has a linear impact on economic growth in the preferred specifications of Dell et al. (2012) and Kalkuhl and Wenz (2020), but in the former study the impact is significant only in poorer countries. In the other four papers, there is a parabolic relationship between temperature and growth. As economic growth is assumed to depend on the temperature, the impact differs between countries—and is therefore calculated separately for each country. Instead of using the estimated country fixed effects, I calibrate the intercepts so that there is no impact if there is no warming. The national impacts are then aggregated, dollar-for-dollar, to the global impact shown in Fig. 2. Some of the studies are limited to mean temperature while other studies also consider variability and precipitation. In order to compare and reconcile these studies, I only consider mean temperature, which is common to all papers. In so doing, I implicitly assume that weather variability and precipitation do not change. This is not realistic, but the literature is too thin and the few findings too contradictory for inclusion in a meta-analysis.

Fig. 2 shows the effect sizes for the world economy. The functions are shifted so that, for each country, pre-industrial temperatures have no effect on growth. The global effect is the weighted average of the national effects, using 2015 GDP as weights. Global effect sizes vary between small positive (in three of six studies for moderate warming) and large negative impacts— Newell et al. (2021) find that only models with positive impacts are supported by cross-validation tests. According to the most pessimistic study (Kalkuhl and Wenz, 2020), 3 °C warming would end economic growth.

Fig. 2 also shows the impact of all six studies together, shrunk to their average.[19] The combined impact is very close to that of the first study (Dell et al., 2012). The confidence interval is narrow. Shrinkage tends to lead to overconfidence and may be inappropriate in this case as these studies use much the same data—the different effect sizes are therefore all the more striking. Fig. 2 also shows the most optimistic estimate plus its standard error and the more pessimistic one minus its standard error. The resulting interval is wide. This is appropriate as the differences between the central estimates are large too.

3.2. Temperature change and economic growth

Four studies[20] estimate the effect of weather shocks using temperature *change* on economic growth: Letta and Tol (2018), Kahn et al.

[15] There is also a large literature on the economic impact of natural disasters. Some papers find that natural disasters reduce economic growth (e.g., Noy, 2009; Krichene et al., 2021) while other studies find no significant effect (e.g., Cavalcanti et al., 2011), or a positive effect (e.g., Skidmore and Toya, 2002). A meta-analysis (Klomp and Valckx, 2014) finds a negative effect, but a recent re-analysis (Crespo Cuaresma, 2022) finds that this is due to omitted variable bias. Significant growth effects, if there are any, are contingent on the level of development (e.g., Kahn, 2005; McDermott et al., 2013), complicating projections of the impact of climate change. The impact of climate change on natural disasters themselves is very heterogeneous.

[16] Rainfall is typically included too, but is often found to be insignificant, except in Kotz et al. (2022).

[17] An eighth study does not report parameter estimates (Callahan and Mankin, 2022). They do report the impact on average income per capita for an increase in heatwaves only. As noted above, Newell et al. (2021) does not report parameter estimates either.

[18] Kalkuhl and Wenz (2020) use regional rather than national growth rates. Their data omit many of the poorer and hotter parts of the world.

[19] Alternatively, use Dell as the prior and update this with the other five studies to find the posterior.

[20] Akyapi et al. (2022) also regress economic growth on temperature change but use variables for which scenarios are not readily available. Newell et al. (2021) do not report parameter estimates.

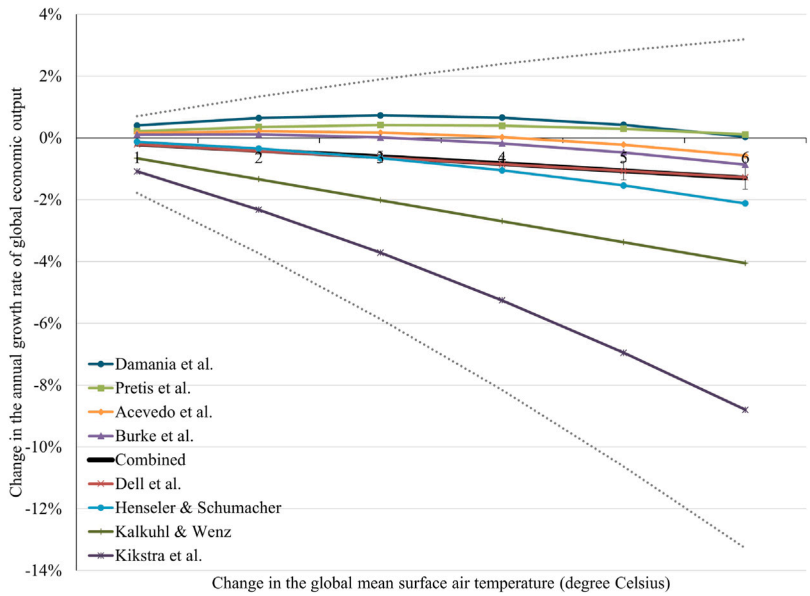

Fig. 2. The impact of climate change relative to pre-industrial times on global economic growth according to studies that relate growth to temperature.
Primary estimates are shown in colour. The black line is the shrunk model average, plus or minus its standard error, the dashed lines the maximum (minimum) estimate plus (minus) its standard error.

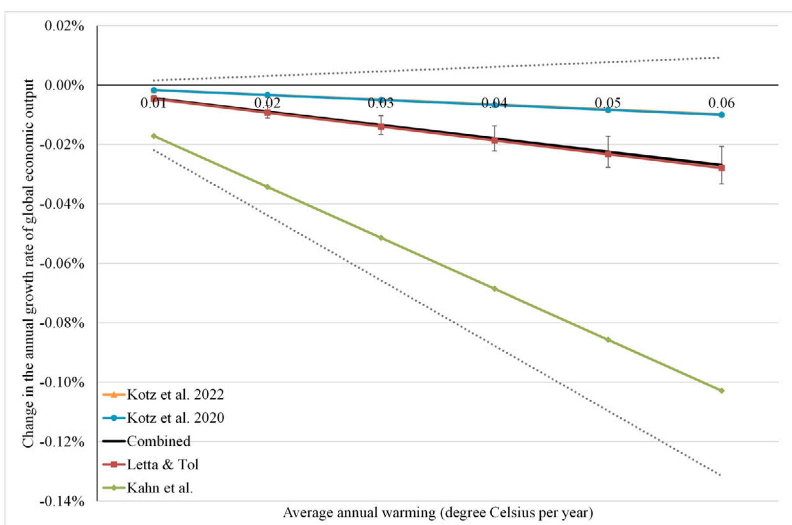

Fig. 3. The impact of climate change relative to pre-industrial times, on global economic growth according to studies that relate growth to warming.
Primary estimates are shown in colour. The black line is the shrunk model average, plus or minus its standard error, the dashed lines the maximum (minimum) estimate plus (minus) its standard error.

(2019), Kotz et al. (2021, 2022).[21] As noted above, Kalkuhl and Wenz (2020) also estimate this but prefer a specification in which the impact of temperature level dominates the impact of temperature change.

Letta and Tol (2018) finds a linear effect that only affects poor countries. Kotz et al. (2021, 2022) also use a linear specification but weather shocks affect all countries; the effect is statistically significantly larger in warmer countries, but the effect size is too small to meaningfully affect projections of climate change. Kahn et al. (2019) find that all countries are affected equally, but that hot shocks have a larger impact than cold shocks.

Weather is stochastic. In a stationary climate, the models of Letta and Tol (2018) and Kotz et al. (2021, 2022) predict that the impact of negative and positive temperature shocks cancel out. In a warming climate, positive shocks are more likely and, as the models are linear, the expected impact on growth is proportional to the rate of warming. In the model of Kahn et al. (2019), a stationary climate does have a negative effect on economic growth, assumed to be offset by the country-fixed effects.[22] In a warming climate, the expected impact on growth is the sum of average reduction in negative shocks and the average increase in positive shocks.

Fig. 3 shows the estimated effect sizes, as a function of the rate of warming rather than its level. The two results by Kotz et al. (2021, 2022) are very similar and least pessimistic. Kahn et al. (2019) shows

[21] Kotz et al. (2021, 2022) use regional rather than national growth rates. Their data omit many of the poorer and hotter parts of the world (Dong et al., 2023).

[22] As they define temperature shocks relative to the mean, the impact of climate change is transient by construction, just as it is in Letta and Tol (2018) and Kotz et al. (2021, 2022), provided that climate change does not affect the skewness of the temperature distribution.

the largest effects. Letta and Tol (2018) is somewhere in between and very close to the combined effect. Shrinkage leads again to overly confident results, so Fig. 3 also shows the top of Kotz' confidence interval and the bottom of Kahn's.

4. Reconciling estimates

There are two sets of estimates of the economic impact of climate change. The first set *directly* studies the impact of climate change. A range of methods is used, including enumerative studies, computable general equilibrium models, Ricardian or other econometric techniques, and elicitation methods. These papers are discussed in Section 2. The results are shown in Fig. 1. The second set studies the impact of weather shocks, exclusively using econometric methods. From this, one *infers* the effects of climate change. These papers are discussed in Section 3. Figs. 2 and 3 show the results. Other key differences between the two sets of studies is that the former leads to a *level* effect on *welfare* while the latter is a *growth* effect on *output*.

Welfare and output effects are easily reconciled if we assume that consumption is proportional to output— Pizer (1999) shows that the impact of climate change on the savings' rate is minimal—and note that output studies are incomplete for ignoring the intangible losses due to climate change. For example, some studies of the impact of climate and weather on output assume that health effects are adequately captured by expenditure on medical and funeral services.

A further complication is that welfare effects may arise from a change in the *composition* rather than the *level* of economic output. Defensive expenditure—additional coastal protection due to sea level rise, for instance—counts *towards* economic output but *against* welfare. Tol et al. (1998) estimate that 7%–25% of impact estimates are the costs of adaptation; I revise their estimate to 15% below. Again, estimates of the impact of weather shocks on economic output are a lower bound on estimates of the impact on welfare.

Level and growth effects are harder to reconcile. Previous studies mixed growth and level effects without further ado in a graph (Kahn et al., 2019; Rose et al., 2022)[23] or in a meta-analysis (Howard and Sterner, 2017). This is inadequate. A growth effect implies a level effect, of course, but for a particular year, and conditional on assumptions on the accumulation of weather shocks into climate change and on the shape of the impact function. Fankhauser and Tol (2005) show that the growth effect implied by a level effect is contingent on the assumed growth model and its parameters. They assume that climate change affects capital depreciation, labour supply, and factor productivity and hence savings, investment and capital accumulation. Below, I assess the growth effect of the level impact. I then accumulate both implied and estimated growth effects along a particular scenario so as to compare the results of these two strands of literature.

4.1. Growth effects

The economic impact of climate change has an apparent effect on economic growth. Suppose that climate change scales down economic output by a factor $\frac{1}{1+D_t}$, where D denotes the economic impact of climate change (Nordhaus, 1992, 1993). If output is a Cobb–Douglas function of capital and labour then, by log-linearization and differentiation, the growth rate of the economy

$$\frac{\dot{Y}_t}{Y_t} \approx \frac{\dot{A}_t}{A} + \lambda \frac{\dot{K}_t}{K_t} + (1-\lambda)\frac{\dot{L}_t}{L_t} - \frac{(1 \dot{+} D_t)}{1+D_t} \tag{2}$$

where Y_t is output at time t, A is total factor productivity, K is the capital stock, L is the labour force and λ is the capital elasticity of output; $\dot{X}_t := \frac{\partial X_t}{\partial t}$. Growth is slower if $D_t > D_{t-1} > 0$, that is, if climate change damages are increasing.

The *apparent* impact on economic growth is probably small. If the impact is 1.00% in year t and 1.01% in the year after, then the growth rate of $1 + D_t$ is about 0.0099%. The apparent growth effect is large only if damages are high, if the impact function is highly non-linear, or if climate change is very rapid.

The *actual* impact is larger than the apparent one, because Eq. (2) ignores the impact of climate change on capital accumulation. In the steady state,

$$K_t = \left(\frac{sA_t}{\delta(1+D_t)}\right)^{1/1-\lambda} L \tag{3}$$

where s is the savings rate and δ the rate of depreciation. Log-linearization, differentiation, and substitution in (2) leads to

$$\frac{\dot{Y}_t}{Y_t} \approx \frac{1}{1-\lambda}\frac{\dot{A}_t}{A} + \frac{\dot{L}_t}{L_t} - \frac{1}{1-\lambda}\frac{(1 \dot{+} D_t)}{1+D_t} \tag{4}$$

If $\lambda = 0.3$, a reasonable choice (Romer, 2018), the actual effect is 1.43 times larger than the apparent growth effect.

Note that, if climate stops changing, it no longer affects economic growth. William Nordhaus (1992, 1993) conceptualized climate change as affecting total factor productivity in the growth model of his PhD advisor Robert Solow (1956). In this framework, climate does not affect economic growth but climate change does. In new growth models (Romer, 1990), where total factor productivity is endogenous, the impact of an output shock like climate change is also transient. In unified growth models (Galor and Weil, 1999), where the labour force too is endogenous, shocks are transient too, unless the shock happens to push the economy from a Solowian to a Malthusian equilibrium or vice versa.

The hypothesis, furthered by Dell et al. (2012) and Burke et al. (2015), that the level of climate change would affect the growth rate of the economy is thus inconsistent with the theory of economic growth (Romer, 2018). Kahn et al. (2019, Appendix A2) and Akyapi et al. (2022) reach the same conclusion and discuss the implied econometric issues. The Dell-Burke hypothesis is tested by Kotz et al. (2021, 2022) and rejected.[24] Kalkuhl and Wenz (2020) similarly estimate a model in which both temperature *level* and temperature *change* affect economic growth, to find that neither is significant but their interaction is; they therefore keep levels in their preferred specification, and this effect dominates numerically. Newell et al. (2021) use cross-validation tests; out of 800 specifications, at most 32 are in the cross-section of their three alternative model confidence sets, and only 9 are highlighted in their Tables 2, 7 where temperature change affects economic growth and 2 where temperature level affects economic growth.[25]

4.2. Results

Fig. 4 compares the above results. I assume that the world was 1.1 °C warmer in 2020 than in the time just before the start of the industrial revolution (Gulev et al., 2021). Following Newell et al. (2021), I assume that the world will warm on average 0.04 °C per year to reach 4.3 °C by 2100.[26]

[23] Rose et al. (2022) also mixed global and national effects; the national impact estimates of a single study thus dominate the graph.

[24] Bastien-Olvera et al. (2022) also test this hypothesis and find in its favour. Whereas Kotz et al. directly test the impact of T against ΔT, Bastien-Olvera et al. use an invalid statistical text: They demean and detrend the explanatory variable and apply Butterworth filters of various lengths. Detrended and filtered, T is not the accumulation of ΔT. They apply this procedure to all countries individually, ignoring the panel structure of the data.

[25] These 9 valid specifications are included in Fig. 1.

[26] This is not very likely Srikrishnan et al. (2022), but makes comparison to previous results easier.

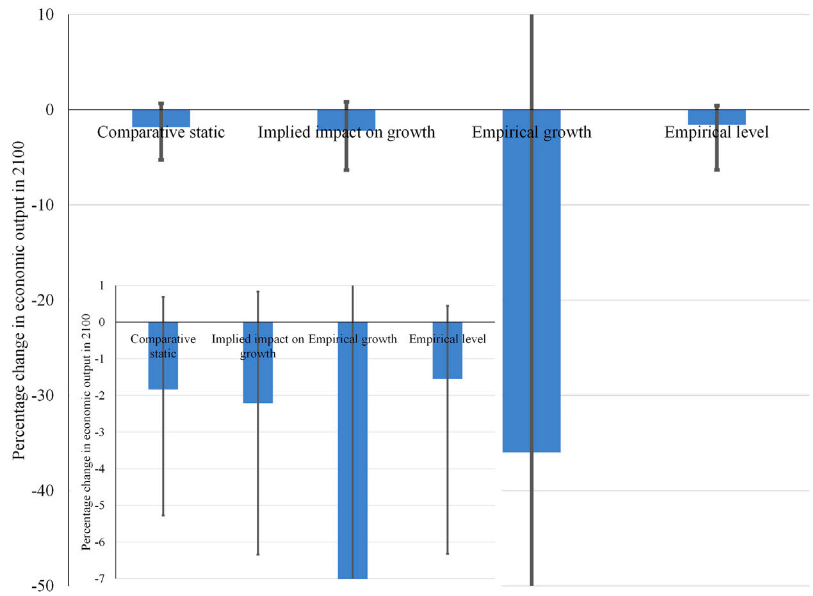

Fig. 4. The impact of 4.3 °C warming relative to pre-industrial times on global economic output in 2100 according to, from left to right, comparative static studies (Fig. 1), the growth effect implied by comparative static studies, econometric studies of the impact of climate on growth (Fig. 2), and econometric studies of the impact of climate change on growth (Fig. 3).
The inset shows the same information but compresses the vertical axis. The error bars are proportional to those shown in Figures 1, 2 and 3..

The first column in Fig. 4 shows the comparative static impact[27] as discussed in Section 2 for 4.3 °C warming, limited to the *market* impacts and assuming that 39% of impacts lead to a *reduction* of economic output.[28] The second column shows the implied impact on economic growth, accumulated over the 80-year period. The latter effect is somewhat larger than the former, 1.8% v 2.2% of GDP.

The third column shows the cumulative effect on economic output according to the econometric studies that assume that the level of temperature affects economic growth. These studies are very pessimistic: Economic output would be 36% smaller with than it would be without climate change.

The fourth and final column shows the cumulative effect for the studies that assume that the rate of warming affects economic growth. The central estimate is 1.6% of GDP. This is somewhat smaller than the growth effect estimated above.

Fig. 4 also includes the indicative 67% confidence intervals. The empirical growth studies show the widest range, the empirical level studies the narrowest. The empirical growth studies are at odds with the rest of the literature. The empirical level studies and the comparative static ones by and large agree.

5. Implications for the social cost of carbon

The social cost of carbon (scc) depends on the total impact of climate change—it is the *marginal* impact. The social cost of carbon also depends on the emissions scenario, the parameterization of the carbon cycle, the rate and extent of warming, and the aggregation of impacts across people, between scenarios, and over time. Instead of exploring that vast parameter space, I report a limited analysis:

- For each of the 69 estimates in Table 1, I fit Nordhaus' impact function, the more common among the four single-parameter ones in Table 2, and compute the social cost of carbon.
- I compute the social cost of carbon for the central line in Fig. 1 and the four graphs in Figure B5.
- I compute the social cost of carbon for the graphs in Figs. 2 and 3.
- I use a single scenario (SSP2), a single carbon cycle, a single climate sensitivity (3 °C/2×CO_2), and a single discount rate (a Ramsey rate with a 1% pure rate of time preference and a relative rate of risk aversion of 1). These are the central values in Tol (2019b).
- I assume away uncertainty and ambiguity. There is no disaggregation of impacts so that inequity aversion is irrelevant.

This makes for a total of 96 estimates of the social cost of carbon.[29]

Table 1 shows the estimated social cost of carbon for the 69 estimates of the impact of climate change. The social cost of carbon ranges from -$355/tC to +$587/tC. The lower bound is due to Tol (2002), who finds positive impacts in the near-term; by construction, impacts are then always positive. The upper bound is due to Horowitz (2009), who finds large negative impacts in the near-term. The weighted average is $59/tC, an estimate that is well in line with the literature (Tol, 2023).

Table 2 shows the estimated social cost of carbon for the 8 alternative impact functions, fitted to all 69 estimates of the total impact. The social cost of carbon varies between $3/tC for the exponential function and $29/tC for the linear function. While the exponential function projects the highest total impacts in the distant future, the linear function projects substantial impacts in the near future. The social cost of carbon is discounted, and thus highest under linearity (Peck and Teisberg, 1994). The higher estimates are a better fit to the data so that the social cost of carbon for the Bayesian model average is $27/tC.

Table B1 shows the estimated social cost of carbon for the four alternative estimation methods, using the best-fitting impact function. Confirming Figure B5. the elicitation studies are the most pessimistic

[27] The enumerative and econometric estimates are truly comparative static. The CGE estimates typically use recursive-dynamic models and would therefore include the impact on capital accumulation. Studies using elicitation report whatever was in the interviewees' minds, which is unknowable. I assume that all these estimates are comparative static.

[28] 54% of impacts are market impacts, of which 15% are either defensive investments (coastal protection, energy, settlements) or changes in the composition of GDP (tourism); see Table 3.

[29] Note that Eq. (1) has that per capita income affects total but not marginal impacts.

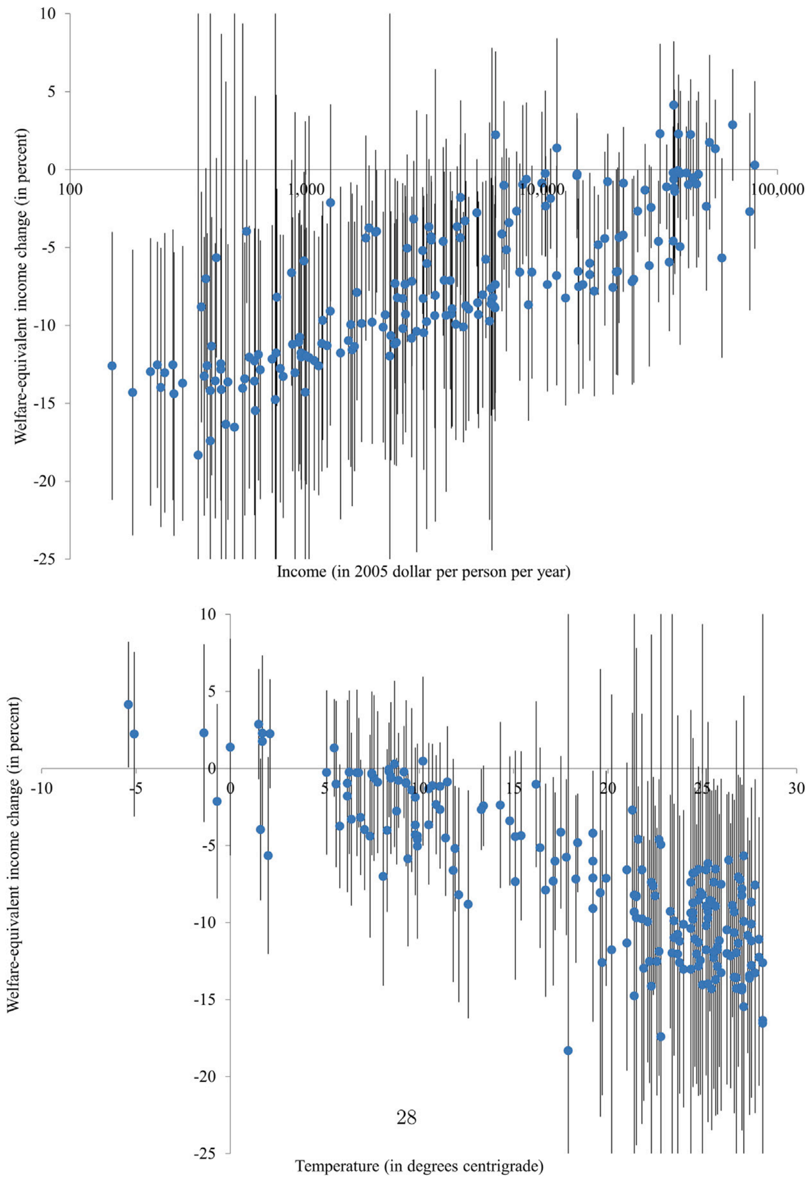

Fig. 5. The economic impact of climate change for a 2.5 °C warming relative to pre-industrial times for countries as a function of their income (top panel) and temperature (bottom panel).
The dots denote the average across studies, the bars the average plus or minus the standard deviation between studies..

with an estimate of \$87/tC. The econometric studies, which are essentially undecided about the impact until it gets really hot, are most optimistic with a social costs of carbon of \$1/tC.

Studies of the impact of weather shocks that relate economic growth to temperature are specific to each country. The global impact is approximately quadratic. See Fig. 3. Table B2 shows the fitted parameters, as well as the estimated social cost of carbon, which ranges from -\$171/tC for the study of Pretis et al. (2018) to +\$539/tC for Kikstra et al. (2021), reflecting the respective impacts in the near- and mid-term. Shrinking the 7 alternative estimates leads to a social cost of carbon of \$218/tC, which is high compared to the estimates based on the impact of climate change.

Table B3 shows the parameters and the social cost of carbon of the weather studies that relate growth to temperature change. Estimates range from \$16/tC for Letta and Tol (2018) to \$60/tC for Kahn et al. (2019). The combined estimate is \$17/tC, close to three of the four studies, and somewhat lower than the climate impact estimates.

Unsurprisingly, the results for the social costs of carbon are in line with the results for the total impact of climate change. There is a wide range of uncertainty. Different methods yield different results. Elicitation leads to pessimistic estimates, and relating economic growth to temperature levels appears to be unreliable.

6. Conclusion and policy implications

I do four things in this paper. First, I update my earlier meta-analysis using the same methods but much more data. Three new results emerge from this. (1) The initially positive impacts have vanished: The central estimate of the economic impact of global warming is always negative. The effects of carbon dioxide fertilization and reduced winter cold on heating costs and human health are still positive, but newer studies reckon these are relatively smaller than earlier studies. (2) The confidence interval about the estimates has widened considerably, and now includes *no impact* for very considerable warming. This is because some newer studies are either more optimistic or more pessimistic than older ones. The more we learn about the economic impacts of climate change, the better we understand our ignorance. (3) Elicitation methods give the most pessimistic results, econometric studies the most optimistic ones, with the enumerative methods and computable general equilibrium models in the middle. Previous meta-analyses did not split the sample by method for lack of data. Two old results remain. (4) The uncertainty about the impact is skewed towards negative surprises. (5) Poorer countries are much more vulnerable than richer ones.

The second contribution is a meta-analysis of the impact of weather shocks, in two parts. Studies that relate economic growth to temperature levels cannot agree on the sign of the impact. Studies that make economic growth a function of temperature change differ an order of magnitude in effect size, but do agree on the sign. The former studies posit that climate change has a permanent effect on economic growth, the latter that the impact is transient.

The third contribution reconciles climate change and weather shocks. The impact on economic growth implied by studies of the impact of climate change are close to the growth impact estimated as a function of temperature change. Growth impacts implied by the temperature level are much larger.

Finally, I assess the implications for the social cost of carbon. The pattern of results for the marginal impact is roughly the same as for the total impact. Because of discounting, the impact of moderate warming is more important for the social cost of carbon than the impact of more pronounced climate change.

The following research gaps appear. Enumerative studies have not been published for a while. New research would reveal whether these papers are really out of date, as is sometimes claimed (NAS, 2017), and whether underestimation is indeed substantial Rising et al. (2022b,a). The impact of climate change on labour productivity is perhaps the main surprise in the recent past. Earlier studies had ignored this, but it is one of the larger impacts in recent CGE studies. If the estimate of Carleton et al. (2022) stands, health impact estimates need to the revised upwards. They find that mortality increases by some 2% per degree warming, well outside the 0.1–1.1% range in previous studies (Cromar et al., 2022). New enumerative studies would approach book length, so it may be better to split such papers by sector while ensuring internal consistency for later aggregation (Rennert et al., 2022). Methods will need to be developed to systematically compare the results of aggregate and disaggregate studies.

Elicitation studies tend to be pessimistic. It is not clear why supposed experts deviate from the published literature. Computable general equilibrium models draw from the same or similar sets of calibrated impacts, yet produce a range of different impacts. Systematic model comparison would be useful.

The econometric studies, however, show the widest range of results. These come in three groups—the impact of climate on income, the impact of weather on income growth, and the impact of changes in weather on income growth.[30] There is considerably variation within groups, even when data used are much the same, and more variation between groups, both numerically and conceptually. Econometricians are adept at testing which specification fits the data best; these methods should be applied here (Newell et al., 2021, set an example). Analyses should be better guided by theory. Data sets should be extended to greater regional detail and longer periods.

For the moment, however, Fig. 1 presents our best knowledge on the economic impacts of climate change. It is this information, warts and all, that should be used to estimate the social cost of carbon and inform the optimal rate of emission reduction—at least until new, hopefully better studies shine a different light on this question.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

[30] A survey of the many sectoral and regional climate and weather studies is beyond the current paper.

Data and code

Data and code are on GitHub. Calculations are done in Excel, except for the social cost of carbon, which is calculated in Matlab, using FUND 4.2 MG.

Appendix A. Differences with Howard and Sterner (2017)

Howard and Sterner (2017) include a number of estimates that I excluded, for the following reasons. The paper by Meyer and Cooper (1995) is confused, as explained in Fankhauser and Tol (1995). Howard and Sterner (2017) report an impact of 11.5% of GDP for 3.0 ° C warming, a number that is not in Meyer and Cooper (1995). Hanemann (2008) presents estimates for the USA only, Bluedorn et al. (2009) present no estimate. Manne et al. (1995) do not present new impact estimates, instead rely on Nordhaus and Fankhauser. Howard and Sterner (2017) misinterpret their estimate, an annuity, as a point on the impact function. Ackerman and Stanton (2012), Bosetti et al. (2007), Gunasekera et al. (2008), Manne and Richels (2005), Tol (2013), Weitzman (2012) do not present *new* estimates of the total impact of climate change. Anthoff and Tol (2022) count over 200 papers that estimate the social cost of carbon, each of which has at least one estimate of the total impact of climate change—but very few of these papers present *new* estimates of the total impact. It is not clear why Howard and Sterner (2017) included 6 of these papers but not the other 140 or so that were published before 2017.

My assessment of the relationship between studies differs from Howard and Sterner (2017). I do not know where they got their information; their Appendix A4 is vague. William Nordhaus published three estimates of the impacts of climate change. An expert elicitation (Nordhaus, 1994b), an econometric estimate (Nordhaus, 2006), and an enumeration (Nordhaus, 1982) that was repeatedly updated over the decades. Howard and Sterner (2017) treat *some* of these updates as new estimates. They regard Tol (1995) and Tol (2002) as the same study, even though the latter had little to do with the former. They cite Tol (2013) as the primary source, when it is a derivative product. They drop Maddison (2003), Rehdanz and Maddison (2005) and Maddison and Rehdanz (2011) as duplicates—they are independent estimates—but it is not clear what study these three estimates are supposed to have duplicated.

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.enpol.2023.113922.

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