

# The distributional impact of climate change

**Richard S.J. Tol**<sup>1 2 3 4 5 6</sup>

<sup>1</sup>Department of Economics, University of Sussex, Falmer, UK

<sup>2</sup>Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands

<sup>3</sup>Department of Spatial Economics, Vrije Universiteit, Amsterdam, The Netherlands

<sup>4</sup>Tinbergen Institute, Amsterdam, The Netherlands

<sup>5</sup>CESifo, Munich, Germany

<sup>6</sup>Payne Institute for Earth Resources, Colorado School of Mines, Golden, CO, USA

**Correspondence**

R.S.J. Tol, Department of Economics,  
Jubilee Building, University of Sussex,  
Falmer, BN1 9SL, UK  
Email: r.tol@sussex.ac.uk

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Poorer, hotter countries are more vulnerable to climate change and will experience more negative impacts. The pattern of vulnerability between countries is used to downscale impact estimates to income deciles within countries, to administrative regions, and to grid cells. Almost three-quarters of people will face worse impacts than their country average. Between-country variation is larger than within-country variation for income deciles and regions, and about as large for grid cells.

**KEYWORDS**

impact of climate change, vulnerability, downscaling

**JEL CLASSIFICATION**

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## 1 | INTRODUCTION

Poorer countries are more vulnerable to climate change. This qualitative insight has long been around [1], but quantification has lagged as estimating the impacts of climate change is difficult. I here revisit earlier estimates of the economic impact of climate change [2] and extend the analysis to the distribution of impacts within countries.

Estimates of the economic impact of climate change are important because they form the basis for estimates of the benefits of climate policy and, in the form of the social costs of carbon, directly compare to the costs of greenhouse gas emission reduction. The distribution of those impacts between and within countries matters because the global total and the social cost of carbon are sensitive to its distribution [3, 4, 5, 6]—unless you want to assume that utility is linear in consumption [7] or that impacts of climate change will be compensated [8]. Furthermore, high and low impacts are not randomly assigned, but rather depend on fundamental factors at least some of which are at least partially malleable by policy [9]. The distribution of impacts between countries informs international climate negotiations, especially on

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**Abbreviations:** GDP, gross domestic product; RCP, representative concentration pathway.

the discussion around loss and damage and the implied historical responsibility and liability. It should also guide the allocation of the moneys in the adaptation fund and other international development assistance. The distribution of impacts within countries informs the targeting of national adaptation projects and other policy interventions to reduce vulnerability to climate change.

While a greater resolution of the estimates of the economic impacts of climate change is welcome for the reasons given above, more detail does not equate to higher accuracy. Some things average out on a national or continental scale, and therefore do not matter at that resolution. When models calibrated at a coarse resolution are used to impute numbers at a fine resolution (as is done below), things that are irrelevant at the coarse resolution are assumed to be irrelevant too at the fine resolution. One example is the particular vulnerability of the coast to sea level rise [10]. Another example is the special position of cities and the synergy between global warming and the urban heat island effect [11]. The downscaled estimates discussed below should therefore not be taken at face value. Rather, these estimates are used to demonstrate that resolution matters and to encourage further economic research at a finer scale.

The paper proceeds as follows. Section 2 revisits estimates of the economic impact of climate change. This material is not original but needed to understand what follows. Section 3 presents new estimates of the economic impact of climate change per country [2, 12] and per income decile [13] and, for the first time, estimates of the impact per subnational region and for grid cells. Section 4 shows measures of inequality. Section 5 concludes.

## 2 | THE TOTAL IMPACT OF CLIMATE CHANGE

Figure 1 plots 26 of the 27 published estimates of the total economic impact of climate change time.<sup>1</sup> The horizontal axis is calendar year. The vertical axis is the welfare equivalent income change, or 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 1.3% of her income. 1.3% is the average of the 11 dots at 2075.

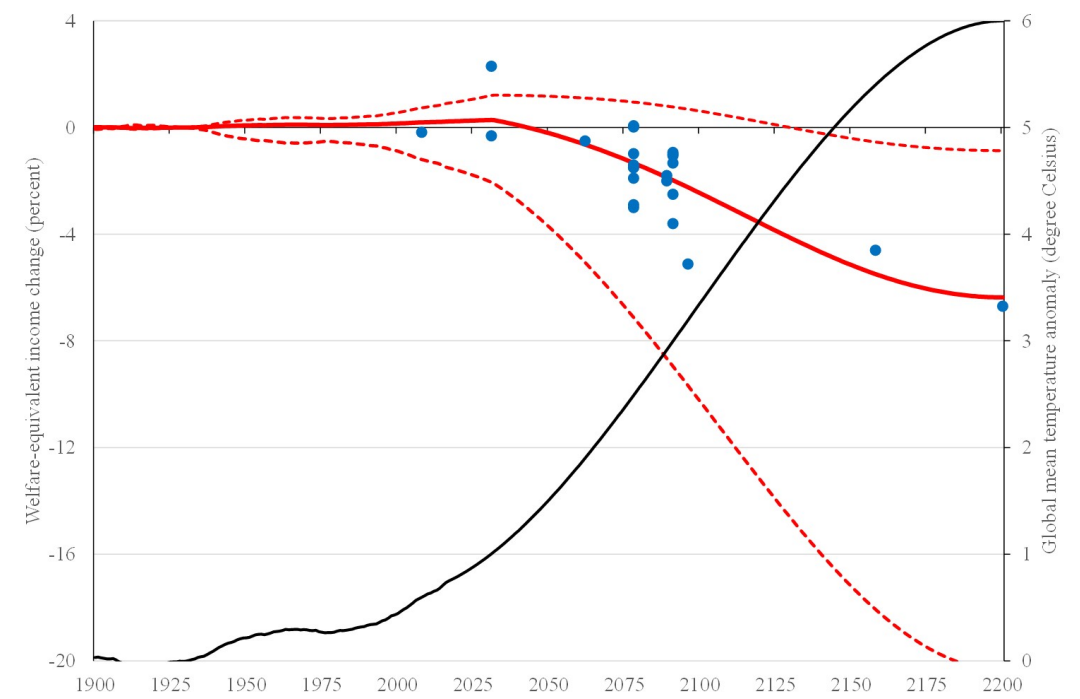
### 2.1 | Methods

The estimates in Figure 1 use a range of methods. In the enumerative method, researchers take estimates of the many impacts of climate change for all parts of the world in their natural units from the relevant literature, estimate the values of these impacts (using either market prices or monetary valuation methods), multiply the quantities and prices, and add everything up [14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26]. The result is an estimate of the direct cost—price times quantity—of climate change. The direct cost is a poor approximation of the change in welfare, for instance because it ignores price changes, but it is an approximation nonetheless. The enumerative approach omits interactions between sectors, such as changes in water resources affecting agriculture.

Other studies use the same physical impact estimates as the enumerative studies above, but as shocks to a computable general equilibrium model [27, 28]. These estimates include both price changes and interactions between economics sectors, be it through output, intermediate or input markets, and between economies through international trade and investment. The typical welfare measure used in these studies is the Hicksian Equivalent Variation, an exact welfare measure. Computable general equilibrium models are based on the national accounts, and thus misrepresent subsistence agriculture and omit direct impacts on welfare, such as on health or nature.

Yet other studies regress an economic indicator on climate [29, 30]. Agricultural land prices, for instance, reflect

<sup>1</sup>One estimate is for the impact of global cooling, not shown on the graph.



**FIGURE 1** The global total annual impact of climate change over time. Primary estimates are shown as dots. The central, solid line is the Bayesian model average, the dashed lines the 90% confidence interval. For reference, the observed 30-year average temperature (1900-2018) and the project temperature (2019-2200) are shown on the right-axis.

the productivity of the land and hence the value of the climate that allows plants to grow [31]. Price differences due to climate variation are used to estimate the direct cost of climate change. Household expenditure [32] and self-reported happiness [33, 34] have also been used. The main advantage of the Ricardian method is that it is based on actual, rather than modelled behaviour. The main disadvantage is that climate variations over space are used to derive the impact of climate change over time. Space and time are different things.

One estimate elicits expert views [35]. The study was done before anyone could reasonably claim expertise on the economic impacts of climate change. 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 | Weather and climate

Climate, the thirty-year average of weather, varies only slowly over time. In Ricardian studies, the impact of climate is identified from cross-sectional variation. However, many other things vary over space too. Panel data help, unless confounders do not change much over time. To overcome this problem, a number of papers estimate the impacts of weather on a range of economic indicators [36, 37, 38, 39]. 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 [40]. See Deryugina and Hsiang [41] and Lemoine [42] for the rather restrictive conditions under which weather variability is informative about climate change. 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. Extrapolating the impact of weather shocks will not lead to credible estimates of the impact of climate change.

## 2.3 | Combining estimates

Besides the primary estimates, Figure 1 also shows a curve. Seven alternative impact functions, proposed in the literature, were fitted to the data. The curve shown is the Bayesian model average, that is, the seven impact functions are weighted according to their fit to the primary estimates. The 90% confidence interval shown is based on the uncertainty reported in 7 of the 27 primary estimates. Using the combined forecast error would imply a confidence and symmetry that is not there. See Tol [12] for details.

## 2.4 | Results

Figure 1 contains many messages, extensively discussed elsewhere [2]. Howard and Sterner [43] and Nordhaus and Moffat [44] offer different reviews of the same literature. First of all, there are only 27 estimates, a thin empirical basis. There are only two estimates beyond 3.2°C of warming.

For 1850-2018, the temperature shown in Figure 1 is the 30 year running mean. For 2019-2200, the temperature roughly follows the RCP8.5 scenario so that the two estimates for high warming can be shown. The return to coal assumed in RCP8.5 is now considered unlikely [45, 46].

Figure 1 shows that initial warming may be positive on net, while further warming would lead to net damages. The initial benefits, due to reduced costs of heating in winter, reduced cold-related mortality and morbidity, and carbon dioxide fertilization, are mostly in the past. For future warming, the negative impacts dominate, such as summer cooling costs, infectious diseases, and sea level rise.

There are 11 estimates for 2.5°C. 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 a few percent—a century of climate change is about as bad as losing a year of economic growth.

The uncertainty is rather large, however. The error bars are probably an underestimate of the true uncertainty, as experts tend to be overconfident and estimates are incomplete. Climate economists also know each other well. The uncertainty is right-skewed. Negative surprises are more likely than positive surprises of similar magnitude. Adding risk aversion, we may argue that a century of climate change is no worse than losing a decade of economic growth.

## 3 | DISTRIBUTION OF IMPACTS

Figure 1 shows the global average impact of climate change, a metric useless for most purposes. Below, I discuss impact estimates with more granularity.

### 3.1 | Countries

13 of the 27 studies include estimates of the *regional* impacts of climate change or, in the studies involving David Maddison, *national* impact estimates. Regressing the estimated regional impact for 2.5°C warming on per capita income and average annual temperature, with dummies  $\alpha_s$  for the studies, yields

$$I_c = \alpha_s + 1.68(0.79) \ln y_c - 0.45(0.14) T_c \quad (1)$$

where  $I_c$  is the impact in country  $c$  (in %GDP),  $y_c$  is its average income (in 2010 market exchange dollars per person per year), and  $T_c$  is the average annual temperature (in degrees Celsius). Hotter countries have more negative impacts. Richer countries have more positive impacts. Equation (1) does not capture the special vulnerability of delta and island nations. 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 Figure 1 is then used to shift all impacts to 2.5°C warming.<sup>2</sup> For each country, the average and standard deviation across studies is taken.

Figure 2 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 negative impact even though the global average impact is roughly zero. This is because the world economy is concentrated in a few, rich countries. The world average 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 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* [47, 48]. 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.

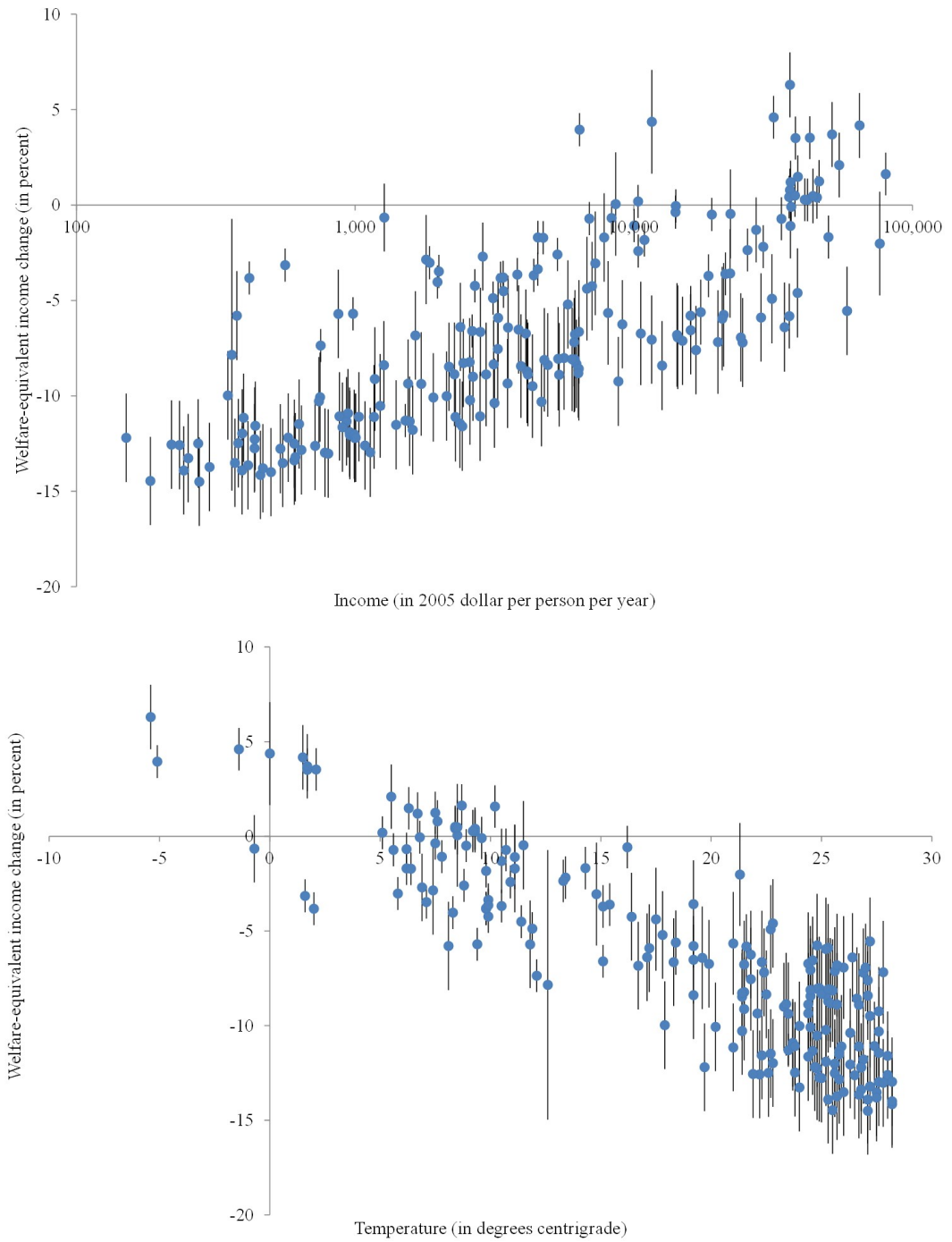
### 3.2 | Income classes

Figure 2 shows that poorer countries are more vulnerable to climate change. Aggregating results by country hides information. If poorer countries are more vulnerable, then poorer people should also be more vulnerable than richer people *in the same country*. Poorer people are more likely to work outdoors, their health is worse, and they are less likely to have heating and air conditioning. The provision of public goods, including coastal protection and irrigation, also tends to be slanted towards the better off. The pattern of vulnerability *between* countries is therefore likely to be repeated *within* countries. For want of data, I assume that the pattern within countries is identical to the pattern between countries.

Figure 3 again shows the impact of 2.5°C warming. The impacts are further downscaled, to income deciles, based on data from the University of Texas Inequality Project, using the same semi-elasticity used to downscale regional to national impact estimates; see Equation (1). Specifically, assume that the impact per income class  $I_{c,p}$  equals

$$I_{c,p} = \alpha_c + \beta \ln y_{c,p} + \gamma T_c \quad (2)$$

<sup>2</sup>Note that I use the *global* function to shift the imputed *national* impacts. [12] shows that this is more robust than estimating *national* impact functions.



**FIGURE 2** The economic impact of climate change for a 2.5°C warming for countries as a function of their income (top panel) and temperature (bottom panel).

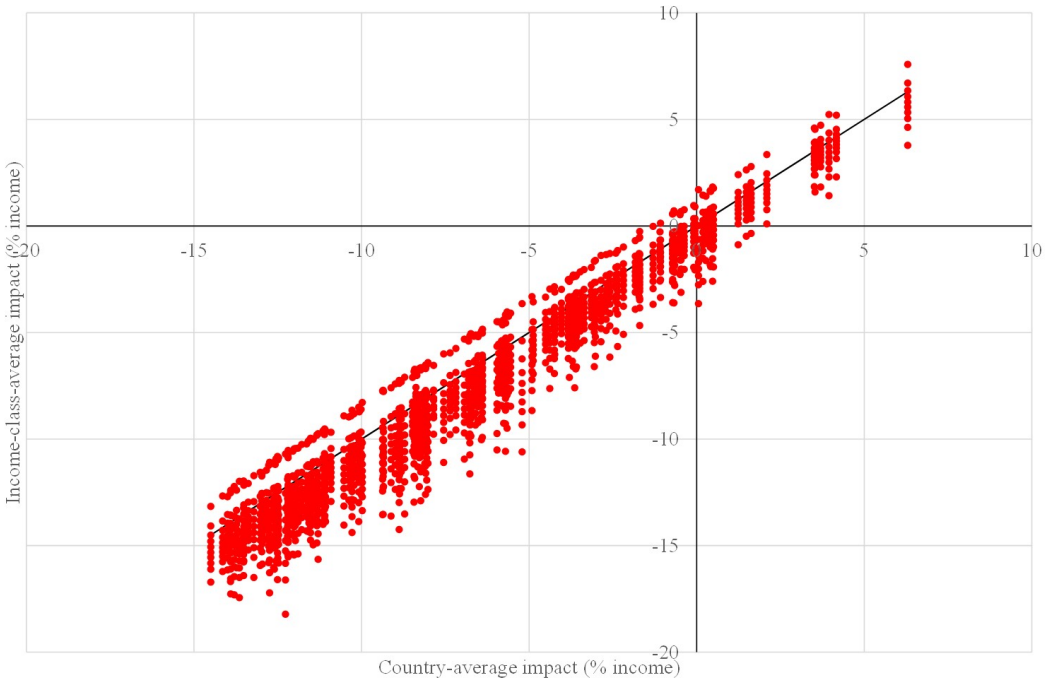
National impact then equals

$$I_c = \sum_p \frac{I_{c,p} y_{c,p} P_{c,p}}{y_{c,p} P_{c,p}} \quad (3)$$

We know  $I_c$  so that

$$\alpha_c = I_c - \gamma T_c - \beta \frac{\sum_p y_{c,p} \ln y_{c,p}}{\sum_p y_{c,p}} \quad (4)$$

Figure 3 plots the impact by decile against the impact per country. For comparison, it also plots country impact against country impact; this is the same data as shown in Figure 2. Most income deciles shows an impact that is worse than the country average. This is because the average counts dollars rather than people, and the income distribution is skewed. For the world as a whole, 72.6% of people are projected to incur worse impacts than their country average. This number is higher in countries with a more skewed income distribution.



**FIGURE 3** The annual impact of 2.5°C global warming by income decile compared to the country average impact.

### 3.3 | Regions

The estimate of the impact of climate change by income decile assumes, for want of data, that rich and poor share the same climate. This is not likely. Most countries show distinct regional patterns of development, and larger countries span different climate zones. The reasons why poorer countries are more vulnerable to climate change than richer countries, and poorer people more vulnerable than richer people, also apply to poorer regions within countries. If such regions tend to be hotter already, as suggested by Nordhaus [30] and Henderson et al. [49], then they are even more vulnerable to climate change.

The Global Data Lab has data on per capita income for subnational administrative units [50]. I used their shape files to compute the average temperature for the period 1981-2010 from the gridded Climate Research Unit data [51].<sup>3</sup>

Figure 4 repeats Figure 2, plotting the impact of 2.5°C warming against current income and temperature. The pattern is the same as before, because the assumptions are the same as above. Poorer regions are more vulnerable to climate change, as are hotter regions. As some regions are poorer, richer, hotter or colder than their country average, the pattern in Figure 4 is more pronounced: The lows are lower and the highs are higher.

### 3.4 | Grid cells

The regional impact estimates above use regional average temperatures, computed from gridded temperatures. That is, the above estimates assume that everyone in a province or state shares the same climate. This is a reasonable approximation for small regions, but not for big ones. I therefore downscale the estimates further, to the  $0.5 \times 0.5^\circ$  grid at which temperature and population numbers are reported. Specifically, I assume that everyone in a grid cell within a region has the same income.<sup>4</sup> The impact per capita follows from Equation (1. I use the  $0.5 \times 0.5^\circ$  Gridded Population of the World data to compute the total impact per country, and shift the gridded impact to match the national impact above.

Figure 5 shows the results for the impact of 2.5°C global warming on the current economy. The pattern is as above, with positive impacts in richer, colder places and negative impacts in poorer, hotter ones. Compared to the results above, there is also variation within regions. This is not immediately visible in Figure 5, but become apparent below.

## 4 | MEASURES OF INEQUALITY

The Lorenz curve is a standard way to depict income inequality. The Lorenz curve orders people (or countries) by their (average) income and plots cumulative income against cumulative number of people. For comparison, the Lorenz curve is typically shown together with the curve for equal income. The area between the two curve is the numerator of the Gini coefficient, the area under the equal income curve its denominator. This works well for absolute quantities, but not for changes, particularly if those changes can be positive or negative. Figure 6 therefore shows an variant of the Lorenz curve, here dubbed the Lorenz' curve. In the top left panel, I order people by their *relative* impact, with the highest positive impact first. For comparison, I show the curve with equal relative impact.<sup>5,6</sup> The two curves are far

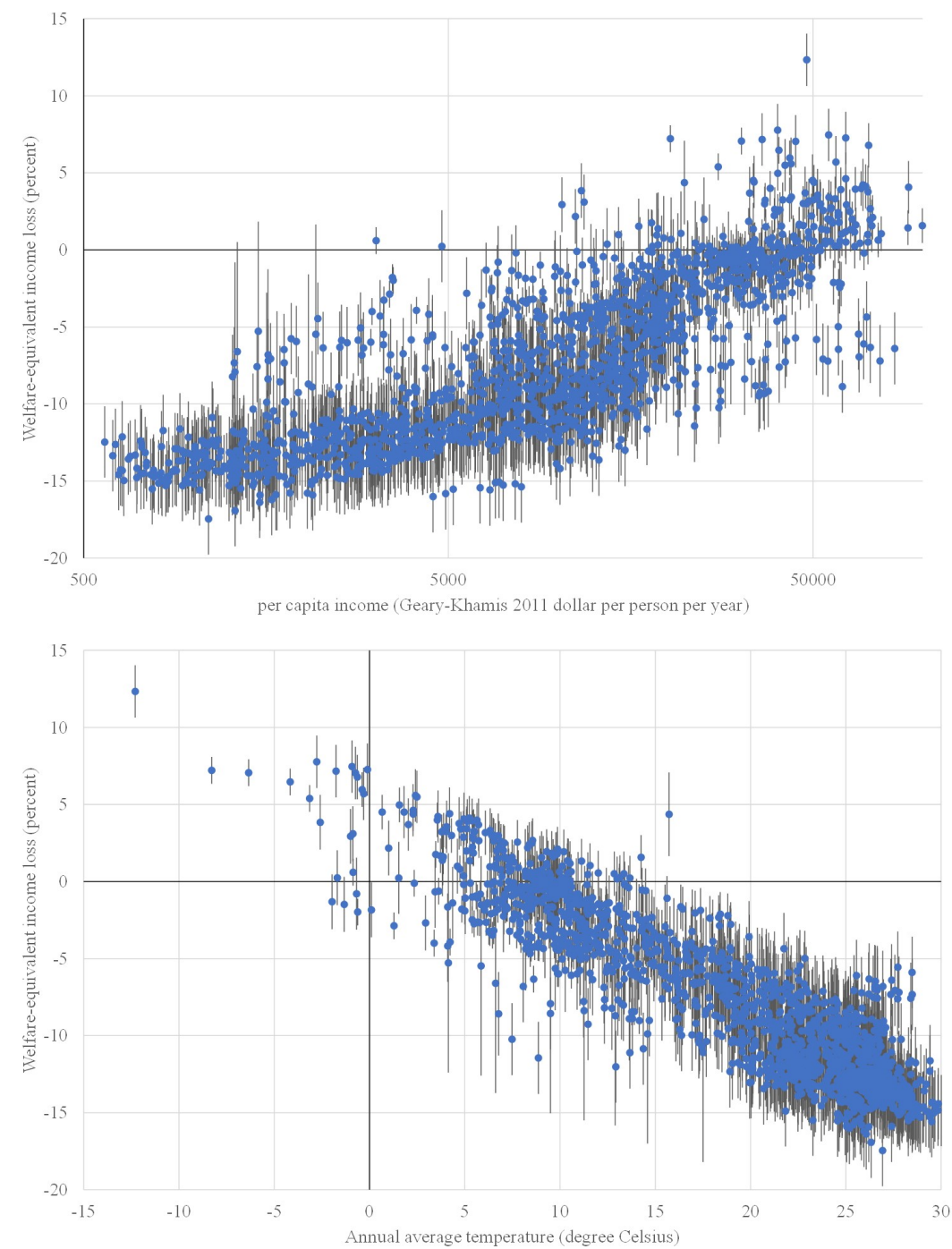
<sup>3</sup>The Matlab code is on GitHub.

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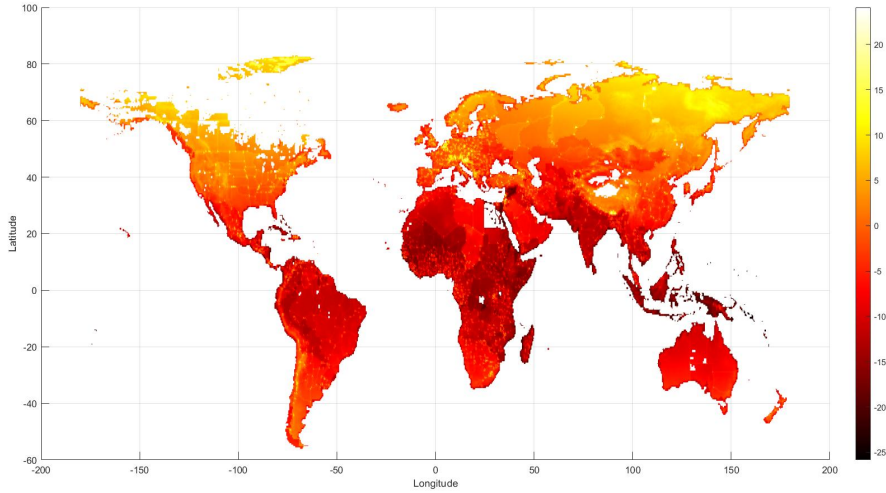
<sup>5</sup>I also show the curve for equal absolute impact, which is the straight line that people expect.

<sup>6</sup>If utility is the natural logarithm of per capita income, equal *relative* impact on *consumption* implies equal *absolute* impact on *utility*.





**FIGURE 4** The economic impact of climate change for a 2.5°C warming for all states c.q. provinces as a function of their income (top panel) and temperature (bottom panel).



**FIGURE 5** The economic impact (% income) of climate change for a 2.5°C warming per grid cell.

apart, highlighting the skewed distribution of the impacts of climate change.

The top right panel of Figure 6 shows the Lorenz' curve for the impact per income decile, the bottom left panel per region, and the bottom right panel for grid cells. For comparison, the Lorenz' curve is also shown for the cases in which the relative impact is the same for all deciles, regions or cells within their countries. For deciles and regions, impact inequalities between countries are larger than inequalities within countries. Impact inequalities within countries do matter for grid cells.

Besides the graphical representation of inequalities, I show four indicators. The first one is the Gini coefficient

$$G = \frac{\bar{y} \sum_c R_c P_c - \sum_c R_c y_c P_c}{\bar{y} \sum_c R_c P_c} \quad (5)$$

where  $y_c$  is average income in country  $c$ ,  $\bar{y}$  is the global average income,  $R_c$  is the rank order of per capita income of country  $c$  with  $R_c = 1$  for the richest country, and  $P_c$  is the size of the population

I also show the Theil-T index

$$T_T = \frac{1}{\sum_c P_c} \sum_c P_c \frac{y_c}{\bar{y}} \ln \frac{y_c}{\bar{y}} \quad (6)$$

the Theil-L index

$$T_L = \frac{1}{\sum_c P_c} \sum_c P_c \ln \frac{\bar{y}}{y_c} \quad (7)$$

and the Atkinson index (for an inequity aversion of one)

$$A = 1 - \frac{1}{\bar{y}} \exp \left( \frac{\sum_c P_c \ln y_c}{\sum_c P_c} \right) \quad (8)$$

These indicators are calculated for current income, and for current income minus the estimated impact of climate change. For income deciles and regions, I use the estimated impact as well as the average impact for the country so as to assess the relative contributions of between- and within-country variations.

I also compute something like the Gini coefficient for the impacts. The Gini coefficient is defined as the area between equal income curve and the Lorenz curve, divided by the area under the equal income curve. The Gini coefficient therefore uses a zero income as the worst case. As in Figure 6, I use impact instead of income and thus order from best to worst. The best case, however, is not zero but positive. I therefore use the highest positive impact as the base, computing the area between the equal relative impact and the highest positive impact. Specifically,

$$G' = \frac{\bar{I} \sum_c r_c y_c P_c - \sum_c r_c I_c y_c P_c}{\bar{I} \sum_c r_c y_c P_c + I_{CY} \sum_c P_c} \quad (9)$$

where  $I_c$  is the relative impact of climate change in country  $c$  and  $r_c$  is its rank with  $r_c = 1$  denoting the worst-off country and  $r_c = C$  the best-off one. I call this the Gini' coefficient.

Table 1 shows the results. At the national level, the impacts are not distributed equally and, as the poorer are hit harder, worsen the income distribution.

Changes in inequality indices are hard to interpret. For the national impact estimates, the change in the Gini coefficient is equivalent to levying a poll tax of \$105 per person per year, and using the proceeds to give everyone a subsidy of 1.4% of their income. The numbers for the Theil-T index are about a fifth higher, for Theil-L and Atkinson about a fifth lower. This makes everyone who earns less (more) than the average \$7611 per person per year worse (better) off.

The Gini' coefficient for the impacts show that the distribution gets more uneven when we move beyond country averages to consider the within-country distribution. This is more pronounced for the regions than for the income deciles, because the regions vary in both climate and income. As above, it is even starker for grid cells.

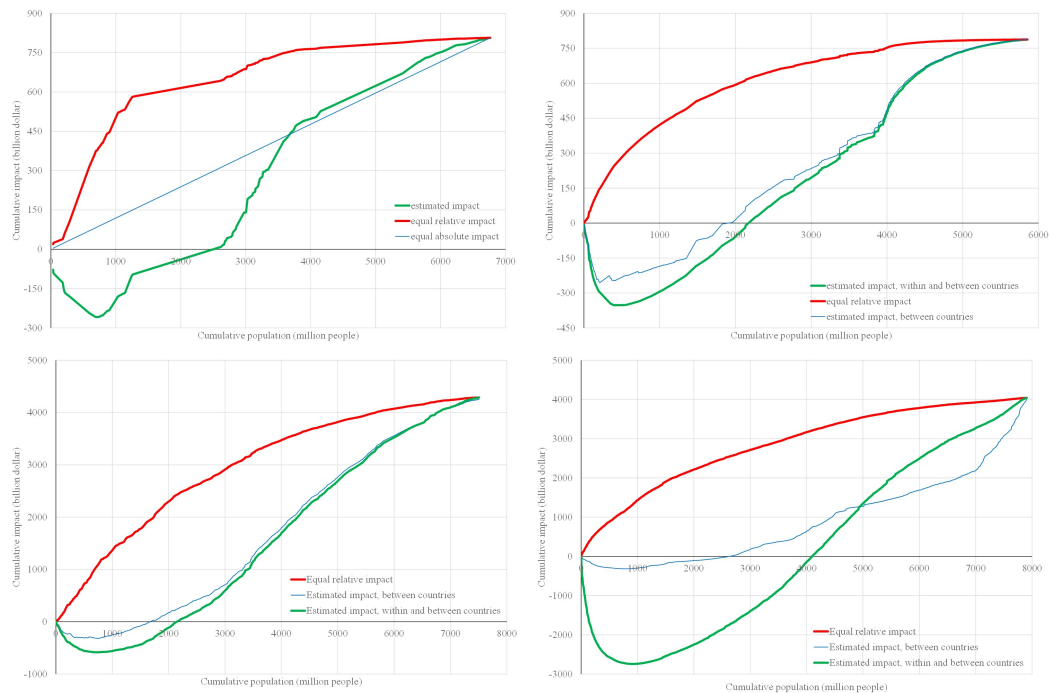
The indicators for income inequality by region or decile show that the distribution of impacts *between* countries is more important than the distribution of impacts *within* countries, as the indicators change more when country-average impacts are used than when decile- or region-specific impacts are used. However, for the analysis on grid cell level, within county variation is about as important as between country variation.

## 5 | DISCUSSION AND CONCLUSION

A meta-analysis of previously published estimates of the economic impact of climate change shows that poorer people in hotter places are more vulnerable to climate change. I use these insights to downscale regional and national impact estimates to income deciles within countries, to subnational administrative units, and to the grid. For the majority of people, the impact of climate change will be worse than their country average. Between-country variation is more important than within-country variation, except for the grid cell analysis in which they are about as important.

There are several caveats to these results. First and foremost, I rely heavily on imputation, extrapolating results for a coarse resolution to a fine resolution. Primary estimates on fine social and spatial scales are hard needed. The resolution needs to be fine. The urban heat island effect, for instance, has a synergetic impact with climate change [11] but is less pronounced in wealthier neighbourhoods [52]. New regional estimates of the economic impact of climate change would also refine our estimates of the income elasticity and the sensitivity of impacts to the current climate.

This paper confirms that the differences in vulnerability to climate change are profound. The distribution of



**FIGURE 6** The Lorenz' curve of the economic impact of climate change for a 2.5°C warming for countries (top left panel), income deciles (top rights panel), states c.q. provinces (bottom left panel) and grid cells (bottom right panel).

**TABLE 1** Indicators of impact inequality.

Scale	Impact	Gini'	Gini	Theil-T	Theil-L	Atkinson
National	None		0.621	0.934	1.035	0.645
	Actual	0.106	0.630	0.967	1.090	0.664
Decile	None		0.708	1.138	1.261	0.717
	Average	0.426	0.717	1.170	1.316	0.732
	Actual	0.447	0.718	1.176	1.325	0.734
Regional	None		0.456	0.380	0.433	0.352
	Average	0.419	0.473	0.410	0.469	0.375
	Actual	0.459	0.473	0.412	0.472	0.376
Grid cell	None		0.505	0.558	0.580	0.440
	Average	0.197	0.509	0.589	0.613	0.458
	Actual	1.126	0.517	0.612	0.635	0.470

The table shows the Gini' coefficient of impact inequality and the Gini, Theil-T, Theil-L and Atkinson indicators of income inequality with and without climate impacts. For income deciles and regional impacts, results are show for the estimated impact and the national average impact.

the impact of climate matters. Differences in vulnerability between countries are important because they affect the international negotiations, through discussions on historical responsibility and liability for impacts. Estimates of impact differentials should also guide the allocation of development aid for adaptation to climate change. The distribution of impacts also affects optimal targets. The distribution of impacts within countries should inform government decisions about targeting adaptation and social programs towards those who need them most.

## references

- [1] Schelling TC. Some Economics of Global Warming. *American Economic Review* 1992;82:1–14.
- [2] Tol RSJ. The Economic Impacts of Climate Change. *Review of Environmental Economics and Policy* 2018;12(1):4–25. <http://dx.doi.org/10.1093/reep/rev027>.
- [3] Fankhauser S, Tol RSJ, Pearce DW. The Aggregation of Climate Change Damages: a Welfare Theoretic Approach. *Environmental and Resource Economics* 1997 Oct;10(3):249–266. <https://doi.org/10.1023/A:1026420425961>.
- [4] Anthoff D, Tol RSJ. On international equity weights and national decision making on climate change. *Journal of Environmental Economics and Management* 2010;60(1):14 – 20. <http://www.sciencedirect.com/science/article/pii/S0095069610000422>.
- [5] Adler M, Anthoff D, Bosetti V, Garner G, Keller K, Treich N. Priority for the worse-off and the social cost of carbon. *Nature Climate Change* 2017;7:443–449.
- [6] Anthoff D, Emmerling J. Inequality and the Social Cost of Carbon. *Journal of the Association of Environmental and Resource Economists* 2019;6(2):243–273. <https://doi.org/10.1086/701900>.
- [7] Bernoulli D. Specimen Theoriae Novae de Mensura Sortis. *Commentarii Academiae Scientiarum Imperialis Petropolitanae* 1738;.
- [8] Schelling TW. Choice and Consequence. Cambridge: Harvard University Press; 1986.
- [9] Anthoff D, Tol RSJ. 14. In: Hahn RW, Ulph AM, editors. Schelling's conjecture on climate and development: A test Oxford: Oxford University Press; 2012. p. 260–274.
- [10] Hinkel J, Lincke D, Vafeidis AT, Perrette M, Nicholls RJ, Tol RSJ, et al. Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences* 2014;111(9):3292–3297. <https://www.pnas.org/content/111/9/3292>.
- [11] Estrada F, Botzen WJW, Tol RSJ. A global economic assessment of city policies to reduce climate change impacts. *Nature Climate Change* 2017 Jun;7(6):403–406. <https://doi.org/10.1038/nclimate3301>.
- [12] Tol RSJ. A social cost of carbon for (almost) every country. *Energy Economics* 2019;83:555 – 566. <http://www.sciencedirect.com/science/article/pii/S014098831930218X>.
- [13] Tol RSJ. 16. In: Soytas U, Sari R, editors. The impact of climate change and the social cost of carbon Abingdon: Routledge; 2019. .
- [14] d'Arge RC. In: Climate and economic activity Geneva: World Meteorological Organization; 1979. p. 652–681.
- [15] Nordhaus WD. How Fast Should We Graze the Global Commons? *American Economic Review* 1982;72(2):242–246.
- [16] Nordhaus WD. To Slow or Not to Slow: The Economics of the Greenhouse Effect. *Economic Journal* 1991;101(444):920–937.
- [17] Nordhaus WD. Managing the Global Commons: The Economics of Climate Change. Cambridge: The MIT Press; 1994.

- [18] Fankhauser S. Valuing Climate Change - The Economics of the Greenhouse, vol. 1. London: EarthScan; 1995.
- [19] Tol RSJ. The Damage Costs of Climate Change Toward More Comprehensive Calculations. *Environmental and Resource Economics* 1995;5(4):353–374.
- [20] Berz G. Insuring against catastrophe. Disasters; <http://www.ourplanet.com/imgversn/113/berz.html>.
- [21] Nordhaus WD, Yang Z. RICE: A Regional Dynamic General Equilibrium Model of Optimal Climate-Change Policy. *American Economic Review* 1996;86(4):741–765.
- [22] Plambeck EL, Hope CW. PAGE95 - An Updated Valuation of the Impacts of Global Warming. *Energy Policy* 1996;24(9):783–793.
- [23] Tol RSJ. Estimates of the Damage Costs of Climate Change - Part I: Benchmark Estimates. *Environmental and Resource Economics* 2002;21(1):47–73.
- [24] Nordhaus WD, Boyer JG. Warming the World: Economic Models of Global Warming. Cambridge, Massachusetts - London, England: The MIT Press; 2000.
- [25] Hope CW. The Marginal Impact of CO<sub>2</sub> from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern. *Integrated Assessment Journal* 2006;6(1):19–56.
- [26] Nordhaus WD. A Question of Balance - Weighing the Options on Global Warming Policies. New Haven: Yale University Press; 2008.
- [27] Bosello F, Eboli F, Pierfederici R. Assessing the Economic Impacts of Climate Change. *Review of Environment Energy and Economics* 2012;p. 1–9.
- [28] Roson R, van der Mensbrugghe D. Climate change and economic growth: Impacts and interactions. *International Journal of Sustainable Economy* 2012;4(3):270–285.
- [29] Mendelsohn RO, Schlesinger ME, Williams LJ. Comparing Impacts across Climate Models. *Integrated Assessment* 2000;1(1):37–48.
- [30] Nordhaus WD. Geography and Macroeconomics: New Data and New Findings. *Proceedings of the National Academy of Science* 2006;103(10):3510–3517. [www.pnas.org/cgi/doi/10.1073/pnas.0509842103](http://www.pnas.org/cgi/doi/10.1073/pnas.0509842103).
- [31] Ricardo D. On the Principles of Political Economy and Taxation. London: John Murray; 1817.
- [32] Maddison DJ. The amenity value of the climate: the household production function approach. *Resource and Energy Economics* 2003;25(2):155–175.
- [33] Rehdanz K, Maddison DJ. Climate and happiness. *Ecological Economics* 2005;52(1):111–125.
- [34] Maddison D, Rehdanz K. The impact of climate on life satisfaction. *Ecological Economics* 2011;70(12):2437–2445. <http://www.sciencedirect.com/science/article/pii/S0921800911003028>.
- [35] Nordhaus WD. Expert Opinion on Climate Change. *American Scientist* 1994;82(1):45–51.
- [36] Deschenes O, Greenstone M. The economic impacts of climate change: Evidence from agricultural output and random fluctuations in weather. *American Economic Review* 2007;97(1):354–385.
- [37] Burke M, Hsiang SM, Miguel E. Global non-linear effect of temperature on economic production. *Nature* 2015;527(7577):235–239.
- [38] Hsiang S, Kopp R, Jina A, Rising J, Delgado M, Mohan S, et al. Estimating economic damage from climate change in the United States. *Science* 2017;356(6345):1362.

- [39] Burke M, Davis WM, Diffenbaugh NS. Large potential reduction in economic damages under UN mitigation targets. *Nature* 2018;557(7706):549–553. <https://doi.org/10.1038/s41586-018-0071-9>.
- [40] Dell M, Jones BF, Olken BA. What do we learn from the weather? The new climate-economy literature. *Journal of Economic Literature* 2014;52(3):740–798.
- [41] Deryugina T, Hsiang S. The Marginal Product of Climate. National Bureau of Economic Research; 2017.
- [42] Lemoine D. Sufficient Statistics for the Cost of Climate Change. National Bureau of Economic Research; 2018.
- [43] Howard PH, Sterner T. Few and Not So Far Between: A Meta-analysis of Climate Damage Estimates. *Environmental and Resource Economics* 2017 Sep;68(1):197–225. <https://doi.org/10.1007/s10640-017-0166-z>.
- [44] Nordhaus WD, Moffat A. A Survey of Global Impacts of Climate Change: Replication, Survey Methods, and a Statistical Analysis. National Bureau of Economic Research; 2017.
- [45] Ritchie J, Dowlatabadi H. The 1000 GtC coal question: Are cases of vastly expanded future coal combustion still plausible? *Energy Economics* 2017;65:16 – 31.
- [46] Srikrishnan V, Guan Y, Keller K, Tol RSJ. Fossil fuel resources, decarbonization, and economic growth drive the feasibility of Paris climate targets. Department of Economics, University of Sussex Business School; 2020.
- [47] Adger WN. Vulnerability. *Global Environmental Change* 2006;16(3):268 – 281. <http://www.sciencedirect.com/science/article/pii/S0959378006000422>, resilience, Vulnerability, and Adaptation: A Cross-Cutting Theme of the International Human Dimensions Programme on Global Environmental Change.
- [48] Yohe GW, Tol RSJ. Indicators for Social and Economic Coping Capacity – Moving Towards a Working Definition of Adaptive Capacity. *Global Environmental Change* 2002;12(1):25–40.
- [49] Henderson JV, Squires T, Storeygard A, Weil D. The Global Distribution of Economic Activity: Nature, History, and the Role of Trade. *The Quarterly Journal of Economics* 2018;133(1):357–406. <http://dx.doi.org/10.1093/qje/qjx030>.
- [50] Smits J, Permanyer I. Data descriptor: The subnational human development database. *Scientific Data* 2019;6.
- [51] Harris I, Osborn TJ, Jones P, Lister D. Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Scientific data* 2020;7(1):109.
- [52] Harlan SL, Brazel AJ, Darrel Jenerette G, Jones NS, Larsen L, Prashad L, et al. In: Wilkinson RC, Freudenburg WR, editors. *In the shade of affluence: the inequitable distribution of the urban heat island Bingley*. Emerald Group Publishing; 2007. p. 173–202.