Climatic Change (2021) 168: 24
https://doi.org/10.1007/s10584-021-03198-7

Global and regional aggregate damages associated with global warming of 1.5 to 4 °C above pre-industrial levels

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Received: 28 February 2020 / Accepted: 5 August 2021 /

Abstract

We quantify global and regional aggregate damages from global warming of 1.5 to 4 °C above pre-industrial levels using a well-established integrated assessment model, PAGE09. We find mean global aggregate damages in 2100 of 0.29% of GDP if global warming is limited to about 1.5 °C (90% confidence interval 0.09–0.60%) and 0.40% for 2 °C (range 0.12–0.91%). These are, respectively, 92% and 89% lower than mean losses of 3.67% of GDP (range 0.64–10.77%) associated with global warming of 4 °C. The net present value of global aggregate damages for the 2008–2200 period is estimated at \$48.7 trillion for ~ 1.5 °C global warming (range \$13–108 trillion) and \$60.7 trillion for 2 °C (range \$15–140 trillion). These are, respectively, 92% and 90% lower than the mean NPV of \$591.7 trillion of GDP for 4 °C warming (range \$70–1920 trillion). This leads to a mean social cost of CO_2 emitted in 2020 of ~ \$150 for 4 °C warming as compared to \$30 at ~ 1.5 °C warming. The benefits of limiting warming to 1.5 °C rather than 2 °C might be underestimated since PAGE09 is not recalibrated to reflect the recent understanding of the full range of risks at 1.5 °C warming.

Keywords Climate change · Economic damages · Risk · Aggregate damages · Integrated assessment model

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This article is part of the topical collection "Accrual of Climate Change Risk in Six Vulnerable Countries", edited by Daniela Jacob and Tania Guillén Bolaños

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1 Introduction

Estimates of the global aggregate damages due to global warming are generally sparse. Recent reviews (Arent et al. 2014, Tol 2018) highlight that the majority of studies focus on a single level of warming, and thus any attempt to create a damage function showing how damages increase with warming has to be made via a meta-analysis of existing publications based on a range of modelling approaches. Until recently, a comprehensive analysis of damages at different levels of global warming using the same integrated assessment model has been lacking (Chen et al. 2020). Further, few of the existing studies examine the outcomes of warming levels consistent with the Paris Agreement's ultimate target of limiting global warming to 1.5 °C above pre-industrial levels, or alternatively, the potential for 4 °C warming, which could still occur if countries' current commitments under the Paris Agreement are not maintained or if other factors lead to higher than expected emissions. As countries ratify the Paris Agreement of the UN Framework Convention on Climate Change, their Intended Nationally Determined Contributions (INDCs) are converted to Nationally Determined Contributions (NDCs), containing their pledges to limit or reduce their greenhouse gas emissions by 2025 or 2030. These pledges are presently inadequate for achieving the long-term temperature goal of the Paris Agreement (that is limiting warming to 'well below 2C' and 'pursuing efforts' to limit global warming to 1.5 °C) (UNFCCC 2016; UNEP 2020) and are generally estimated to result in warming levels around 2.9 °C (https://climateactiontracker.org/).

In this study, we estimate the global aggregate damages associated with the full range of mean global temperature rises from 1.5 to 4 °C above pre-industrial levels by 2100, using PAGE09. PAGE09 is a well-established model that fully accounts for uncertainties in key model parameters such as transient climate response and discount rate. We also explore how the accrual of damage differs across eight world regions. This builds on earlier published findings from PAGE09, which have previously been limited to comparisons between two emission scenarios. Finally, we place these results in the context of projections made recently using an update to the PAGE09 code in the form of PAGE-ICE (Yumashev et al. 2019, Chen et al. 2020), and recent progress with another prominent integrated assessment model, DICE2016R2 (Hänsel et al. 2020).

2 Methodology

The PAGE09 is used to estimate the global aggregate economic damages associated with future climate scenarios exhibiting between 1.5 and 4 °C of global warming relative to pre-industrial levels (Fig. 2). This temperature range spans the potential outcome of mitigation efforts consistent with the Paris Agreement and the possible outcome of a 'no-policy' baseline. The range includes scenarios representing the NDCs with a warming level of approximately 3 °C. The scenarios for this analysis (Section 2.2) have been produced using the IMAGE model (Stehfest et al. 2014). Using PAGE09 and the IMAGE scenarios, we first calculate the unweighted global aggregate damages (as %GDP) for each warming level in 2100 and deduce the % damages avoided in 2100 resulting from constraining warming to the lower level compared to the reference scenario (4 °C). We subsequently repeat the calculation measuring damages as a net present value of weighted global aggregate damages for the whole period 2008 to 2200. Finally, we explore regional variation within the global aggregate analysis. The PAGE09 model is described in Section 3.1.

2.1 The PAGE09 model

The PAGE09 model (Hope 2013) is a significantly revised update of the PAGE2002 integrated assessment model of climate change (Hope 2006). The model is designed to help policymakers understand the costs and benefits of action and inaction on climate change. It is the gold standard version of the PAGE model. PAGE09 has been successfully re-programmed from scratch in Fortran (Kanellos et al. 2017) and Mimi (Moore et al. 2018) by independent research groups, who have verified the absence of errors in the original formulation used here. It calculates a valuation of the damages due to climate change, under uncertainty, for eight world regions and ten time periods spanning 2008–2200. It can also be used to calculate the costs of mitigation and adaptation policies, although this is not done here.

PAGE09 uses simple polynomial equations to simulate the results from more complex specialised scientific and economic models. It does this while accounting for key uncertainties in climate change science, such as the relationship between emissions, radiative forcing and global and regional temperature rise. It also accounts for the uncertainties in the relationship between climatic changes and the resultant economic and non-economic damages arising from both climate and sea level changes. Separate equations represent projected future climate change damages in four sectors: damage associated with sea level rise, economic and non-economic damages associated with changes in climate (but not sea level rise) and damage arising due to potential non-linear earth system responses to global warming, commonly known as 'discontinuities'.

In PAGE09, damages associated with sea level rise (before adaptation) are modelled as a polynomial function of sea level rise. Other economic and non-economic damages (again without adaptation) are represented as a polynomial function of the regional temperature. Economic damages included either directly affect GDP or are so-called non-market damages. The first category includes agricultural losses and air-conditioning costs. The second (not included directly in GDP) include human health and ecosystem damages. The default triangular distributions for these parameters in the focus region of the EU are shown in Table 1, giving the damage as a %GDP at the calibration sea level rise or temperature and the exponent of each polynomial function.

They produce a mean damage before adaptation of just under 2% of GDP for a temperature rise of 3 °C (Warren et al. 2006), including the associated sea level rise of just under half a metre (Anthoff et al. 2006). Sea level damages rise less than linearly with sea level rise, as land and people (and hence GDP) are concentrated in the most low-lying areas (Anthoff et al. 2006, Fig. 1). Economic and non-economic damages rise on average as just over a quadratic function of temperature, the same form and range as Ackerman et al. (2009). The range of damages is

Table 1 Damage function parameters in the default PAGE09 model

Parameter	*Short name*	*Mean*	Min	Mode	Max
Calibration sea level rise (m)	*SCAL*	*0.50*	0.45	0.50	0.55
Sea level damage at SCAL (%GDP)	*W_S*	*1.00*	0.50	1.00	1.50
Sea level exponent	*POW_S*	*0.73*	0.50	0.07	1.00
Calibration temperature (degC)	*TCAL*	*3.00*	2.50	3.00	3.50
Economic damage at TCAL (%GDP)	*W_1*	*0.50*	0.20	0.50	0.80
Economic exponent	*POW_1*	*2.17*	1.50	2.00	3.00
Non-economic damage at TCAL (%GDP)	*W_2*	*0.53*	0.10	0.50	1.00
Non-economic exponent	*POW_2*	*2.17*	1.50	2.00	3.00

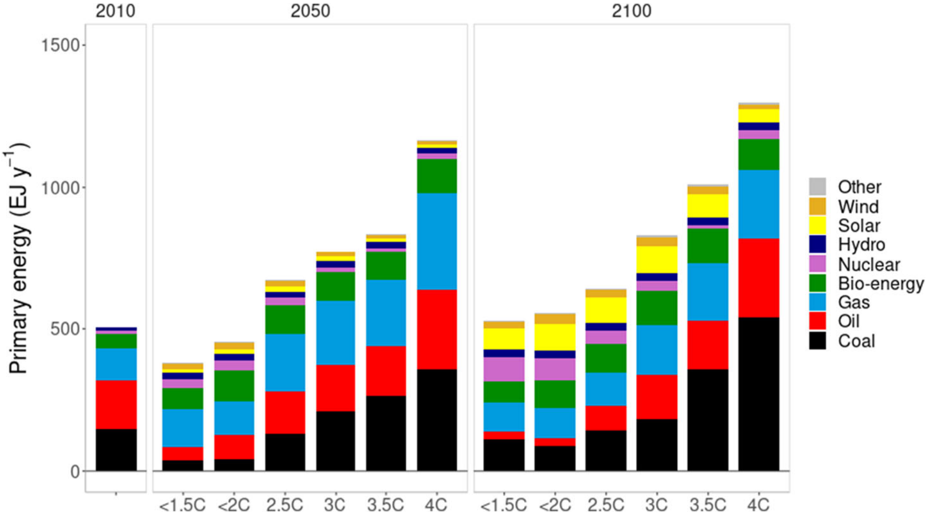

Fig. 1 Global primary energy use per energy carrier (IMAGE model output shown)

consistent with the range of 0–3% of GDP for a 2–3 °C warming, with higher costs in low-income countries, quoted in Stern (2007, p143).

In PAGE09, triangular distributions are used to describe the parameters for the risk of a possible future large-scale discontinuity. The modal parameter values imply that a large-scale discontinuity starts to become possible when the temperature has risen by 3 °C above pre-industrial levels (Lenton et al. 2008, Table 1), with a range of 2–4 °C (Stern 2007, box 1.4), and that for every 1 °C rise in temperature beyond this, the chance of a large-scale discontinuity occurring rises by 20%, so that with modal values, it is 20% if the temperature is 4 °C above pre-industrial levels, 40% at 5 °C and so on (Ackerman et al. 2009). Discontinuity losses build up gradually in PAGE09, with a characteristic lifetime of between 20 and 200 years (Table 2).

A further refinement in PAGE09 is that the model allows for the possibility of potential initial benefits that may arise from small increases in regional temperature (Tol 2002; Stern 2007), links damages explicitly to GDP per capita and allows damages to drop below their polynomial on a logistic path once they exceed a certain proportion of remaining GDP to reflect a saturation in the vulnerability of economic and non-economic activities to climate change (as some activities, such as primary extraction, education and computer gaming are clearly not so vulnerable to climate change as others such as agriculture) while ensuring they do not exceed 100% of GDP (Hope 2013).

The results reported in this paper are the sum of the damages in all four sectors (sea level, economic, non-economic and discontinuity), which we call aggregate damages. For the net

Table 2 Discontinuity parameters in PAGE09

Parameter	*Short name*	*Mean*	Min	Mode	Max
Tolerable before discontinuity (degC)	*TDIS*	*3.00*	2	3	4
Chance of discontinuity (% per degC)	*PDIS*	*20.00*	10	20	300
Loss if discontinuity occurs (%GDP)	*WDIS*	*15.00*	5	15	250
Half-life of discontinuity (years)	*DISTAU*	*90.00*	20	50	200

present value (NPV) calculations, the default PAGE09 ranges for the pure time preference (PTP) rate and elasticity of the marginal utility of consumption (EMUC) are used. These are triangular distributions of <0.1, 1 and 2> % per year for PTP and <0.5, 1, 2> for EMUC. These give initial mean consumption discount rates of around 3% per year in developed regions and 48% per year in developing ones. As in PAGE2002, calculations are performed probabilistically, using Latin hypercube sampling to build up probability distributions of the results.

The base year for PAGE09 is 2008. Emissions, realised temperature and sea level rise changes are all initialised to match reality in 2008. Regional population and GDP and global emissions of CO_2, CH_4, N_2O and F gases out to 2100 are provided by the IMAGE model as described below. To calculate damages for the twenty-second century, population and emissions are held at their 2100 levels throughout the century, with GDP growth continuing at 1.7% per year in all regions.

2.2 The scenarios from the IMAGE model

The integrated assessment model IMAGE is used to provide our climate change scenarios and their associated greenhouse gas emissions time series (van Vuuren et al. 2017, 2018). IMAGE includes a detailed representation of the energy and land use system. It also includes a representation of land cover and climatic change and covers key climate change feedbacks on vegetation and other systems. Climate policy in IMAGE is typically introduced via a universal price on carbon, exploring least-cost pathways to meeting the target.

The scenarios are derived from the Shared Socioeconomic Pathways (SSPs, Riahi et al. 2017). The key scenario is SSP2 which describes a ‘middle-of-the-road’ development for all key drivers, including population, macro-economic and technology assumptions. In particular, the global population rises from 7.2 billion in 2015 to 9.2 billion by 2100 and global GDP from 81.1 trillion US$2005 in 2015 to 537 trillion by 2100. The SSP2 baseline does not include climate policy beyond that already implemented in 2015. Energy use in the baseline SSP2 more than doubles from about 500 to over a 1000 EJ/y in 2100. A large share of this energy is supplied by fossil fuels, leading to emissions levels of about 100 Gt CO_2-eq/y. The scenario leads to a warming in 2100 of about 3.5 °C (although not designed to meet a target, this is somewhat comparable to RCP6). In our comparison, we also included the IMAGE SSP5 scenario. This scenario represents a high fossil fuel-driven economic growth and hence reaches a temperature level of 4 °C in 2100 (comparable to a forcing of around 7.0 W/m2 and thus allows us to explore the upper warming range) (see Table 3).

In addition, using the SSP2 baseline, a set of mitigation scenarios has been derived by implementing a universal carbon price (see Table 3). As a result, efficiency measures, fuel switching, CCS, land use measures and measures to reduce non-CO_2 greenhouse gas emissions are implemented. Figure 1 shows the resulting impact on primary energy supply. The mitigation scenarios were designed to reach a temperature level in 2100 of about 1.5 °C, 1.7 °C (well below 2 °C), 2.5 °C and 3.0 °C. The lower temperature targets correspond to lower primary energy demand and a higher share of renewable energy supply such as solar, wind and bio-energy. Scenarios 1 and 2 correspond in terms of warming to the SSP variants published as part of the total set of SSP scenarios, i.e. SSP1–1.9 and SSP1–2.6 (Riahi et al. 2017; Rogelj et al. 2018). Scenario 3 leads to a warming level comparable to the SSP2–4.5 scenario.

Figure 2 shows the global mean temperature outcomes of these scenarios. The temperature impacts were calculated using the MAGICC model (Meinshausen et al. 2011), and the median results from 10,000 runs of the PAGE09 model. The PAGE09 model calculates a full probability distribution of temperatures in each analysis year from the emissions supplied to it.

Table 3 Characteristics of the six scenarios

Scenario	Description	Global mean temperature rise above pre-industrial levels °C (median)	
		PAGE09	MAGICC
1: <1.5 °C	Mitigation is employed from 2020 onwards aiming to stay below 1.5 °C in 2100 with 66% probability	1.42	1.43
2: <2 °C	Mitigation is employed from 2020 onwards aiming to stay below 2 °C in 2100 with 66% probability	1.75	1.76
3: 2.5 °C	Mitigation is employed from 2020 onwards, constraining warming in 2100 close to 2.5 °C	2.62	2.51
4: 3 °C	Mitigation is employed from 2020 onwards, constraining warming in 2100 close to 3.0 °C	3.07	2.97
5: 3.5 °C	Mitigation is employed from 2020 onwards, constraining warming in 2100 close to 3.5 °C	3.65	3.53
6: 4 °C	No mitigation is implemented beyond the Cancun pledges	4.05	3.95

3 Results

3.1 Global aggregate damages in alternative scenarios

We find mean global aggregate damages in 2100 of 0.29% of GDP in scenario 1 (66% probability of remaining <1.5 ℃). The 90% confidence interval (CI) for this is 0.09–0.60% of GDP. The mean damage is 0.40% of GDP in scenario 2 (66% probability of remaining <2 ℃) (90% CI 0.12–0.91% of GDP). These are, respectively, 92% lower and 89% lower than the mean losses of 3.7% of GDP in scenario 6 (90% CI 0.64–10.77% of GDP) which has no action taken to abate climate change and corresponds to a warming level of 4 ℃ (Table 4).

Figure 3 a and Table S1 show the unweighted global aggregate damages (as %GDP) for these scenarios, as well as the intermediate scenarios 3 (2.5 ℃), 4 (3 ℃) and 5 (3.5 ℃). The final column of Table S1 shows an estimate of the slope of the damage curve with respect to global mean temperature derived from the differences between scenarios, which is the marginal damage in terms of %GDP loss avoided in 2100 per degree of global warming.

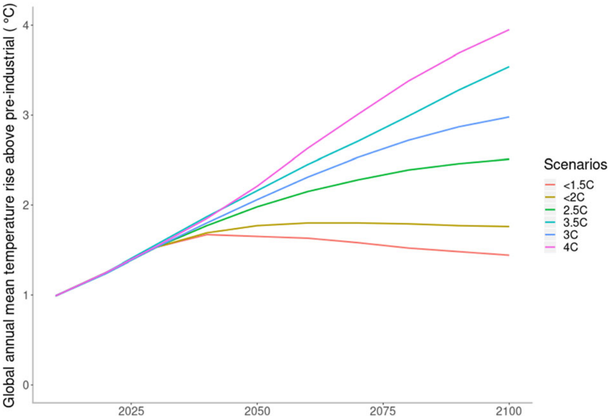

Fig. 2 Time evolution of global mean temperature rise in the scenarios analysed. These originate from the MAGICC model (Meinshausen et al. 2011)

Table 4 Mean damages avoided compared to scenario 6:4 °C globally and by world region in 2100

	Scenario 1: <1.5 °C (%)	Scenario 2: <2 °C (%)	Scenario 3: 2.5 °C (%)	Scenario 4: 3 °C (%)	Scenario 5: 3.5 °C (%)
Globe	92	89	71	54	25
EU	93	89	69	52	24
USA	92	87	66	51	23
Other OECD	92	88	67	49	21
FSU & ROE	92	88	66	49	21
China & CP Asia	91	86	67	53	25
India & SE Asia	93	91	76	57	24
Africa & ME	92	88	69	52	23
Latin America	91	87	67	51	23

FSU Former Soviet Union, *ROE* Rest of Europe, *CP* Centrally Planned, *ME* Middle East. For details of countries in each region, see Table S3

Limiting warming to 1.5 °C rather than 2 °C (both with 66% probability) reduces the mean damages in 2100 from 0.40% of GDP to 0.29% of GDP while reducing the median global mean temperature rise in 2100 from around 1.8 to less than 1.5 °C. This implies a slope of damage loss of 0.36% of GDP per °C over this temperature range. However, the slope of the marginal damage curve increases monotonically as the median GMT in 2100 rises.

The damages have a long right tail, which is particularly pronounced for the scenarios with higher levels of global warming. In all scenarios, the long right tail causes a mean value that is higher than the median. This is again most pronounced in the higher emission scenarios. Figure 3 a shows this pronounced 'fat-tailed' distribution of damage outcomes, in which the upper end of the range of potential damage outcomes increases much more rapidly with global warming than does the median estimate. While the 95 percentile outcome for damages in scenario 2 is greater than that in scenario 1 (0.91 vs. 0.60% GDP), under a 4 °C scenario, the 95 percentile outcome reaches 10.77% GDP, while the median value increases to 3.67%. Figs. S1–6 show the full probability distributions of the global aggregate damage in 2100 from the six scenarios.

Runs in the long right tail are typically those in which the climate sensitivity is towards the higher end of its range, and the tolerable temperature before triggering a discontinuity is towards the lower end of its range, so that a discontinuity, or tipping point, such as triggering the loss of the Greenland and West Antarctic ice sheets, has been reached before 2100.

When we repeat the calculation measuring damages as a NPV of weighted global aggregate damages for the whole period 2008 to 2200, the distribution remains fat-tailed(Fig. 3b). We find the mean NPV of global aggregate damages to 2200 to be $48.7 trillion in scenario 1:<1.5 ℃ (90% CI $13–108 trillion) and $60.7 trillion in scenario 2:<2 ℃ (90% CI $15–140 trillion). These are, respectively, 92% lower and 90% lower than the mean NPV of $591.7 trillion of GDP in scenario 6 (90% CI $70–1920 trillion) which has no action taken to abate climate change and corresponds to a warming level of 4 ℃. All dollar results in this paper are in $US of the year 2005, the default in the PAGE09 model[1].

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[1] To convert to $2019, increase all values by 25% (Source: US Bureau of Economic Analysis). This 25% adjustment applies only to the NPV of damages, not to the % of GDP in 2100, which remains unchanged.

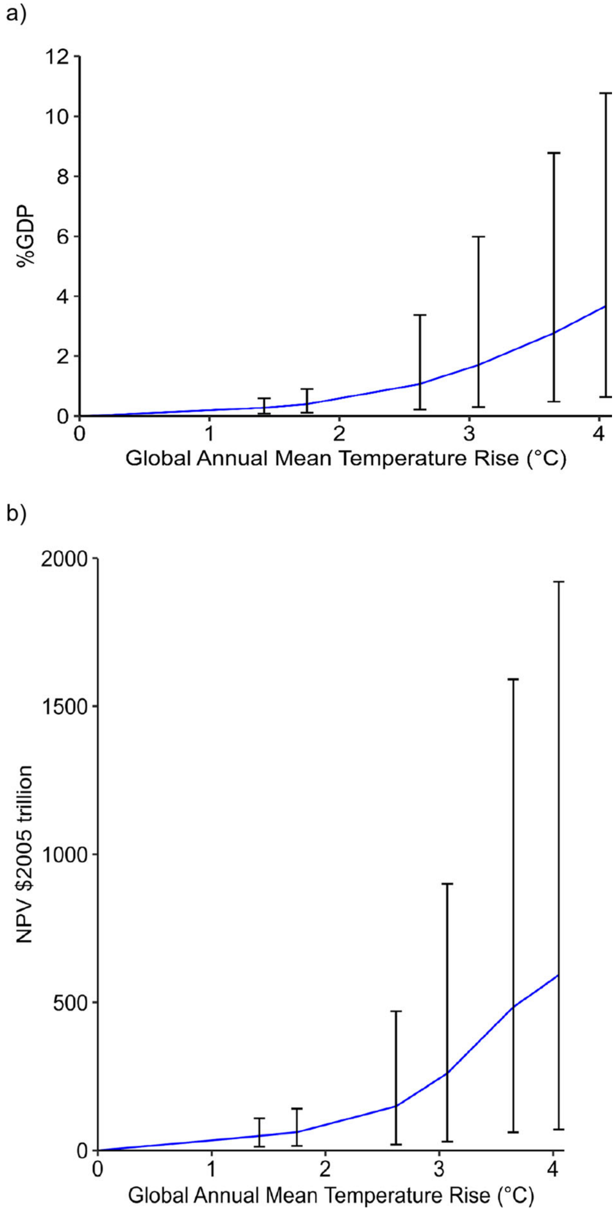

Fig. 3 Global aggregate damages by median global mean temperature rise in 2100 expressed as **a** %GDP in 2100 and **b** the net present value (NPV) for the period 2008–2200. Values shows are means and 90% confidence limits

Figure 3 b and Table S2 shows the results for these scenarios and the intermediate scenarios 3:2.5 °C, 4:3 °C and 5:3.5 °C. The 2008 base year global world product (GWP) is $66.5 trillion. So for scenario 6:4 ℃, the mean NPV of global aggregate damages to 2200 is 8.9 times the base year GWP; for scenario 1:<1.5 ℃, it is 0.7 times the base year GWP. These ratios should be treated with caution as we are comparing an unweighted base year GWP with a weighted NPV, with higher weights in low-income regions.

The final column of Table S2 shows an estimate of the slope of the damage curve with respect to global mean temperature derived from the differences between scenarios, when damage is measured as the mean NPV of global aggregate damages from 2008 to 2200. The first entry shows that moving from scenario 2:<2 ℃ to scenario 1:<1.5 ℃ reduces the mean NPV of damages from \$60.7 trillion to \$48.7 trillion while reducing the median GMT in 2100 from 1.75 to 1.42 ℃, a slope of \$36 trillion per ℃, only about one-third of the slope going from scenario 3:<2.5 °C to scenario 2:<2 °C. It is this flattening of the damage curve below 2 °C combined with the increasing cost and difficulty of cutting emissions enough to reach 1.5 °C that makes the decision to aim for 1.5 °C rather than 2 °C such a complicated one.

The slope of the damage curve increases monotonically as the median GMT in 2100 rises until the median GMT in 2100 is between 3.07 and 3.65 ℃, at which point it is \$387 trillion per ℃. Beyond this, the slope decreases to \$269 trillion per ℃. This is an artefact of the decision to keep all emissions at their 2100 levels throughout the twenty-second century rather than allowing them to continue to rise.

Damages also increase strongly with global warming in all regions (Fig. 4). Previous work (Hope 2011, Table 10) has shown that about 80% of the NPV of damage occurs in developing regions (after correcting for purchasing power parity and equity weighting). However, when expressed as a percentage of GDP without equity weighting, the proportion is more similar in all regions, being highest in the 'other OECD' region, which includes Australia, and lowest in the Former Soviet Union and Rest of Europe (Fig. 4). Avoided damages in 2100, as a percent of the damages in scenario 6:4 ℃, are very similar across the eight world regions in PAGE09, as shown in Table 4. Strong action to limit climate change will have large benefits for all world regions, particularly developing regions where the majority of equity-weighted damages occur.

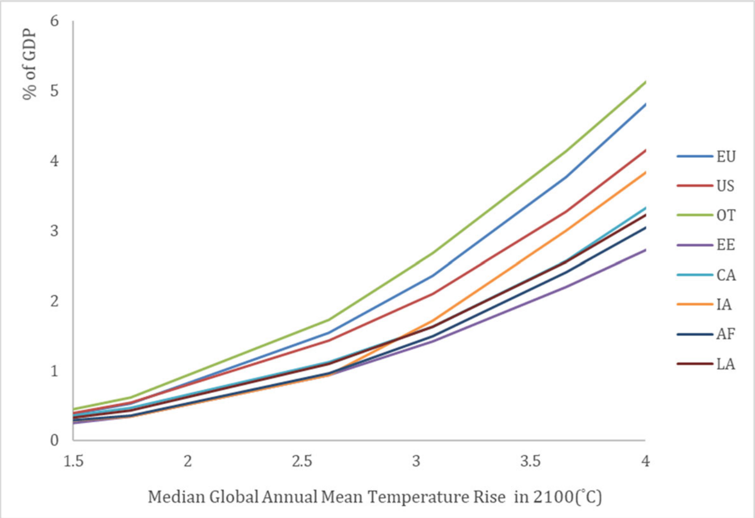

Fig. 4 Mean aggregate damages by region and median global mean temperature rise in: EU, US, OT, Other OECD (including Australia, Japan, New Zealand and Canada); EE, Former Soviet Union and Rest of Europe; CA, China and Centrally Planned Asia; IA, India and SE Asia; AF, Africa and Middle East; LA, Latin America. For detailed region definitions, see Table S3

One other result of interest is the social cost of carbon dioxide under each of the scenarios. This is the extra marginal damage caused by an additional tonne of CO_2 emitted on top of the emissions in the scenario. It is also the carbon price that should be imposed in the EU in this scenario to internalise the damages from climate change. Earlier investigations with PAGE2002 have suggested that the mean social cost of CO_2 might be relatively insensitive to the emissions scenarios under which it is calculated (Hope 2008).

Table 5 shows our mean results if this extra tonne is emitted in 2020. The variation across the scenarios is about a factor of 5. In the highest emission scenarios, one extra tonne of CO_2 emitted in 2020 would cause about another $150 in mean damages. In the lowest emission scenario 1:<1.5 °C, it would only be about $30. This is a consequence of the upward form of the damage curve and particularly the correct accounting for the full equity impact of the discontinuity damages in PAGE09 which increase rapidly at higher temperatures.

4 Discussion and conclusions

Analysis with a simple probabilistic integrated assessment model PAGE09 indicates the mean global aggregate damages in 2100 of the different scenarios and their uncertainty ranges. These are 0.29% of GDP (5–95% range 0.09–0.60%) from constraining warming to 1.5 °C with 66% probability, 0.40% of GDP (5–95% range 0.12–0.91%) from constraining it to 2 °C with 66% probability and 3.67% of GDP (5–95% range 0.64–10.77%) from allowing emissions to rise along a no-policy baseline, leading to a mean GMT rise of 4 °C in 2100. Warming associated with the NDCs allows mean global aggregate damages in 2100 to reach 1.70% of GDP (5–95% range 0.31–5.99%). The net present value of global aggregate damages for 2008–2200 is estimated at $48.7 trillion for ~1.5 °C global warming (5–95% range $13–108 trillion) and $60.7 trillion for 2 °C (5–95% range $15–140 trillion). Correspondingly, the mean net present value of *avoided* damages that would otherwise accrue by 2200, associated with limiting warming to 1.5 °C rather than 4 °C, is estimated as 543 trillion US$ (2010), as compared with 531 trillion due to limiting warming to 2 °C.

However, these damages are likely conservative because the damage functions described in Section 2.1 are based on literature published before 2009, mostly matching the IPCC Third Assessment Report (IPCC 2007). The overall assessment of risk from climate change with global warming finds greater risks for the same level of warming than in 2009 (IPCC 2014,

Table 5 Mean social cost of CO_2 in 2020 by scenario

Scenario number	Year 2100 PAGE09 median (°C)	Mean SCCO2 in 2020 ($/t$CO_2$)
1:<1.5 °C	1.42	30
2:<2 °C	1.75	43
3:2.5 °C	2.62	95
4:3 °C	3.07	123
5:3.5 °C	3.65	151
6:4 °C	4.05	154

Note: These mean values come from 100,000 runs of the PAGE09 model. The 5–95% CI for the mean values is plus or minus $1 for scenarios 1 and 2 and $2 for the other scenarios

2018; Zommers et al. 2020). For example, between 2014 and 2018, the assessed levels of concern 'increased for four of the five Reasons for Concern' for global warming of 2 °C (IPCC 2018). Also, apart from the discontinuity sector, the damage functions in PAGE09 depend only on the climate in a particular year, so any dynamic damages, where damage accumulates due to indirect consequences of climate change in earlier years, is not yet included (Burke et al. 2015).

A further contribution to the potential for damages to be underestimated here is that damages associated with arctic feedbacks leading to the release of CO_2 and CH_4 from permafrost are excluded from this analysis. In parallel with our work, independent updates to the PAGE09 model were made. This includes the development of PAGE-ICE(Yumashev et al. 2019) to reflect non-linear transitions in arctic feedbacks (permafrost and albedo effect), the calibration of equilibrium climate sensitivity values to match IPCC AR5 and other earth system science models, changes in the treatment of regional cooling by sulphate aerosols, a revised carbon cycle consistent with recent literature (Joos et al. 2013) and the use of a fat-tailed distribution for sea level rise to represent possible contributions to sea level rise from melting of the Greenland Ice Sheet. The damage functions were also upgraded in PAGE-ICE to reflect a recent macro-econometric analysis of the effect of historic temperature shocks on economic growth in multiple countries (Burke et al. 2015).

PAGE-ICE was subsequently used to estimate aggregate economic damages under different combinations of socioeconomic and climate change futures (Chen et al. 2020). Comparing the SSP2-based projections emerging from PAGE-ICE(Chen et al. 2020) vs PAGE09 reported here is interesting (Tables S4, S5, S7). At global warming of 2.5C in 2100, PAGE09 projects mean damages of 1.08% GDP (5-95% range 0.22–3.37), while PAGE-ICE projects damages of 6% GDP already at 2.7 °C (Chen et al. 2020)(Table S4). Similarly, PAGE09 estimates the mean NPV of damages in 2200 for warming of 2.5 °C at US$148 trillion (5-95% range $20–470), whereas at 2.7 °C, Chen et al. (2020) report US$569 trillion (5–95% range − 119–1722) including only damages to 2100 (Table S5). Inconsistencies notwithstanding, this represents a four-fold increase in damages comparable with the threefold increase emerging from the independent study of Hänsel et al. (2020).

The relatively small differences produced in PAGE09 between the damages associated with 1.5 rather than 2 °C global warming might be due to the PAGE09 damage function not yet well capturing the findings of IPCC (2018), and also the limited coverage of the effects of extreme weather events which will play an important role in determining aggregate damage. Nevertheless, these small increases represent a 41% increase in damages for the 2 °C scenarios with respect to the 1.5 °C scenario, increasing further to a 66% increase in Chen et al.(2020). Hence, the use of PAGE-ICE increases both the absolute damages avoided by limiting warming to lower temperatures and also increases the relative (percentage) increase.

Arent et al. (2014) review global aggregate damage estimates originating from various integrated assessment models, including various versions of FUND, DICE and PAGE and generally find aggregate damage estimates of between 1 and 3% of global GDP for global warming of 3 °C, while a more recent review (Tol 2018) finds similar values. A study with the integrated model DICE2016R2, which includes a blanket 25% uplift to damages to account for discontinuities (Nordhaus and Sztorc 2013), produces a year 2100 damage estimates of 2.0% of income at 3 °C and 7.9% of global income at a global temperature rise of 6 °C (Nordhaus 2018). This is similar to the PAGE09 mean estimate of 1.7% income at 3C warming (Table S1). It should be noted that the calibration of DICE2016R2 included output from PAGE09 as one of its calibration points (Nordhaus 2018), while an uncertainty analysis performed with DICE2016R2's baseline scenario yielded damage ranges (within one standard deviation) of approximately 1.5–6% GDP for warming of 3.3–4.8 °C (see Fig. 7A, B in Nordhaus 2018).

More recently, further updates were made to the DICE2016R2 model (Hänsel et al. 2020), including changes to the carbon cycle, making it consistent with the IPCC Special Report on 1.5 °C warming (Rogelj et al. 2018), a recalibration to update the treatment of energy balance, the use of emerging literature to recalibrate the temperature-damage relationship, use of an exogenous pathway for non-CO_2 forcing, the availability of negative emission technologies and the technologically feasible speed of decarbonisation. The utilised damage-temperature relationship (Howard and Sterner 2017) indicates damages of 6.69% of global GDP for a 3 °C global temperature rise while noting that there is empirical evidence for even larger damages (Burke et al. 2015)—increasing the damages by a factor of 3. DICE2016R2 now finds an optimal limit to global warming of 1.77 °C in 2100, producing a mean social cost of carbon dioxide in 2020 of 119US$/tCO2 (including all model updates) (Table S6) as compared with mean values of 30–43 $/t$CO_2$ for 1.5–2 °C warming in 2100 here (Table 5 and Table S6), representing an approximately three-fold increase.

Both these comparisons indicate how recent updates in the understanding of the earth's climate system and in the observation and projection of risks associated with global warming have had a profound effect on the estimates of associated economic damages. Updates to integrated assessment models have often lagged behind increases in scientific understanding, leading to these damages being underestimated in the past, as noted previously (Warren et al. 2006; Warren et al. 2010; Van Vuuren et al. 2011).

While Hänsel et al. (2020) and Chen et al. (2020) address many of the issues raised in those earlier publications, neither PAGE09 nor PAGE-ICE 'explicitly model other known climatic tipping elements such as Amazon rainforest, boreal forest, coral reefs and El Niño–Southern Oscillation (ENSO), as well as ocean acidification and climate-induced large-scale migration and conflict' (Yumashev et al. 2019), while Hänsel et al. 2020 note that excluded factors include 'tipping points, relative scarcity of non-market goods, and climate-induced migration'. Projected risks to biodiversity will interact, via loss of ecosystem services, with the projected risks estimated here, creating a risk cascade (Warren 2011). Such systemic linkages, and their consequences, are difficult to quantify. Hence, the projections provided here are likely conservative and in particular will not reflect the findings of IPCC (2018), which outline important reductions in climate change damages associated with limiting warming to 1.5 °C rather than 2 °C, for example, in terms of reduced damages on ecosystems, terrestrial and marine biodiversity and ocean acidification. This, together with ongoing improvements of understanding of climate change science and climate change-related risks, means that estimates of aggregate economic damages associated with climate change inevitably continue to fall short of a complete representation within integrated assessment models, and hence, even these latest projections probably still lead to underestimates of global aggregate economic damage associated with climate change that would be expected to actually occur.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10584-021-03198-7.

Author contributions DVV and DG provided the IMAGE scenarios, CH carried out the PAGE09 simulations, KH provided supplementary Tables S4-S6. RW designed and led the work and wrote the paper, to which all authors contributed.

Funding This research leading to these results received funding from the UK Government, Department for Business, Energy and Industrial Strategy, as part of the 1.5–4 °C warming project under contract number UK SBS CR18083-S2.

Declarations

Conflict of interest The authors declare no competing interests.

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