NET ZERO-EMISSION PATHWAYS REDUCE THE PHYSICAL AND ECONOMIC RISKS OF CLIMATE CHANGE

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ABSTRACT

Mitigation pathways exploring end-of-century temperature targets often entail temperature overshoot. Little is known about the additional climate risks generated by overshooting temperature. Here, we provide the first assessment of the benefits of limiting overshoot. We compute the probabilistic impacts for different warming targets and overshoot levels, based on an ensemble of integrated assessment models. We explore both physical and macroeconomic impacts, including persistent and non-persistent climate impacts. We find that temperature overshooting affects the likelihood of many critical physical impacts, such as those associated with heat extremes. Limiting overshoot reduces risk in the right tail of the distribution, in particular for low-temperature targets where larger overshoots arise as a way to lower short-term mitigation costs. We also show how, after mid-century, overshoot leads to both higher mitigation costs and economic losses from the additional impacts. The study highlights the need to include climate risk analysis in low-carbon pathways.

Multiple mitigation trajectories are consistent with climate stabilization [1] which may lead to different climate change risks [2, 3]. One important feature of the pathways is the extent to which the temperature is allowed to temporarily exceed a given target, commonly known as 'overshoot'. Given historical emissions, stringent long-term temperature targets, such as limiting the temperature increase to 1.5°C in 2100, often entail temporary temperature exceedance to be compensated by net negative carbon emissions in the second half of the century [4]. These pathways are the outcome of Integrated Assessment Models (IAMs) constrained to meet fixed year targets, often for 2100 [5, 6, 7]. The extent of overshoot is a function of many variables defining how rapidly human systems can be transformed, including socio-economic and technological progress ones. For example, the assumptions of bioenergy technologies with carbon dioxide capture and geologic storage vary substantially across models [8]. It is also rooted in the choice of normative parameters. For example, time discounting consistent with proper consideration of future generations reduces overshoot and reliance on carbon dioxide removal [9]. Finally, the overshoot might depend on the way scenarios are designed and executed [10]. To overcome some of the limitations of end-of-century target scenarios, a scenario design has been recently proposed. It caps the peak temperature reached during the century limiting 'net zero' carbon emissions [11].

One reason for the temperature overshoot is that, usually, cost-minimizing emission pathways don't account for the climate benefits associated with different temperature trajectories. Detailed process IAMs, such as those providing input to the Intergovernmental Panel on Climate Change [12], are tools primarily designed for mitigation analysis. As such, they don't take into account that overshoot trajectories lead to worse heat extremes than no-overshoot trajectories [13]. Benefit-cost IAMs include climate impacts, but lack mitigation strategy details and focus solely on monetary impacts [14]. Thus, their capacity to evaluate the full trade-offs implied by different intertemporal mitigation trajectories compliant with given climate stabilization targets is limited. Still, recent benefit-cost studies have highlighted the economic inequality repercussions in low-temperature cases [15]. Here, we combine mitigation pathways with a postprocessing analysis of both physical and economic climate impacts, employing advanced statistical approaches. We use a large set of scenarios generated by a multimodel ensemble of nine leading detailed process IAMs, which explore end-of-century budget scenarios (where overshoot is allowed) versus net zero emission constrained budget scenarios. The pairwise comparison highlights the overshoot implications while reaching Paris Agreement compliant targets. We generate probabilistic climate outcomes from the scenario ensembles. We use the latest impact science to derive probabilistic climate impacts for a wide array of physical and economic indicators. Results show that the climate benefits of limiting overshoot can be significant, especially for stringent climate targets with larger overshoot. The benefits occur for both physical and macroeconomic impacts, albeit interesting differences occur. Limiting overshoot is effective in reducing low probability, high consequence climate change repercussions.

This study is part of a multimodel comparison effort, which is looking at different insights from the same scenario dataset. Other studies are focusing on the near-term energy system investments [16], the mitigation costs of overshooting (Riahi *et al.*, submitted) and on the land-use sector (Hasegawa *et al.*, accepted).

This study is part of a multimodel comparison exercise, which also focuses on the near-term energy system investments [16], the mitigation costs of overshooting (Riahi *et al.*, submitted) and on the land-use sector (Hasegawa *et al.*, accepted).

SCENARIO PROTOCOL

This study involves nine global integrated assessment models: AIM/CGE, COFFEE, GEM-E3, IMAGE, MESSAGEix-GLOBIOM, POLES, REMIND-MAgPIE, TIAM-ECN and WITCH (see Supplementary Material). These models have been widely used to assess global climate change mitigation pathways [6, 7, 17]. They are representative of a wide spectrum of approaches, spanning from simulation to optimisation models, and from game-theoric frameworks to least-cost optimisation models. They all have a detailed representation of the energy and land-use systems and a wide array of decarbonisation options. Used in conjunction, the models generate an ensemble of pathways that span a plausible range of technological developments, allowing us to assess the results' robustness and highlight trajectories characterized by fat tail risk, i.e. the likelihood of high impact is much greater than that of a normal distribution.

Each modelling team followed the same protocol to ensure comparative results (see Supplementary Methods). After 2020, the models impose a remaining carbon budget, i.e., the cumulative CO_2 emissions over the period 2018–2100, consistent a given long-term temperature target, for two different scenario designs. The ‘End Of Century’ (EOC) scenario design implements the remaining carbon budget without restriction; while the ‘Net Zero’ (NZ) scenario design implements the remaining carbon budget until CO_2 emissions reach net zero CO_2 emissions. After that point, net CO_2 emissions are kept at zero. This ensures that the temperature peaks and stabilizes. The emission pathways are produced for a large range of remaining carbon budgets, from 500 $GtCO_2$ to 2000 $GtCO_2$, to explore the space of climate targets systematically [18]. Models constrain their cumulative CO_2 emissions and price the other greenhouse gases emissions at the CO_2 price adjusted by the 100-year global warming potential equivalent. We compare the pair of trajectories produced by each model for the same remaining carbon budget (Figure 1).

We use the climate emulator MAGICC [20, 21] to project the global mean temperature consistently across scenarios, in a setup reproducing the IPCC AR5 climate sensitivity uncertainty assessment [22, 23]. EOC and NZ scenarios, under the same budget, lead to nearly the same temperature increase in 2100, but the timing and the level of the warming peak vary across scenario designs and across models (Figure 1, panel a). The IAMs don’t directly control the overshoot magnitude, which rather depends on the model structure and its mitigation options. EOC scenarios rely heavily on negative CO_2 emissions at the end of the century, while NZ scenarios reduce CO_2 emissions earlier and to lower levels (Figure 1, panel b and Supplementary Figure 22). As a consequence, peak warming happens earlier and it is lower in the NZ scenario than in the EOC scenario (Figure 1, panel a) and Supplementary Figure 1).

The cumulated temperature overshoot, i.e., the cumulated difference in temperature between EOC and NZ along the century’s path (highlighted as the yellow area in Figure 1, panel a), depends on the model but also on the remaining carbon budget: the more stringent the remaining carbon budget and hence the lower the temperature increase in 2100, the larger the overshoot, robustly across all models (Supplementary Figure 2). Similarly, the maximum overshoot, the temperature difference between the maximum temperature in EOC and NZ, is declining with the larger remaining carbons budget, although model differences exist (Supplementary Figure 3). These temperature trajectories suggest we shall expect the largest climate impact differentials between EOC and NZ scenarios with smaller remaining carbon budgets.

Across models, the same remaining carbon budget may not necessarily lead to the same 2100 temperature, as the models reduce differently the non-CO_2 greenhouse gases emissions

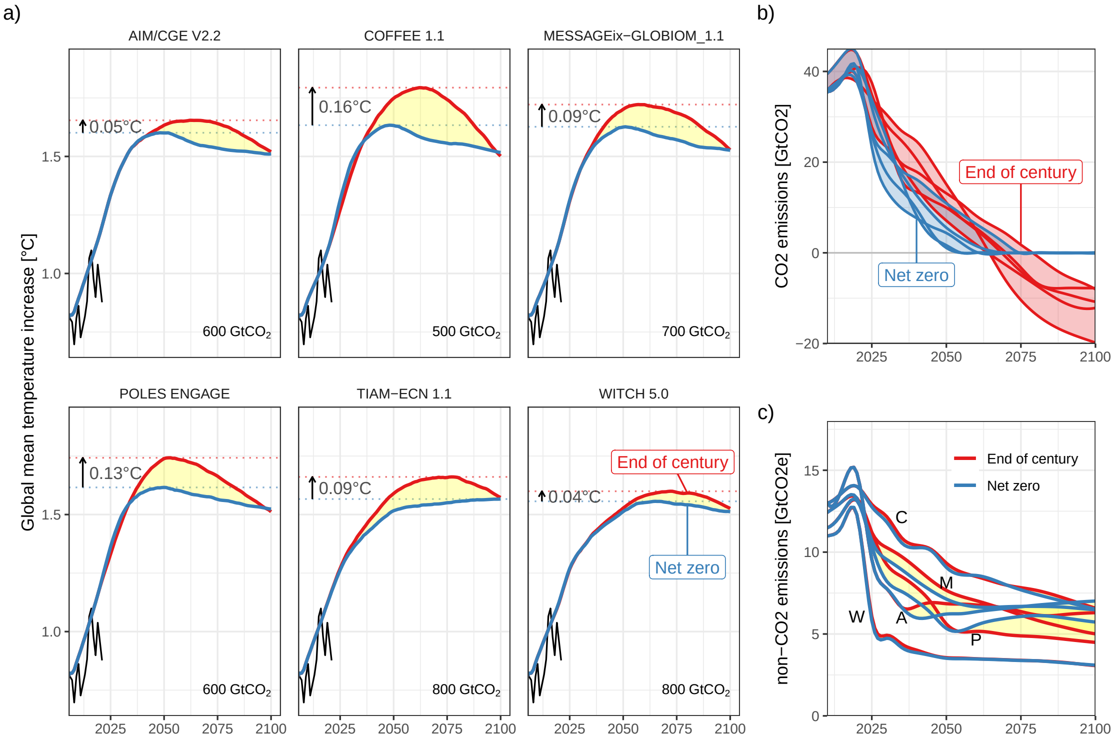

Figure 1: Influence of emission target formulation on the temperature and emission projections across models. Panel a) shows the global mean temperature increase for an illustrative selection of model scenario combination, leading to a similar temperature in 2100, likely 1.5°C. Each sub-panel displays two scenarios for the same amount of cumulative emissions. The 'Net Zero' (NZ) design is in blue, and the 'End of Century' (EOC) design is in red and allows for overshoot. The difference between the two trajectories is highlighted in yellow. Historical temperatures from HadCRUT4 [19] are shown until 2019 in black lines. The maximum temperatures of trajectories are highlighted by horizontal dashed lines and their difference is shown beside the up arrow. Panel b) shows the global CO_2 emission projections for each model and scenario design, highlighting the ranges. Panel c) shows the global non-CO_2 emission projections (CH_4, N_2O and f-gases), expressed as CO_2-eq using GWP-100. Differences between EOC and NZ are highlighted. The letters are the models' initials. Supplementary Figure 1 reports all temperature pathways of the cluster (likely 1.5°C). Supplementary Figure 28 provides model details for panel b) and c).

(Figure 1, panel c). As temperatures represent our key input to impact calculations, we cluster the model carbon budget pairs (EOC and NZ) according to the temperature reached in 2100. We characterize the scenarios: as likely 1.5°C for a temperature of 1.55°C in 2100, as likely 1.6°C, for a temperature between 1.55°C and 1.65°C, below 1.8°C for a temperature between 1.65°C and 1.8°C and below 2°C for a temperature between 1.8°C and 2°C. The temperature clusters contain a similar number of scenarios, for a diversity of models and temperature trajectories (Supplementary Table 1 and Supplementary Figures 1 and 23).

PHYSICAL IMPACT DISTRIBUTION

We start off by gauging the probabilistic climate implications of a wide array of physical indicators based on regional impact functions, also representing the uncertainty in the regional pattern of climate change from CMIP5 models [24]. The temperature distributions coming from the range of IAM scenarios of the comparison exercise are translated into physical impact distributions for each temperature cluster and scenarios. We produced the distributions for different impacts: heat extremes (four different indicators), energy demand (two), agriculture (seven), and water resources (two) both at the global and regional scale.

Table 1 and Supplementary Figure 4 present the global maximum impact for all indicators for the lower and upper-temperature clusters (see Supplementary Figure 6 for all temperature clusters). The most striking difference is observed between likely 1.5°C to below 2°C, where the median values significantly increase for all impacts, showing the high sensitivity of impacts to temperature [2, 4]. The differences in impacts related to heatwaves are amongst the most severe. The most affected regions by the changes in heatwaves are Brazil, West and Southern Africa (Supplementary Figure 7).

Table 1: Global geophysical maximum impacts over the century. The table reports the median values, the 5th and 95th percentiles in brackets, of the distributions of maximum impacts over the century for the Net Zero and End Of Century scenarios, for two temperature clusters. The impact indicator definitions are provided in Supplementary Table 5.

	likely 1.5°C		**below 2°C**	
	Net zero	**End of century**	**Net zero**	**End of century**
Heatwave duration [days/year]	5.6 [4.2;7.4]	6.6 [4.8;9.1]	9.6 [7.2;12.7]	10.1 [7.4;13.6]
Heatwave frequency [%]	74 [68;79]	77 [70;82]	84 [78;87]	84 [79;88]
Major heatwave frequency [%]	28 [22;35]	32 [25;40]	42 [35;50]	44 [36;52]
Frost days [days/year]	54 [53;55]	53 [52;55]	52 [50;53]	52 [50;53]
Cooling degree days [°C]	1826 [1784;1864]	1853 [1798;1903]	1921 [1874;1971]	1931 [1878;1983]
Heating degree days [°C]	1628 [1601;1653]	1611 [1577;1643]	1569 [1535;1595]	1562 [1525;1590]
Crop duration lost: Maize [days]	6.7 [5.7;7.6]	7.3 [6.1;8.3]	8.8 [7.7;9.7]	8.9 [7.8;10]
Crop duration lost: Rice [days]	4.9 [4.1;5.6]	5.4 [4.5;6.2]	6.6 [5.7;7.4]	6.8 [5.8;7.6]
Crop duration lost: Soybean [days]	7.4 [5.7;8.9]	8 [6.2;9.8]	9.7 [7.7;11.6]	9.9 [7.9;11.9]
Crop duration lost: Spring Wheat [days]	7.4 [5.7;8.9]	8 [6.2;9.8]	9.7 [7.7;11.6]	9.9 [7.9;11.9]
Crop duration lost: Winter Wheat [days]	7.7 [6.4;8.9]	8.4 [7;9.9]	10.3 [9;11.9]	10.5 [9.2;12.2]
Agricultural drought frequency [%]	24 [17;30]	26 [18;32]	31 [22;38]	31 [22;39]
Agricultural drought : time [%]	12 [10;14]	13 [10;15]	15 [11;17]	15 [11;18]
Runoff decreases [% of area]	9.5 [4.5;17]	10.7 [5.2;18.8]	13.5 [7.1;22.7]	13.8 [7.4;23.1]
Runoff increases [% of area]	7.6 [3.2;15.7]	8.6 [4;17.5]	11.2 [6;20.8]	11.5 [6.4;21.8]

We explore the role of temperature overshoot comparing the characteristics of the impact distributions. The differences in median impacts between EOC and NZ scenarios are modest but still statistically indistinguishable (under the 90% confidence interval), e.g., overshoot increases the median of maximum heatwave duration by 1 day for likely 1.5°C scenarios and 0.5 day for below 2°C scenarios (see also Figure 2, panel a)). In addition, the maximum impacts are always lower in NZ scenarios, consistent with the temperature trajectories. The same conclusions hold at the regional level, but with a different ranking for the various impacts (Supplementary Table 2).

We compare the distributions of the maximum impact occurring over the century, with and without overshoot at likely 1.5°C, using a Kolmogorov-Smirnov test (Supplementary Figure 5). Globally, the most significant climate benefits of reduced overshoot are the ones related to the growth crop duration (in particular for rice and winter wheat) and energy demands (cooling degree days and heating degree days). At the regional level, impacts related to heatwaves would most likely be reduced in Africa and North America. In Europe, crop duration would be the most likely to be affected for maize, soybean, winter wheat, and rice (Supplementary Figure 5).

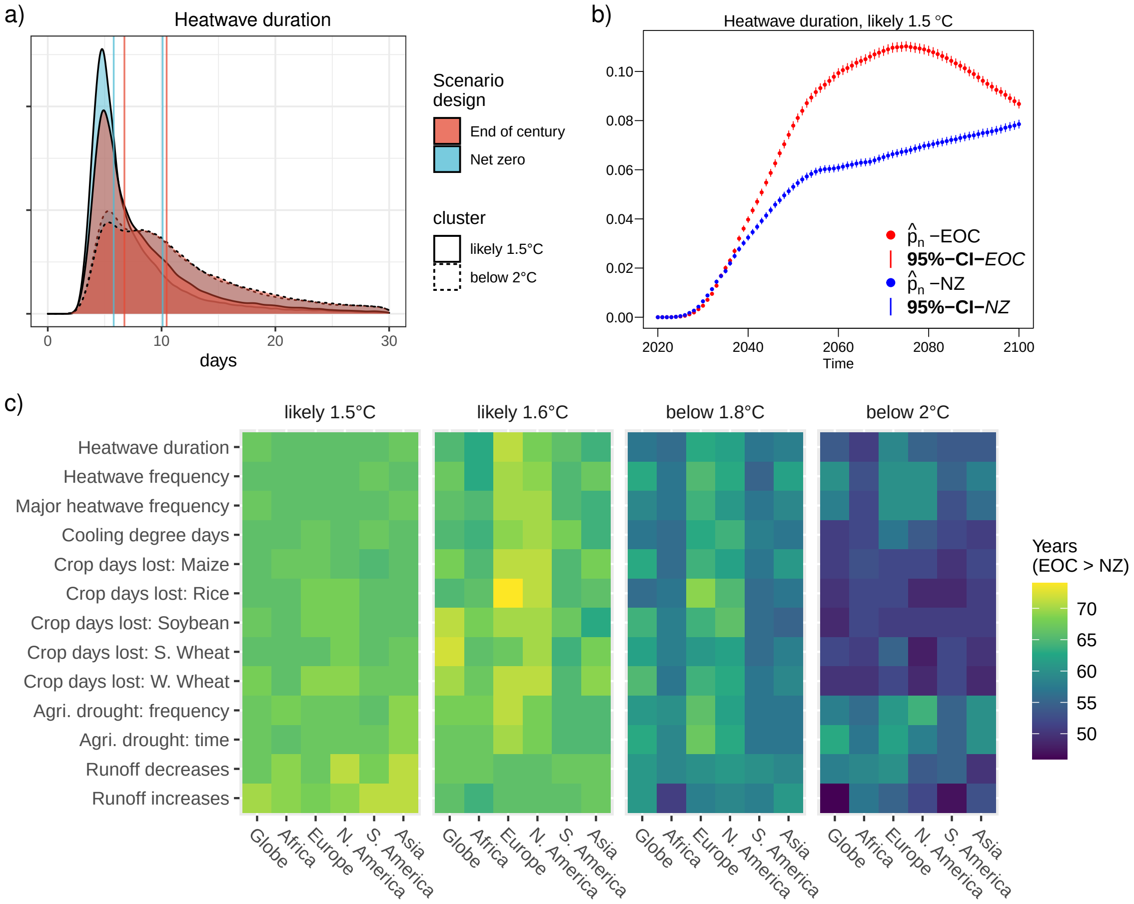

Figure 2: Influence of the scenario design on the impact distribution. Panel a) presents the probability density of the maximum heatwave duration over the century, expressed in days per year. The color highlights the scenario design. Linetype distinguishes the temperature clusters. The vertical line shows the median. Panel b) plots the probability of exceeding threshold over time for heatwave duration, for the likely 1.5°C cluster. The threshold is defined as heatwave duration over the century in the NZ scenario at the 95th quantile (=15 days). The segments represent the 95% confidence interval of the exceeding probability. The color highlights the scenario design. Panel c) shows the number of years where the impact tail distribution in the EOC scenario is significantly longer than the one in the NZ scenario. Impacts are displayed along the y-axis and regions are along the x-axis. The sub-panels correspond to the four temperature clusters. In all panels, the sources of uncertainty are the scenarios, the climate sensitivity, and the CMIP5 model impact response (Supplementary Figure 14).

In Figure 2 panel a), we report results for impacts related to heatwaves, which are the most critical ones in terms of sensitivity to temperature change, even at low temperatures [24, 25]. The difference between blue (NZ) and red (EOC) distributions helps to appreciate the extra burden imposed by allowing the temperature to overshoot. The implications of overshooting are most visible at low-temperature levels. Tail events, or high-consequence, low-probability events, have often been used to justify stringent action in the face of climate change [26].

For all impacts, we explore the probability of exceeding “high” values and then perform empirical tests to determine whether the exceeding probabilities differ across NZ and EOC scenarios. In our case, as we are lacking observations, the “high” value is the median of the impacts in the NZ scenario over the century. While the median might not be a high threshold for a given year, it is for some specific year and it helps understanding how the exceeding probability evolves across years. For example, Figure 2 panel b) reports the exceeding probability for heatwave duration at the global level and under the likely 1.5°C cluster. After 2040, the probability of exceeding 5.02 days of heatwave in the EOC scenario is significantly higher than in the NZ scenario. Similar analyses were conducted systematically across impact indicators and regions (Supplementary Figure 13). Figure 2 panel c) reports the number of years for which exceeding probabilities differ across impacts and regions for each temperature cluster. For several impacts and regions under the likely 1.5°C cluster, overshooting might mean 60 years of higher exceeding probability. The number of years with significant differences due to overshooting decreases when the temperature target increases, but there are some disparities across indicators (extreme heat and crop duration are the most at risk) and across regions (Africa is the most at risk with South America, while Europe and North America are less at risk).

Finally, we project sea-level rise from the temperature projections to look at the potential benefits of NZ scenarios on impacts based on cumulative warming. Over the period 2020–2200, the global mean sea-level rise increase due to temperature overshooting alone is 0.2–3.5cm at likely 1.5°C, while the increase under the NZ scenario for the same temperature cluster is 72cm (53–107cm) (Supplementary Figure 8 and 9). Thus, temporary temperature exceedance in Paris compliant scenarios doesn’t have a significant impact on the sea level rise, given the uncertainties surrounding it.

ECONOMIC IMPACTS

An increasingly rich literature explores the long-term implications of climate change on the macroeconomy [27, 28, 29]. The estimates from this literature vary widely depending on the methods used and the underlying assumptions. There are obvious limits in any exercise aiming at monetization of climate damage, and for this reason, the economic assessment should only serve as a way to complement the physical impact analysis. However, detailed physical impact assessment is limited to selected channels and misses additional repercussions rippling through the economy, e.g., from interactions, feedbacks, and exacerbations through repeated events. Therefore, it is critical to use macroeconomic estimates capturing general equilibrium effects and using sectorial damage functions. The existing macroeconomic damage estimates differ primarily on the extent to which economic damages persist, and whether climate shocks are assumed to affect the growth rate or the level of the economy [30, 28]. To represent this diversity, we use a set of damage functions that encompass both approaches, based on recent literature.

First, we rely on empirical estimates on the relation between temperature variations and GDP growth [31]. For this, we downscale the global mean temperature change to the country-level and apply the warming effect to country-level GDP projections. In this case, climate change impacts are persistent over time and observed additional adaptation is accounted [31]. Secondly, we apply a quadratic damage function, calibrated on the most recent estimates of global impacts from climate change [32], that reduces the GDP level, with non-persistent damages. Finally, we consider another quadratic damage function, reproducing the estimates computed by a general equilibrium model including regional and sectoral damage functions [33]. The three damage functions include no or few accountings of nonmarket damages and probably underestimate the total economic impact.

Figure 3 reports the climate economic benefits, or avoided damage, of the NZ scenario over the EOC ,i.e., by limiting the temperature overshoot for the four temperature clusters and the three alternative damage functions. The median climate economic benefits accrue over time and are higher for more stringent temperature targets, since the avoided overshoot is larger in these cases. The growth versus level damage functions yields qualitatively and quantitatively different results. For growth-based estimates, the avoided impacts are larger and increase in absolute terms over time, as a result of the persistence of the benefit of lower transient temperatures. For level-based functions, the climate benefits of reduced overshoot are mostly transient and vanish by the end of the century as temperatures converge.

From an economic point of view, comparing NZ and EOC scenarios is not trivial, as it

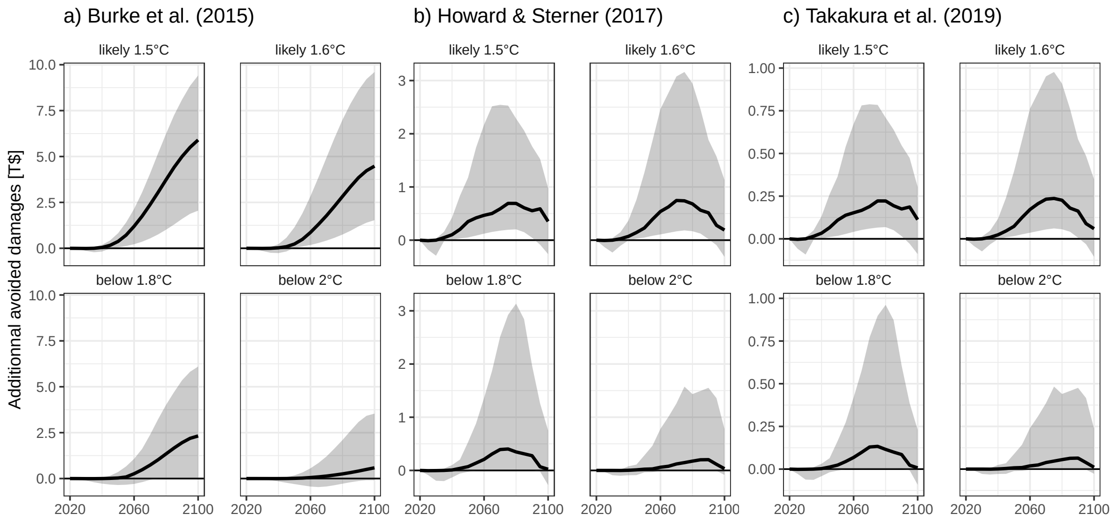

Figure 3: Global macroeconomic benefits of reduced overshoot, from the ‘end of century’ to ‘net zero’ scenario, overtime for two damage functions and across temperature clusters, expressed in USD2018 (T$=$10^{12}$$). The thick line presents the median value of the distribution. The gray ribbon shows the 5–95% distribution range. In all panels, the sources of uncertainty are the scenarios and the climate sensitivity. Panel a) includes, in addition, the CMIP5 model temperature downscaling pattern (Supplementary Figure 14).

implies comparing different intertemporal mitigation profiles as well as the avoided impacts by overshooting. The flexibility to smooth the mitigation effort across time implied by EOC scenarios reduces short-term cost of otherwise more rapid decarbonization, but it concurrently increases the risks. We compare the mitigation cost differences and climate benefits in Figure 4. The cost-benefit tradeoff in favour of limiting temperature overshoot evolves over time — for those scenarios for which the overshoot is significant, at likely 1.5°C. The timing and magnitude of net benefits are driven by the type of damage function. In all cases, scenarios with limited overshoot yield benefits after 2050 both in terms of reduced climate impact and lowered mitigation costs (Supplementary Figures 10 and 12). The net present value of the stream of benefits and costs for the different scenarios (Supplementary Figure 30) shows larger net present benefits than costs for two of the three damage functions, for all temperature clusters (although this difference is not always statistically distinguishable from zero). In the case of the impact model in [33], the net present value is negative for all temperature clusters, but this result also cannot be statistically distinguished from zero. The net present value of the difference between the two scenario designs is reported in Supplementary Figure 29: only for the two lowest temperature clusters and for the impact model based on [31] the no overshooting policy design passes the net present value test.

For all other cases, the two policy designs cannot be discriminated against on the basis of this test.

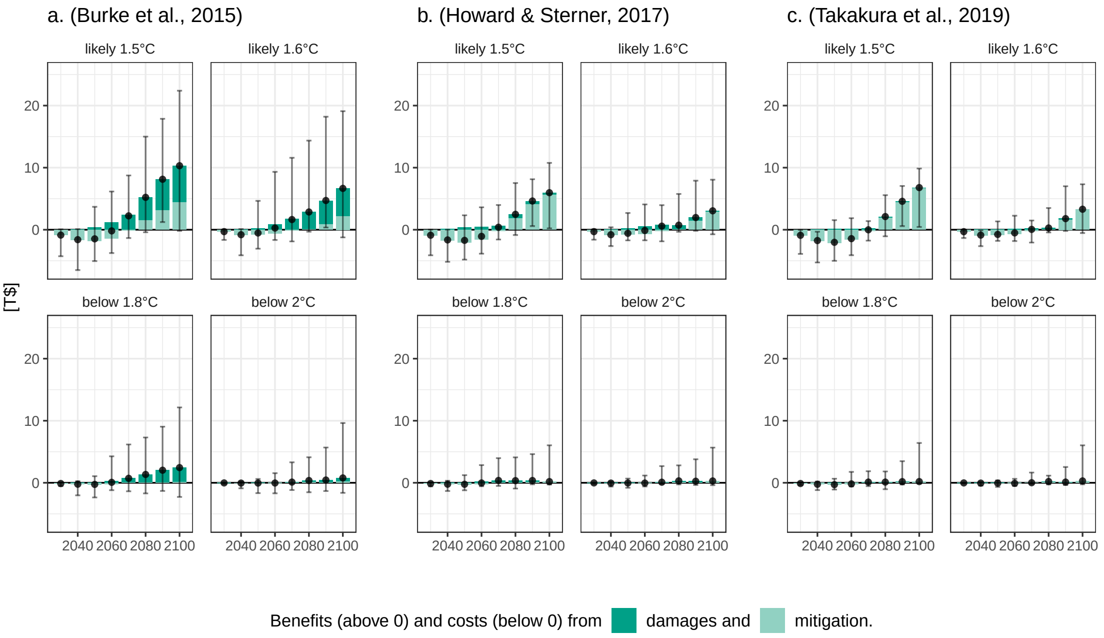

Figure 4: Global benefits and mitigation costs of reduced overshoot, differences between ‘end of century’ and ‘net zero’ scenario, over time, across damage functions and temperature clusters, expressed in USD2018 ($\text{T\$}=10^{12}\text{\$}$). The stacked bars show the median of the distribution over IAMs scenario and CMIP5 models. The darker green bars show the median of the additional avoided damages as in Figure 3. The lighter green bars show the median of the reduction in mitigation costs. The errors bars show the 90% confidence range across IAM model results and CMIP5 models.

DISCUSSION

The analysis presented here has explored the physical and macro-economic impacts associated with mitigation pathways with different levels of temperature overshoot.

This work provides a novel bridge between the detailed process assessment of mitigation pathways, which typically explores the costs and risks associated with climate transition, and the climate impact community, which investigates the costs and risks of climate change.

The results confirm the centrality of intertemporal and risk preferences when assessing alternative mitigation strategies. Limiting temperature overshoot by anticipating mitigation efforts leads to a stream of climate change benefits, cuts the right tail of the distribution of different impact indicators, and eventually lowers mitigation costs. All these benefits accrue during the second half of the century. Therefore, the choice of the discount rate, as well as preferences over these extreme risks, determine whether overshooting can be considered as a viable option or not.

Economic assessments of avoided climate damage alone might overlook some of the physical impacts we might face in the future, reinforcing the need to complement the economic analyses with work on physical impact estimates.

Finally, exploring the different economic impact models and assumptions (e.g., damage persistence), we found that early mitigation costs are never significantly larger than the climate benefits of not overshooting.

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METHODS

Model scenarios. For this analysis, we use the results from nine integrated assessment models, AIM/CGE, COFFEE, GEM-E3, IMAGE, MESSAGEix-GLOBIOM, POLES, REMIND-MAgPIE, TIAM-ECN and WITCH. They generated emission trajectories consistent with a large number of carbon budgets (i.e., cumulative CO_2 emissions) using two families of scenarios: 'end of the century', which allowed for temperature overshoot, and 'Net zero', which did not (See the modelling protocol in Supplementary information). Models are not constrained to the level of temperature over the century and it can overshoot the temperature reached in 2100. We select the scenarios entailing maximum warming of 2°C in 2100. The protocol included a vetting exercise to ensure that model results were sufficiently close to historical data up to 2020. In particular, attention was devoted to hamonising of the energy system (i.e., installed power plant capacities, investments, and activities), greenhouse gases and aerosol emissions, the land-use sector, and economic growth. Models also implemented policies in force, such as carbon taxes, constraints on fossil fuels, renewables standards, etc. The protocol did not require capturing the effect of the COVID-19 pandemic. A comprehensive description of the modelling process and the model scenarios is provided by Riahi et al. (forthcoming).

Uncertainty analysis. Various sources of uncertainty are considered in the analysis: the emission trajectories to reach a carbon budget, the global mean temperature through the climate sensitivity, and the CMIP5 model patterns in terms of geophysical impact response and country-level temperature. Supplementary Figure 14 lists these sources of uncertainty and provides a representation of the uncertainty propagation.

Global mean temperature The emissions pathways from all model scenarios were given as an input to the climate emulator MAGICC[20, 21], to compute global mean temperature projections until 2100 (median estimate, 5%, 10%, 25%, 75%, 90% and 95% quantiles). MAGICC is calibrated to represent the climate sensitivity uncertainty assessed in the Intergovernmental Panel on Climate Change special report on the impacts of global warming of 1.5°C. The model scenarios are clustered based on the median of the 2100 global mean temperature (See Supplementary Table 1).

Temperature downscaling. Country-level annual population-weighted temperature projections are obtained from the median estimates of the global mean temperature using a linear response function calibrated for each CMIP5 model. We gathered monthly mean temperatures from historical data records and the RCP runs of 20 CMIP5 models with all available ensemble members (ACCESS1-0 (3 runs), BNU-ESM (4), CCSM4 (29), CMCC-CMS (3), GFDL-CM3 (8), GFDL-ESM2G (5), GFDL-ESM2M (5), GISS-E2-H (15), GISS-E2-H-CC (3), GISS-E2-R (15), GISS-E2-R-CC (3), HadGEM2-CC (7), HadGEM2-ES (19), IPSL-CM5A-LR (19), IPSL-CM5A-MR (7), IPSL-CM5B-LR (2), MPI-ESM-LR (12), MPI-ESM-MR (8), NorESM1-M (7), inmcm4 (3)). We computed the gridded annual mean temperature and corrected the bias using a 1980–2016 observational baseline from the University of Delaware air temperature UDEL v5.01 dataset [34] (See Supplementary Figure 21). Unbiased gridded annual mean temperatures were aggregated at the country level with population density weights based on the gridded population of the world in 2010 (GPW, v4) [35]. Results are comparable with the original baselines from [31] (see sensitivity analyses in Supplementary Figures 26 and 27). Finally, to obtain an estimate of the annual local temperature, from the global mean temperature increase relative to 2005, we performed a linear regression over the period 1900–2100, for each CMIP5 model for each year and each country individually.

Physical impacts. For each model scenario, we compute 15 impact indicators (see the list and definition in Supplementary Table 5) every year for 6 regions (global and 5 macro regions: Africa, Europe, North America, South America, Asia). The physical impacts are computed from a look-up table of global and regional impacts of climate change at different levels of global temperature increase, differentiated for 23 CMIP5 climate models [24]. To apply those functions, the global mean temperature is shifted down by 0.014°C, so that the average temperature increase relative to pre-industrial is equal to 0.61°C over the period 1981–2010, to replicate [24]. The impacts of intermediate temperatures are interpolated linearly. Linear interpolation provides better consistency across the impact functions (Supplementary Figure 17). We also evaluated the spline interpolation, which, however, results in some values out of credible bounds (e.g., negative values), for a few combinations of temperature and impact (Supplementary Figure 18). The difference between the two methods of interpolation is much smaller than the impact values (Supplementary Figures 19 and 20). The impact distribution results from the combination of the model scenarios, the global mean temperature distribution, and the CMIP5-specific impact function. Using these distributions, yearly values and maximum over the century comparisons are performed for the impact analyses. Note that our study focuses on the transient response of climate and impacts, which cannot be fully captured by simple pattern scaling techniques [36]. However, this is the best available method that allows us to capture the uncertainties stemming from consistent impact estimates spanning 5 levels of warming and 23 climate patterns [24].

Economic impacts using the growth-based damage function. The economic impacts are computed at the country level. We follow the procedure as described in [31] and implemented in [37, 38]. GDP per capita is $G_{i,t} = G_{i,t-1}(1 + \eta_{i,t} + \delta(T_{i,t}))$, where η_i is the growth rate coming from the SSP reference projection in which no climate change occurs [39] and $\delta(T_{i,t})$ is a response function of the temperature increase at year t. The projected warming effect is adjusted by the baseline temperature in 2000–2010. The analysis is using the main damage function specification called BHM SR from [31]

Economic impacts from the level-based damage functions. These economic impacts are only computed at the global level. They are computed as the global output loss relative to the SSP reference projection without climate change (GDP_gross). The GDP loss is $\Delta GDP\_cc = GDP\_gross \times (\alpha gmt_t + \beta gmt_t^2 + \gamma)$, where gmt is the global mean temperature increase from preindustrial levels and α and β are the two parameters of the quadratic damage function. For the Howard & Sterner function [32], we use the preferred model specification of non-catastrophic damage, which is increased by 25% to account for the omitted damage in the empirical estimates ($\alpha = \gamma = 0$, $\beta = -0.7438$). For the Takakura *et al.* function [33], we derived and used the SSP2 function parameters ($\alpha = 0.07625$, $\beta = 0.21465$, $\gamma = -0.11746$).

Tail heaviness analysis. We perform a statistical analysis to test whether the EOC distribution has a longer tail than the NZ distribution. The assumptions and the methodology of the tail heaviness analysis are provided in detail in Supplementary Methods.

Sea-level rise. We compute the global mean sea-level rise using the physical model provided by [40], using their calibration. For this specific impact, we extended the time horizon of the computations until 2200 with a constant global mean temperature beyond 2100. Sea levels keep rising through the twenty-second century. We compute the sea-level rise for 3 quantiles (5%, 50%, and 95%).

Avoided damages and mitigation costs. The additional damages associated with the overshooting of the temperature target are obtained by comparing GDP in the EOC and in the NZ scenario, when impacts from climate change are accounted for in both scenarios, see Supplementary Figure 11. Depending on the model characteristics, the proxy for mitigation costs used is either GDP losses or the additional energy system cost calculated with respect to a reference scenario where only policies in force are considered, the 'NPi2100' in the modelling protocol (see Supplementary Methods). To ensure consistency across impact and mitigation costs, all economic values are expressed in USD2018 using the reference GDP projection.

DATA AVAILABILITY

To access and visualize the scenario data, please go to https://data.ene.iiasa.ac.at/engage/#/login, and log in using the following credentials:

- Username: EOPreview
- Password: EOPpassword

For tutorials on how to use the scenario explorer, please visit https://software.ene.iiasa.ac.at/ixmp-server/tutorials.html.

CODE AVAILABILITY

The code of the data analysis and figures will be available in a Github repository. For review, a zip file is provided with the source code.

AUTHOR CONTRIBUTIONS

L.D., and V.B. designed the research with contributions from K.R.; L.D., V.B, L.A.R, C.B., F.D.L., J.D., J.E., F.F., S.Fr., K.F., O.F., S.Fu., M.H., V.K., L.P.N., K.O., L.P., F.P., R.S., J.T., K.R., P.R.R.R, D.v.V., M.T., Z.V., M.W., K.I.v.d.W, B.Z. and B.v.d.Z produced the IAM scenario results; L.D.

postprocessed the data and performed the data analysis; S.P. performed the statistical analysis; L.D., V.B. and M.T. wrote the paper draft; L.D., V.B., J.E, M.T. and L.A.R. finalized the manuscript with contributions from F.P, R.S, J.T., and M.W.; All authors reviewed the manuscript.

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