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Overconfidence in climate overshoot

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Abstract

Global emission reduction efforts continue to be insufficient to meet the temperature goal of the Paris Agreement[1]. This makes the systematic exploration of so-called overshoot pathways that temporarily exceed a targeted global warming limit before drawing temperatures back down to safer levels a priority for science and policy[2,3,4,5]. Here we show that global and regional climate change and associated risks after an overshoot are different from a world that avoids it. We find that achieving declining global temperatures can limit long-term climate risks compared with a mere stabilisation of global warming, including for sea-level rise and cryosphere changes. However, the possibility that global warming could be reversed many decades into the future might be of limited relevance for adaptation planning today. Temperature reversal could be undercut by strong Earth-system feedbacks resulting in high near-term and continuous long-term warming[6,7]. To hedge and protect against high-risk outcomes, we identify the geophysical need for a preventive carbon dioxide removal capacity of several hundred gigatonnes. Yet, technical, economic and sustainability considerations may limit the realisation of carbon dioxide removal deployment at such scales[8,9]. Therefore, we cannot be confident that temperature decline after overshoot is achievable within the timescales expected today. Only rapid near-term emission reductions are effective in reducing climate risks.

STS51I-44-0052 Hurricane Elena, Gulf of Mexico September 1985 Image Science and Analysis Laboratory, NASA-Johnson Space Center., Public domain, via Wikimedia Commons https://commons.wikimedia.org/wiki/File:Hurricane_Elena.jpg

Main

The possibility of surpassing and subsequently returning below dangerous levels of global warming has been a topic of discussion for decades[10] with large-scale carbon dioxide removal (CDR) identified early on as playing an important part

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in this temperature reversal[11,12]. Since the adoption of the Paris Agreement in 2015 the issue has risen to further prominence.

The temperature goal of the Paris Agreement allows for some ambiguity in its interpretation but establishes 1.5 °C of global warming as the long-term upper limit for global temperature increase[13,14]. This means that if 1.5 °C is temporarily exceeded (subsequently referred to as overshoot), a reversal of warming below it is part of meeting the long-term ambition of the Paris Agreement[13]. The Paris Agreement text does not indicate that temperature must stabilise but instead establishes upper limits below which temperatures must peak and may then decline. This understanding is further strengthened when considering other elements of the Paris Agreement. Achieving global net-zero greenhouse gas (GHG) emissions, as implied by Article 4.1 of the Agreement, is expected to lead to declining temperatures[6,13].

Global GHG emission pathways have a central role in informing the development of policy benchmarks in line with the Paris Agreement and are a core part of climate change assessments by the Intergovernmental Panel on Climate Change (IPCC)[2,15]. These assessments categorise pathways principally based on their peak temperature outcome[2,15]. Because a peak and gradual reversal of global warming turns out to be a fundamental feature of Paris-compatible pathways[16], we propose to henceforth categorise pathways in terms of their peak and decline characteristics (Table 1).

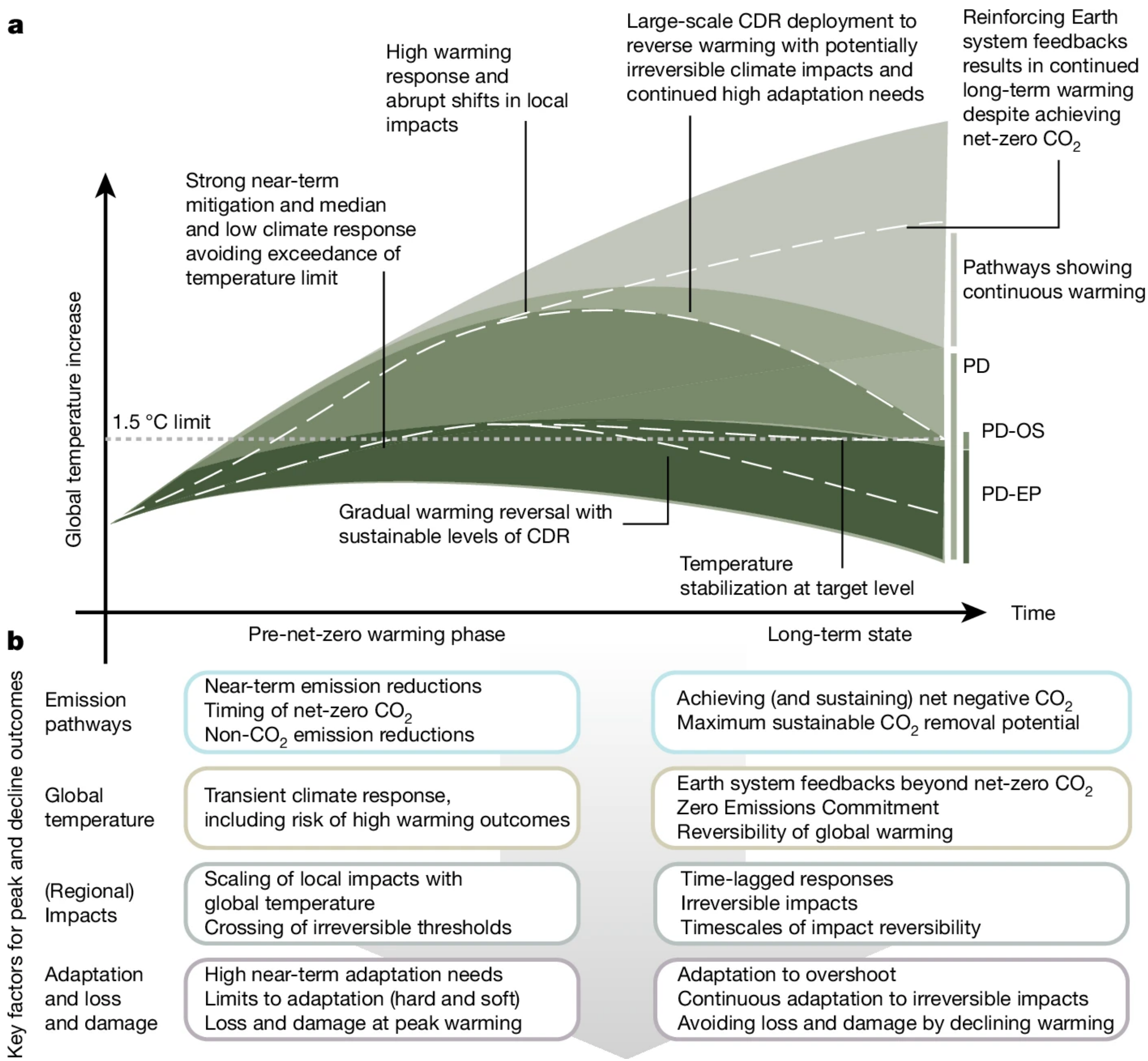
Table 1 Conceptual categories of peak and decline emission pathways

Pathway category	Temperature characteristics	Emission characteristics (best estimates)
PD: peak and decline pathways	Pathways that aim to achieve temperature peak and a sustained long-term temperature decline of at least several decades in duration	Emission reductions in all GHGs towards achieving net-zero CO_2 emissions, and net-negative CO_2 emissions thereafter
PD-OS: overshoot pathways	PD pathways establish a target warming level to be achieved at some point in the far future but allow it to be exceeded with high likelihood over the near term in the conviction that warming can be reversed again at a later stage. These pathways typically envision temperature to be kept at the target level upon returning after overshoot	As peak and decline pathways, but rate of emission reduction, carbon budget, timing of net-zero CO_2 and amount of net-negative emissions depend on the characteristics of the envisaged overshoot including considerations of climate response uncertainties
PD-EP: enhanced protection pathways	PD pathways that aim to keep peak global warming as low as possible and gradually reverse warming thereafter to reduce climate risks. Given the timescales involved for warming reversal, these pathways typically do not reach an ultimate lower target temperature level within the scenario time frame considered	Stringent and rapid GHG emission reduction as much and as early as possible, achieving net-zero CO_2 emissions as soon as possible while minimizing residual emissions, and achieving sustainable levels of net-negative CO_2 emissions thereafter in order to potentially reach net-zero or net-negative GHGs

See Extended Data Table 1 for a comparison with categories proposed in the scientific literature.

Peak and decline pathways are differentiated by the stringency of emission reduction efforts in the near term and up to achieving net-zero CO2 emissions, and the assumed net-negative CO2 emissions in the long term[16]. The former determines the maximum cumulative CO2 emissions of a pathway and thereby approximately the magnitude and time of peak warming for median climate outcomes[6,16] (Fig. 1a). The latter determines the pace of potential temperature reversal[16]. Both aspects are further dependent on the temporal evolution of non-CO2 emissions.

Fig. 1: Illustrative climate outcomes under different conceptual categories of peak and decline pathways



a, Different classes of pathways with a peak and decline of global mean temperature (see also Table 1). Stylised individual pathways (dashed lines) are highlighted to illustrate the specific impact, adaptation and CDR dimensions associated with the different categories. b, An overview of key factors affecting pathway and potential peak and decline outcomes along the impact chain for the warming phase until net-zero CO2 and for the long term beyond net zero. PD, peak and decline pathways; PD-EP, enhanced protection pathways; PD-OS, overshoot pathways.

Several categories of peak and decline pathways have been proposed in the scientific literature[2,17] (Extended Data Table 1). A prominent example is the latest contribution of Working Group III (WGIII) to the Sixth Assessment Report (AR6) of the IPCC, which includes two pathway categories explicitly referring to the term overshoot (Extended Data Table 1).

Temperature overshoot pathways are a sub-category in the peak and decline categorisation we present here, with the distinguishing characteristic of these pathways being that their intended maximum temperature limit (1.5 °C) is temporarily exceeded.

Although defined in terms of probabilities of temporarily exceeding 1.5 °C, the IPCC AR6 pathway categories frame a possible overshoot concretely: limited overshoot (C1) refers to exceeding the specified limit by up to about 0.1 °C, whereas high overshoot (C2) refers to exceeding it by more than 0.1 °C and up to 0.3 °C (refs. 2,15) (Extended Data Table 1). This seems to suggest that temperature overshoots in these pathway categories are constrained to a few tenths of a degree with high certainty. But this is not the case. These overshoot numbers refer only to median outcomes and substantially higher warming cannot be ruled out as shown below. A strong focus on median outcomes might lead to overconfidence in the risks under overshoot pathways.

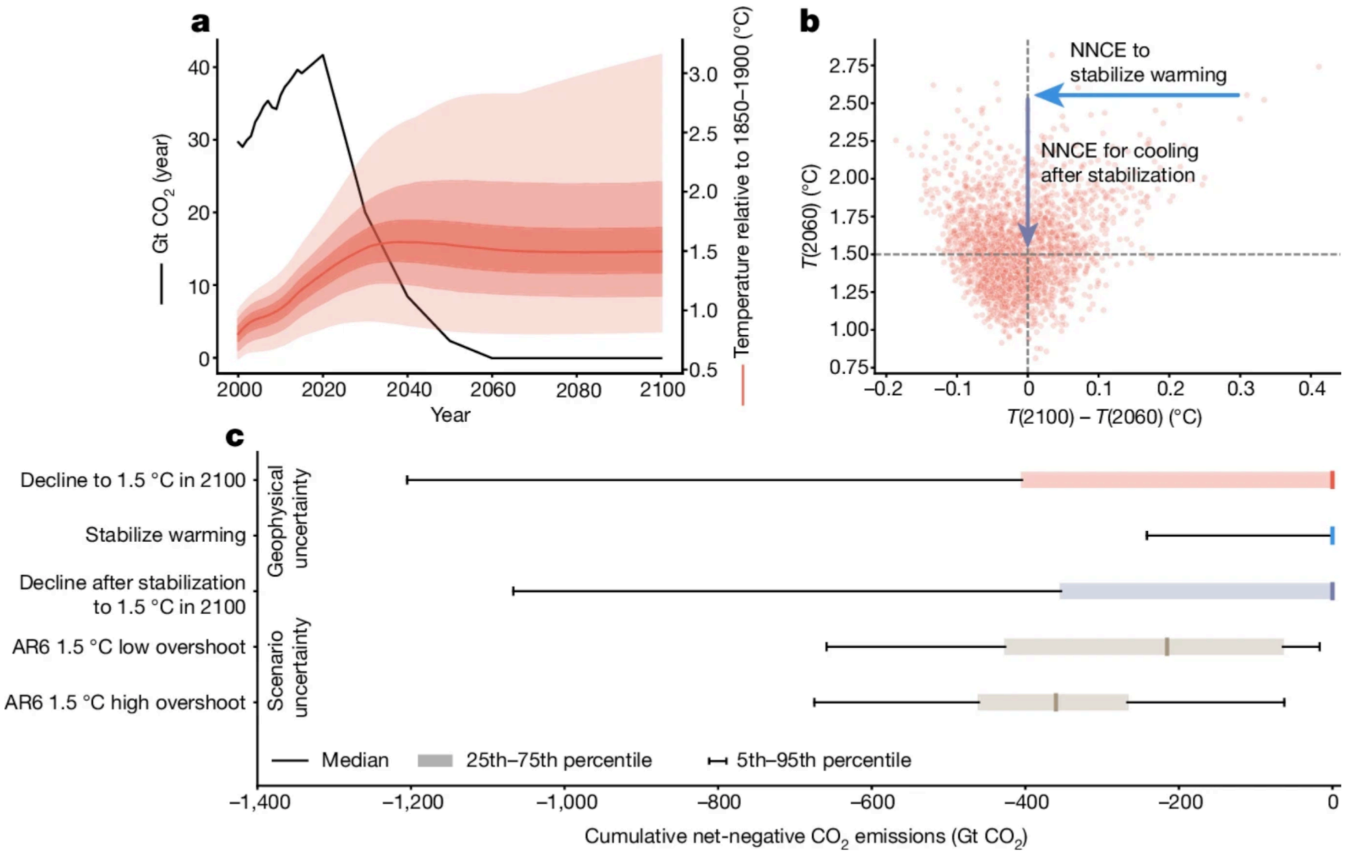
In the following, we outline the dimensions of overconfidence in overshoot from emission pathways to adaptation implications (Fig. 1b). We start by exploring the uncertainties in global temperature outcomes and their implications for the required net-negative CO2 emissions to achieve the intended reversal of warming. Based on these insights, we then discuss the consequences for mitigation strategies considering the feasibility and sustainability constraints of deploying gigatonne-scale CDR. Yet, even if global temperatures were in decline, it is an open question if and how this translates into a reversal of climatic impact drivers6 and subsequent impacts and risks. We provide insights for both long-term regional climate changes and irreversible risks such as sea-level rise. Finally, we discuss what considering or experiencing temperature overshoot implies for climate change adaptation. Based on this comprehensive perspective, we contend that it is essential to redirect the overshoot discussion towards prioritising the reduction of climate risks in both the near term and long term and that overconfidence in the controllability and desirability of climate overshoot should be avoided.

Uncertain climate response and reversal

Peak warming depends on the cumulative CO2 emissions until global net-zero CO2 and the stringency of reductions in non-CO2 GHGs. Achieving net-negative CO2 emissions (NNCE) after peak warming can result in a long-term decline in warming6. Most estimates of NNCE consistent with a long-term reversal of warming in peak and decline pathways have focused on median warming outcomes[15]. However, to comprehensively assess overshoot risks and NNCE requirements for warming reversal, uncertainties in the climate response must also be considered. These include uncertainties during the warming phase (for example, high warming outcomes due to amplifying warming feedbacks)[18] and in the long-term state (potential for continued warming post-net-zero CO2 and the response of the climate system to NNCE)[7].

We explore NNCE requirements for an illustrative pathway with the following characteristics (Fig. 2a): (1) it achieves net-zero CO2 around mid-century; (2) limits median peak warming close to 1.5 °C above pre-industrial levels; and (3) requires no NNCE to do so (for the median warming outcome). We use 2,237 ensemble members of the simple carbon cycle and climate model Finite Amplitude Impulse Response (FaIR) v.1.6.2 to estimate the range of physically plausible warming outcomes for this pathway, consistent with the uncertainty assessment of IPCC AR6 (Fig. 2a and Methods). Two groups of plausible futures stand out. The first includes relatively low-risk futures in which warming peaks below 1.5 °C at the time of, or before, net-zero CO2 is achieved (Fig. 2b, bottom left); in these cases, no NNCEs are required. We also identify relatively high-risk futures in which warming exceeds 1.5 °C at the time of net-zero CO2 and continues beyond (Fig. 2b, top right).

Fig. 2: Estimating cumulative NNCE needs when accounting for climate response uncertainty



a, Net CO2 emissions for the PROVIDE REN_NZCO2 pathway (black line) and the warming outcome uncertainty (derived using FaIR v.1.6.2; Methods). The median warming outcome is the red solid line, with each subsequent plume of varying transparency representing the 25th–75th percentile, 5th–95th percentile, and minimum to maximum ranges, respectively. b, Warming at the time of net-zero CO2 (2060) compared with the change in temperature between net-zero CO2 and 2100. c, Estimated NNCE to return warming for each peak warming outcome shown in b to 1.5 °C in 2100 (Methods). These estimates reflect NNCE implied by geophysical uncertainty of the warming outcome based on the REN_NZCO2 pathway (from top to bottom: NNCE to achieve 1.5 °C in 2100, NNCE to stabilize warming, NNCE for decline after stabilization). For comparison, the scenario uncertainty across the C1 and C2 categories from the IPCC AR6 WGIII report is shown (bottom rows). Note that this scenario uncertainty considers only median estimates of the geophysical response to emissions.

For each respective FaIR run, we estimate the NNCE requirement to return warming to 1.5 °C in 2100 (Methods). We find that a need for large NNCE deployment cannot be ruled out because of the heavy-tailed climate response uncertainty distribution[18] (Fig. 2c). The scale of this deployment (interquartile range: 0 to −400 Gt CO2 cumulatively until 2100, or 0 to −10 Gt CO2 yr−1 after 2060) is of the same order of magnitude as the spread of deployed NNCE across the scenarios assessed in IPCC AR6 WGIII (Fig. 2c). Although we find that NNCE requirements resulting from a higher-than-average peak warming due to a strong transient climate response dominate, cumulative NNCE until 2100 of up to 200 Gt CO2 (or 5 Gt CO2 yr−1, upper 95% percentile, Fig. 2c) could be required to hedge against further warming past net zero[19]. Our results show that a narrow focus on scenario uncertainty and median warming alone is insufficient to assess potential CDR deployment requirements even for merely achieving a stable global mean temperature in the twenty-first century.

CDR requirements here refer to additional carbon removal due to anthropogenic activity in line with the conventions and definitions of the models underlying our assessment. It is important to note that parties to the United Nations Framework Convention on Climate Change use a different definition for defining land-based carbon fluxes, which results in an approximately 4–7 Gt CO_2 yr^{-1} difference between national GHG inventories and scientific models that needs to be considered when translating these insights into policy advice[20].

Our simple illustrative approach has several limitations that would benefit from further exploration, including with dedicated state-of-the-art Earth system models (ESMs)[21]. Particularly relevant questions arise around issues of asymmetry in the Earth system response to either positive or negative CO_2 emissions[22,23] (Methods). Owing to the lack of appropriate training data, the response of simple climate models to NNCE is not well constrained. Moreover, the ESMs used to calibrate simple climate models may miss nonlinear responses in the climate system, including abrupt destabilisation of natural carbon sinks[24] (for example, permafrost CO_2 and CH_4 release, peat carbon loss from climate change and degradation or conversion of peatland, extreme fires and drought mortality of forests). We explore permafrost and peatland responses to overshoot below (Fig. 4).

Relying on CDR

Achieving NNCE requires the deployment of CDR that exceeds residual emissions in hard-to-abate sectors. Pathways assessed by the IPCC WGIII deploy CDR in different ways and to different extents[3]. Scale-up of CDR is most rapid in pathways with the lowest peak warming (low or no overshoot 1.5 °C pathways, C1, Extended Data Fig. 3). Across the ensemble of emission pathways, CDR levels by the end of the century are generally higher in high overshoot (C2) pathways, but the full (5–95%) range is similar to the C1 pathway range. Pathways that keep warming below 2 °C but do not limit warming to 1.5 °C in 2100 (C3) see a substantial CDR ramp-up in the second half of the twenty-first century reaching levels comparable to C1 pathways by 2080 (Extended Data Fig. 3). The total CDR amount deployed in pathways until 2100 depends predominantly on the effective reduction of residual positive CO_2 emissions and mitigation of non-CO_2 GHGs[17].

In the previous section, we showed how the extent of CDR required to achieve stable temperatures in the twenty-first century might be strongly underappreciated. Here we highlight that there are multiple areas in which current pathways might be overconfident in their assumed use of CDR (Extended Data) Table 2). Upscaling of CDR may be constrained considerably[9] by factors such as lack of policy support and business models, technological uncertainty and public opposition (for example, perceived risks of delaying mitigation[25]). Even if technical removal potentials prove to be large, sustainability and equity considerations would limit acceptable deployment scales[8,9]. Insufficient technological readiness may be an important bottleneck, as current removal rates from CDR methods other than afforestation and reforestation are minuscule (about 2 Mt CO_2 yr^{-1})[26] and would require a more than 1,000-fold increase by 2050 (ref. [27]). Beyond technological concerns, an array of unintended or uncertain permanence issues and system feedback (Extended Data Table 2) might reduce or offset the contribution of CDR to mitigation[26,28].

Squaring these feasibility concerns with the potential need for gigatonne-scale CDR deployment to address climate uncertainty (Fig. 2) is challenging. We argue that deployment pathways that address this challenge should be guided by the principle of harm prevention[29] under enhanced protection pathways (Table 1). This approach requires two complementary actions: (1) reduce gross CO_2 emissions rapidly to reduce the total CDR requirements and (2) address feasibility concerns to facilitate the deployment of CDR beyond the achievement of net-zero CO_2 to hedge against potentially high warming outcomes.

Regional climate change reversibility

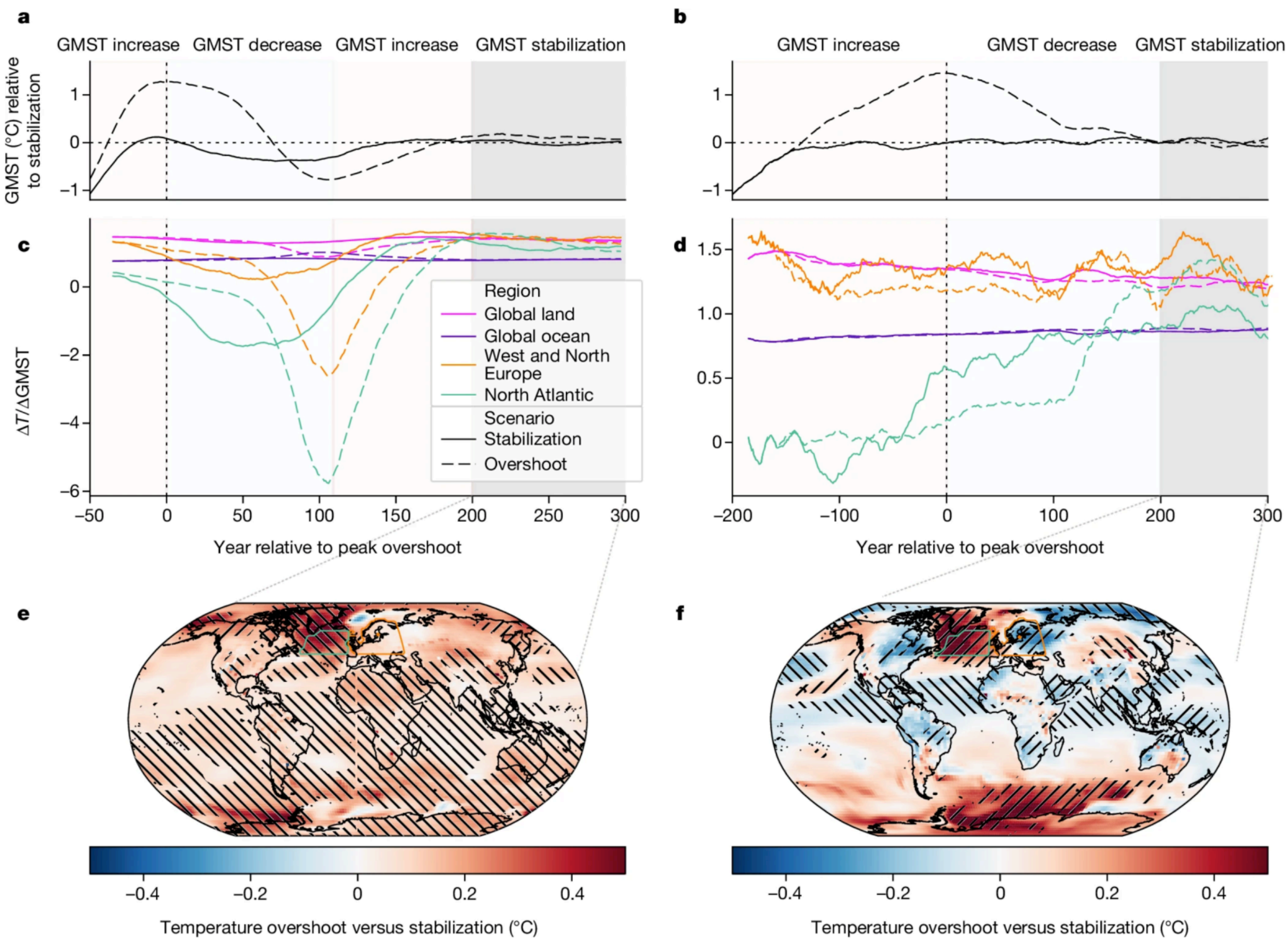
The proposition of overshoot pathways is that failure to keep warming below a desired temperature limit is acceptable provided global warming is returned below a certain level, that is, 1.5 °C, in the long run. Even if global temperatures are reversed, this is not a given for regional climatic changes. Therefore, understanding the implications of a global temperature overshoot for regional changes is important. Even if global warming is stabilised at a certain level without overshoot, the climate system continues to change as its components keep adjusting and equilibrate[30], with implications for regional climate patterns. The question then becomes what additional imprints on regional climate may originate directly from the overshoot.

Here we explore a unique set of dedicated modelling simulations comparing overshoot and long-term stabilisation in two ESMs and find substantial differences in regional climate impact drivers on multi-century timescales (Fig. 3 and (Extended Data Fig. 5). We use the results of the NorESM2-LM model following an emission-driven protocol conceptualising an overshoot of the carbon budget, as well as GFDL-ESM2M simulations following the Adaptive Emission Reduction Approach (AERA) to match a predefined global mean temperature trajectory (Methods and (Extended Data Fig. 4). Despite these differences in the modelling protocols, we find some features within the overshoot versus stabilisation regional patterns emerging in both modelling simulations, in particular in high northern latitudes as a result of a time-lagged response of the Atlantic Meridional Overturning Circulation (AMOC)[4,31].

In the NorESM2-LM model, we observe a reversal of regional temperature scaling with Global mean surface air temperature (GMST) change for the North Atlantic and adjacent European land regions under overshoot (Fig. 3c), leading to a temporary regional cooling and subsequent regional recovery and warming[32] (Fig. 3e). The pattern in which the North Atlantic cools regionally despite planetary warming is also present in the stabilisation scenario but is less pronounced. In the GFDL-ESM2M model, the imprint of overshoot and stabilisation on regional climate is less pronounced. But temperature changes associated with a time-lagged AMOC recovery about 100 years after peak warming and to higher levels than in the stabilisation scenario are also evident (Fig. 3d,f). We note that these simulations do not include increased Greenland meltwater influx that may suppress a potential AMOC recovery under overshoot[33]. Similarly pronounced features emerge for precipitation in both models, in particular, related to movements of the Inter-Tropical Convergence Zone in response to changes in the AMOC4 ((Extended Data Fig. 5). Multi-model transient overshoot simulations further corroborate the finding that AMOC dynamics and related changes in regional climate are a dominant feature of overshoot pathways[5,32] (Methods and (Extended Data Figs. 7 and 8). They also indicate a continuous warming of the Southern Ocean relative to the rest of the globe as a result of fast and slow response patterns, and changes in regional climate following reduced aerosol loadings (in particular in South and East Asia)[18]. Taken together, our results suggest that regional climate changes cannot be approximated well by GMST after peak warming.

We find substantial long-term imprints of overshoot on regional climate (Fig. 3c,d) that are distinct from transient changes in stabilisation scenarios (Extended Data Fig. 6). However, substantial differences in model dynamics (compare Fig. 3e,f) remain. Dedicated multi-model intercomparison experiments are required to further investigate the long-term consequences of overshoot compared with stabilisation[21]. We also note the importance of biophysical climate feedback of land-cover changes associated with large-scale land-based CDR deployment ((Extended Data Table 2) that could be explored in these experiments.

Fig. 3: Evolution of regional temperatures before and after overshoot compared with global temperature stabilisation



Results for a carbon budget overshoot protocol with the NorESM model[4] (a,c,e) and a global temperature-focused protocol (GFDL-ESM2M)[49] (b,d,f). a,b, GMST trajectories for dedicated climate stabilisation (solid) and overshoot (dashed) scenarios. c,d, Temporal evolution of scaling coefficients of annual regional temperatures with GMST for the global land and ocean areas as well as the North Atlantic Ocean (north of 45° N) and Western and Northern Europe (31-year averaged anomalies relative to 1850–1900). e,f, Regional differences in annual temperature between overshoot and stabilisation scenarios over 100 years of long-term GMST stabilisation (grey shaded area in a,b). Hatching in e,f highlights grid cells in which the difference exceeds the 95th percentile (is below the 5th percentile) of comparable period differences in piControl simulations (Methods).

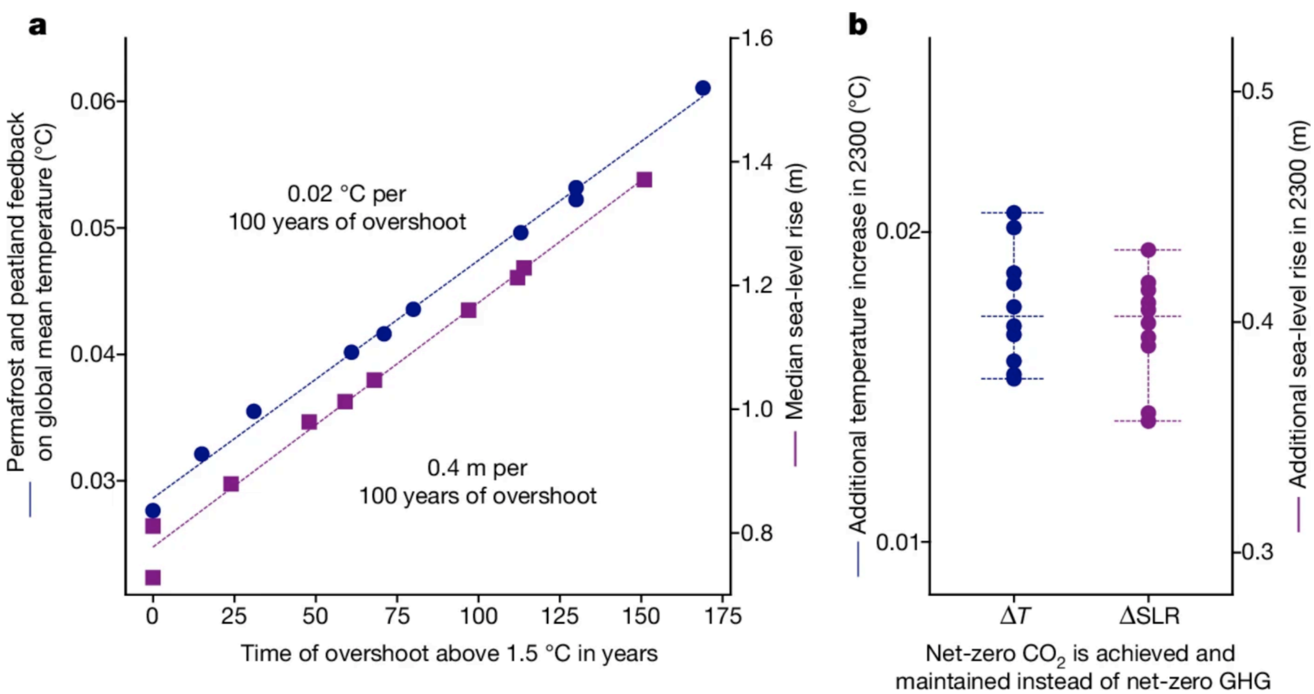
Time-lagged and irreversible impacts

For a range of climate impacts, there is no expectation of immediate reversibility after an overshoot. This includes changes in the deep ocean, marine biogeochemistry and species abundance[34], land-based biomes, carbon stocks and crop yields[35], but also biodiversity on land36. An overshoot will also increase the probability of triggering potential Earth system tipping elements[33]. Sea levels will continue to rise for centuries to millennia even if long-term temperatures decline[37].

Comprehensively assessing future climate risks under peak and decline pathways requires a focus not only on the (irreversible) consequences of a temporary overshoot but also on the benefits of long-term temperature reversal, compared with stabilisation at higher levels. Here we explore the consequences of overshoot in an ensemble of peak and decline pathways (Methods) that achieve net-zero GHGs and thereby long-term temperature decline compared with stabilisation at peak warming (by maintaining net-zero CO2).

For global sea-level rise, we find that every 100 years of overshoot above 1.5 °C leads to an additional sea-level rise commitment of around 40 cm by 2300 (central estimate) apart from a baseline of about 80 cm without overshoot (Fig. 4a). For high-risk outcomes, the 2300 sea-level rise commitment could be about three times (95th percentile) above the central estimate[37] ((Extended Data Fig. 10). Long-term temperature decline at about 0.03–0.04 °C per decade (broadly consistent with achieving net-zero GHGs) avoids about 40 cm of 2300 sea-level rise (median estimate, 95th percentile about 1.5 m) compared with stabilisation at peak warming (Fig. 4b).

Fig. 4: Long-term irreversible permafrost, peatland and sea-level rise impacts of overshoot



a, Feedback on 2300 global mean temperature increase by permafrost and peatland emissions (blue markers and left axis) and 2300 global median sea-level rise (SLR, purple markers and right axis, from ref. 37) as a function of overshoot duration. Circles (squares) mark results for temperature change (sea-level rise) for individual scenarios from ref. 37. b, Additional global mean temperature increase from warming-induced permafrost and peatland emissions and sea-level rise implied by stabilising temperatures at peak warming (achieving and maintaining net-zero CO2 emissions) compared with a long-term temperature decline resulting from achieving and maintaining net-zero GHGs. Dashed horizontal lines in b provide the ensemble median and minimum and maximum range.

A similar pattern emerges for 2300 permafrost thaw and northern peatland warming leading to increased soil carbon decomposition and CO2 and CH4 release (Fig. 4 and (Extended Data Fig. 9). The effect of permafrost and peatland emissions on 2300 temperatures increases by 0.02 °C per 100 years of overshoot (best estimate, upper 95% percentile 0.04 °C, (Extended Data Fig. 10), whereas achieving long-term declining temperatures would reduce the additional 2300 temperature increase by a similar order of magnitude. We warn that the diagnosed linear relationship between overshoot length and impact outcome may depend on the set of pathways that it was derived from. The underlying pathways assume overshoots starting from a period of delay in climate action followed by a steady reduction to net-zero GHG emissions implying a similar rate of long-term temperature decline in all pathways. The relationship could be different for more, or less extreme overshoot outcomes.

Socioeconomic impacts

The severity of climate risks for human systems under overshoot depends markedly on their adaptive capacity[38], as well as the potential transgression of limits to adaptation[39]. An overshoot above 1.5 °C would likely emerge during the first half of the twenty-first century, a period still characterised by comparably low adaptive capacity in large parts of the globe even under optimistic scenarios of socioeconomic development[38]. The coincidence of overshoot and low adaptive capacity can amplify climate risks. This has profound consequences for the ability to achieve climate-resilient and equitable development outcomes under overshoot, in particular, for the most vulnerable countries, communities and peoples.

Climate impacts on health, ecosystem services, livelihoods and education can leave lasting and intergenerational negative effects on the well-being of people[40] such as climate-related excess deaths linked to heat extremes during an overshoot period. Overshoots might also leave a long-term legacy in the economic performance of countries, particularly those least developed, because of the lasting impacts of climate change on economic growth[41]. Therefore, overshoot entails deeply ethical questions of how much additional climate-related loss and damage people, especially those in low-income countries, would need to endure.

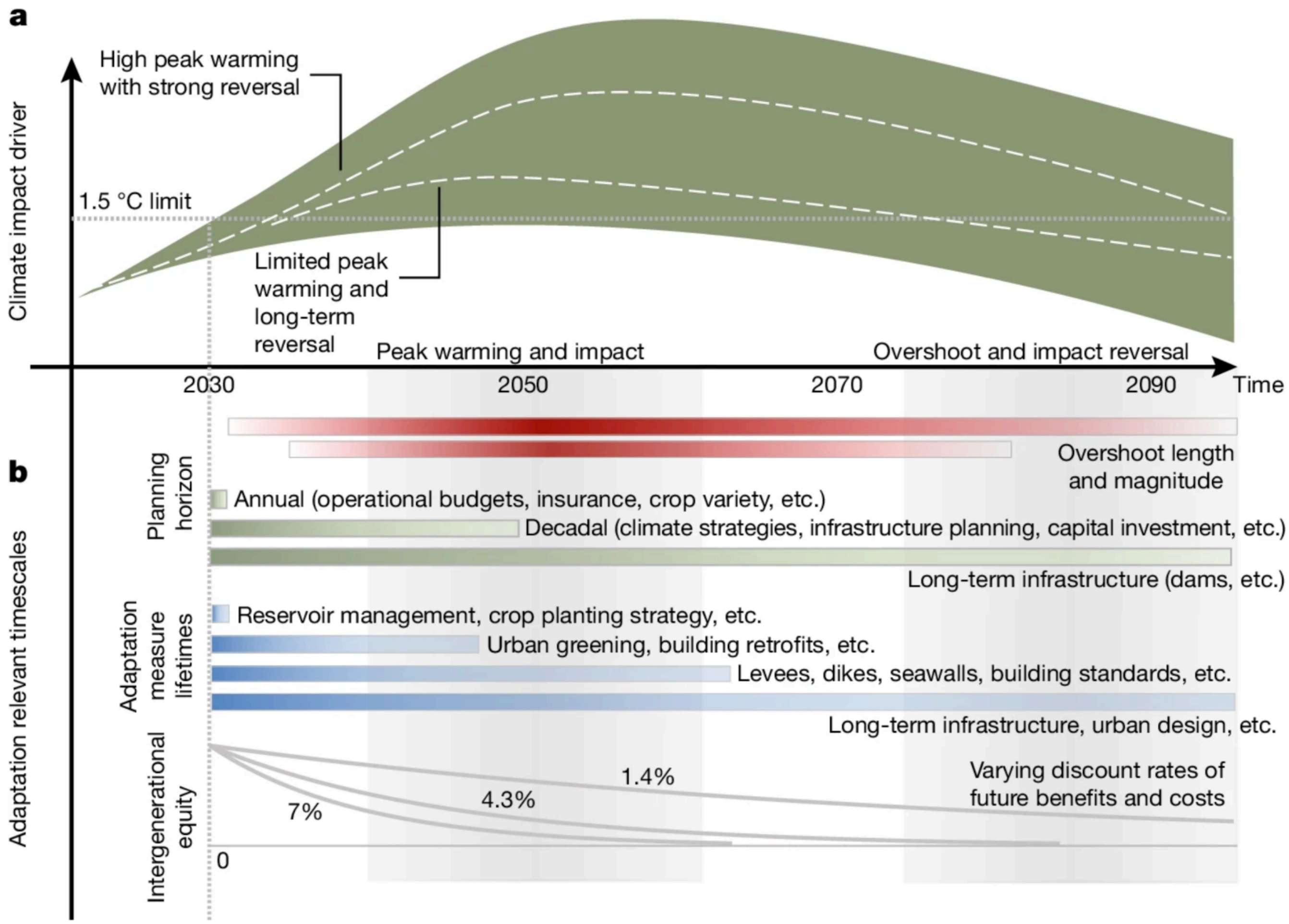
Adaptation decision-making and overshoot

In contrast to the prominence of overshoot pathways in the mitigation literature, their implications for adaptation planning have not been widely explored[42]. This poses the question of whether the possibility of impact reversal in the long-term future is relevant for adaptation planning today, in comparison with the more imminent threat of near-term climate change and the magnitude of peak warming[43].

Even under the optimistic assumption of nearly full reversibility of a climate impact driver under overshoot, a planning horizon of 50 years or more might be required before prospects of a long-term decline would start to affect adaptation decisions today or in the immediate future (Fig. 5a). Few adaptation plans and policies operate on these timescales: for example, the EU Adaptation Strategy spans three decades, whereas other national adaptation plans have similar or shorter time horizons[44]. Adaptation planning horizons and lifetimes of infrastructure can differ widely (Fig. 5b). At the long end of the planning scale, a hydropower dam may operate for a century or more, yet the management of that dam (and whether management should include flood control as an objective) would occur in concession periods (decades) as well as annual and sub-annual budget cycles (Fig. 5b).

The application of cost–benefit approaches in adaptation measures, and the time scale over which these are assessed, requires decisions on intergenerational equity reflected in the choice of the intertemporal discount rate[45]. Higher discount rates limit the time horizon relevant for economic adaptation decision-making to a few decades (Fig. 5b), in which case adapting to peak warming might always be preferable to adapting to a lower long-term outcome.

Fig. 5: Adaptation-relevant timescales and overshoot.



a, Stylised temporal evolution of a reversible climate impact driver under a peak and decline scenario. Dashed lines indicate a low and high overshoot outcome with median timescales of GMST reversibility typically in line with those from the IPCC AR6 database. b, A stylized illustration of adaptation-relevant timescales starting in 2030, including different planning horizons for adaptation planning and lifetimes of individual adaptation measures (horizontal bars, illustrative from years to decades[50], actual time frames vary strongly by context), and the effect of applying discounting (reflecting societal preferences towards intergenerational equity) to future damages and adaptation benefits. We show the effect of discounting for three illustrative discount rates.

It therefore seems that long-term impact driver reversibility after overshoot may be of relevance only in specific cases of adaptation decision-making. A notable exception is adaptation against time-lagged irreversible impacts such as sea-level rise for which overshoots will affect the long-term outlook (Fig. 4). However, as we have shown above, long-term global temperature decline cannot be relied on with certainty. Thus, a resilient adaptation strategy cannot be based on betting on overshoot, and only limiting peak warming can effectively reduce adaptation needs.

Limits to adaptation, both soft and hard, constrain the option space available for adaptation[39]. This includes hard limits in which, for example, adaptation is reliant on ecosystem-based measures that are themselves negatively affected by climate change, as well as soft limits such as lack of resources or governance systems[38]. Transgressing hard adaptation limits, for example, by destroying sensitive ecosystems as a result of unbridled climate change, and high peak warming levels may render these measures unavailable under future warming reversal, reducing the available pool of adaptation measures compared with a no-overshoot case. The risk of transgressing adaptation limits, rather than uncertain prospects of long-term reversibility, seem to be most consequential for adaptation decision-making under overshoot.

Reframing the overshoot discussion

In this Article, we argue that it is misleading to frame overshoot as an alternative way to achieve a similar climate outcome. We show that several climate impacts in a pre- and post-overshoot world are different, indicating impact reversibility is not a given. Even in cases in which impacts are reversible, the timescales for reversibility may be longer than typical decision horizons for adaptation planning, with peak warming impacts (as opposed to expected longer-term impacts) providing the backdrop for global adaptation needs assessments. From a climate justice perspective, overshoot entails socioeconomic impacts and climate-related loss and damage that are typically irreversible and fall most severely on poor people. This ethical dimension should be explicitly considered when assessing overshoot pathways and the possibilities to limit overshoot risks by near-term emissions reductions.

It has been argued that climate impacts during overshoots could be reduced or masked by the deployment of solar geoengineering (SG) intervention techniques[46] that would temporarily cool the planet. This idea is referred to as peak-shaving. These suggestions, however, make strong assumptions about the applicability, effectiveness and governance of SG interventions. Accounting for uncertainties in the physical climate response, and in the evolution of future emissions after SG is deployed, implies that an SG intervention aimed at peak-shaving an overshoot could result in a multi-century commitment of both SG and CDR deployment[23]. Apart from the fundamental concerns about SG deployment in general[47], a peak-shaving discourse is prone to the same overconfidence in reversibility and effectiveness we have conceptualised in this Article.

A central motivation to pursue a long-term temperature draw-down under peak and decline scenarios is to reduce climate impacts. We have shown that this temperature draw-down would be effective in reducing the time-lagged impact emergence over centuries, including sea-level rise and cryospheric changes. The consequences of multi-metre long-term sea level rise will affect coastal regions globally and drawing down global temperatures is important to minimise these long-term risks. Similarly, the probability of crossing irreversible thresholds may remain substantial in the long term unless global mean temperature is brought back down below 1 °C above pre-industrial levels[33].

Based on these insights, we argue for a reframing of the science and policy discourse on overshoot to focus on minimising climate risks in peak and decline temperature pathways (Table 1). We draw two overarching conclusions:

First, emissions reductions need to be accelerated as quickly as possible to slow down temperature increase and reduce peak warming. Pursuing such an enhanced protection pathway (Table 1) is the only robust strategy to, if not avoid then, at least minimise, far-reaching climate risks over the twenty-first century.

Second, we suggest that there is a need to prepare for an environmentally sustainable CDR capacity to hedge against long-term high-risk outcomes resulting from stronger-than-expected climate feedbacks. We find that this preventive CDR capacity might need to be of the order of several hundred gigatonnes of cumulative NNCE, a scale that might be just about possible within sustainable limits of CDR deployment[9] leaving little room for CDR use for offsetting residual emissions beyond hard-to-abate sectors. This further underscores the importance of very stringent near-term emission reductions to limit long-term risks. Although we argue that the build-up of a preventive CDR capacity is required to hedge against high warming outcomes, this same CDR capacity could, in case high warming outcomes do not materialise, also be deployed to draw down long-term temperatures and thereby reduce climate risks.

The need for a preventive capacity has implications for the design of stringent emission reduction pathways in light of constraints that limit overall CDR deployment. Pathways relying on large amounts of CDR to merely achieve net-zero CO2 often exhaust or exceed sustainability limits[15], leaving little to no room for course corrections in case of high warming outcomes. By contrast, pathways that do not plan for the future development of CDR may fail to build up the technological solutions required to establish a preventive CDR capacity, thereby exposing future generations and, in particular, the most vulnerable communities to risks that could at least be partly hedged against. Incorporating preventive CDR in pathway design requires further reflection, including regarding risks and policy design, but also about how to assign responsibilities and incentives different actors for providing for this preventive CDR capacity[48].

As a consequence of ever-delayed emission reductions, there is a high chance of exceeding global warming of 1.5 °C, and even 2 °C, under emission pathways reflecting current policy ambitions[1]. Even if global temperatures are brought down below those levels in the long term, such an overshoot will come with irreversible consequences. Only stringent, immediate emission reductions can effectively limit climate risks.

Methods

Data availability

The PROVIDE v.1.2 scenario data used for Fig. 2 is available at Zenodo[69] (https://doi.org/10.5281/zenodo.6963586). The data underlying the GFDL-ESM2M and NorESM2-LM simulations included in Fig. 3 and Extended Data Figs. 5 and 6 are available at Zenodo[70] (https://doi.org/10.5281/zenodo.11091132 and https://doi.org/10.11582/2022.00012). Data required to reproduce Extended Data Figs. 7 and 8 can be found at https://esgf-data.dkrz.de/search/cmip6-dkrz/. Data required to reproduce Fig. 4 and Extended Data Figs. 3, 4, 9 and 10 are included in the code repository.

Code availability

The analysis was performed with Python and spatial projections rely on the cartopy package. The scripts to replicate Figs. 2–5 are available at Zenodo[71] (https://doi.org/10.5281/zenodo.13208166).

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