Overconfidence in climate overshoot

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Global emission reduction efforts continue to be insufficient to meet the temperature goal of the Paris Agreement. This makes the systematic exploration of so-called overshoot pathways that draw temperatures back down to safer levels in the long term a priority for science and policy. Here we show that global and regional climate change in a post-overshoot world would be substantially different from a world that avoided overshoot, bearing profound implications for adaptation needs. Irrespective of the peak warming, we find that achieving declining global temperature remains critical for limiting long-term *climate risks including sea-level rise and cryosphere changes. Reversal of warming by deploying carbon dioxide removal (CDR) at scale, however, is not guaranteed. In addition to uncertain technical and sustainability limitations of CDR, we find that a preventive CDR capacity of several hundred gigatonnes might be desirable to hedge against strong Earth system feedbacks that amplify warming. Aiming for temperature decline is thus not a robust strategy to achieve a climate objective, but rather one part of a broader approach towards managing long-term climate risks. It is no replacement for stringent near-term emission reductions to limit risks at peak warming in the first place.*

The possibility of exceeding dangerous levels of global warming and subsequently returning below those levels in the long run has been discussed in the scientific literature for decades[1–3]. A central motivation has always been mitigation cost considerations, i.e. whether a delay in mitigating emissions and later 'making-up-for-it' is economically beneficial[4,5]. The potentially important role of large-scale carbon dioxide removal (CDR) in achieving such a reversal of climate change was identified early on[6]. With the adoption of the Paris Agreement and its long term temperature goal in 2015,[7] the issue of potentially reversing climate change has risen to further prominence. The Paris Agreement long-term temperature goal allows for a certain level of ambiguity in its interpretation[8], but establishes 1.5°C as the long-term upper limit for global temperature increase even after a temporary exceedance (or overshoot) of that level[9,10].

Although we are focussing here on temperature overshoot, we acknowledge that the concept of overshoot is not limited to global mean temperatures. It was originally applied to atmospheric CO_2 concentrations[1], and is prominent in climate change mitigation scenarios that limit radiative forcing levels[11] or aim to stay within a remaining carbon budget[12]. Temperature overshoot pathways were for the first time comprehensively assessed in the Special Report on Global Warming on 1.5°C of the Intergovernmental Panel on Climate Change (IPCC)[13,14].

Given the outstanding importance of assessments of emission pathways, and in particular emission reduction and net-zero benchmarks derived based on them, transparent and policy-relevant classes of pathway are required. A range of different pathway types can be identified based on their temperature and emission characteristics (Table 1). Achieving the Paris Agreement climate objectives, including global net-zero greenhouse gas (GHG) emissions (assessed using GWP100) as implied by Article 4.1, would lead to declining temperatures (central estimate) in the long term[15,16]. This also applies to pathways in which anthropogenic global warming (assessed as global mean temperature increase averaged over 20 or 30-years) may never exceed the 1.5°C limit following sufficiently stringent near-term GHG emission reductions. Notably, the Paris Agreement does not establish the idea of temperature stabilisation, but rather establishes upper limits. Based on these considerations, we establish a broad category of peak and decline (PD) pathways in which global warming is gradually reversed after peaking (Table 1). The class of pathways that is commonly referred to as "temperature overshoot" is a specific case of this broader conceptual category, but is specifically designed to return warming below a certain warming level (with a given probability) after a temporary exceedance.

Several classes of pathways have been proposed in the scientific literature that can be considered a part of the overarching PD category[15,17] (Table 1). A prominent example is the latest Working Group III (WGIII) contribution to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), which includes two pathway categories that explicitly refer to the term overshoot in their name (that is, categories C1 and C2, which are consistent with a 50% chance of limiting 2100 temperatures to 1.5°C after no/limited overshoot or a high overshoot, respectively). The end-of-century time horizon for an overshoot in these categories is a pragmatic, yet subjective choice which has no legal basis in the Paris Agreement or subsequent decisions[15]. Although defined in terms of probabilities of temporarily exceeding 1.5°C of global warming, the IPCC pathway categories are also quite concrete in terms of the implied absolute level of overshooting. As part of the category definitions, the IPCC states that limited overshoot refers to exceeding the specified limit by up to about 0.1°C, while in high overshoot pathways it does so by up to 0.3°C[17] (Table 1).

These levels of temperature overshoot highlighted in this definition refer to the median warming outcome under these pathways, and can give rise to the impression that the temperature overshoot risk under such scenarios is constrained to a few tenths of a degree[14]. This is potentially misleading, however, as the geophysical uncertainties surrounding the global warming outcome of emission pathways imply a possibility of peak warming half a degree or more above the median (central) estimate[12]. The possibility of high warming outcomes applies to all emission pathways, but the strong focus on very specific temperature outcomes under overshoot, also reflected in name and description (Table 1), renders it particularly relevant in this context. We identify the strong focus on median outcomes as an area of overconfidence in perceptions of the risks implied by overshoot pathways.

Table 1 | Conceptual and literature categories of peak and decline emission pathways.

Pathway Category	**Temperature Characteristics**	**Emission Characteristics (Best Estimates)**
Conceptual Categories		
PD: Peak and decline pathways	Pathways that aim to achieve temperature peak and a sustained long-term temperature decline	Emission reductions in all GHGs towards achieving net-zero CO2 emissions, and net-negative CO2 emissions thereafter

PD-OS: Overshoot pathways	PD-pathways that aim to limit warming to a targeted warming level at some point in the far future but allow for a high likelihood to exceed it over the near term in the conviction that warming can be reversed at a later stage to again land below the targeted limit	As peak and decline pathways, but rate of emission reduction, timing of net-zero CO2 and amount of net-negative emissions all depend on the characteristics of the envisaged overshoot
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	Stringent and rapid GHG emission reduction to reduce emissions as much and as early as possible, achieving net-zero CO2 emissions as soon as possible while minimising residual emissions, and achieving sustainable levels of net-negative CO2 emissions thereafter
Literature Categories		
Pathways that limit warming to 1.5°C (>50%) with no or limited overshoot (C1)[17]	Pathways that limit warming to 1.5°C in 2100 with a likelihood of greater than 50%, and reach or exceed warming of 1.5°C during the 21st century with a likelihood of 67% or less. Limited overshoot refers to exceeding 1.5°C global warming by up to about 0.1°C and for up to several decades. C1 pathways that achieve net-zero GHG are included in the category C1a.	2030 reductions of total GHG emissions relative to 2019: 43% [34-60 %, 5th-95th percentile range] Timing of net-zero CO2: 2050-2055 [2035-2070] Timing of net-zero GHG (only category C1a pathways): 2070-2075 [2050-2090] Cumulative net-negative CO2 after net-zero: 220 $GtCO_2$ [20-660]
Pathways that return warming to 1.5°C (>50%) after a high overshoot (C2)[17]	Pathways that limit warming to 1.5°C in 2100 with a likelihood of greater than 50%, and exceed warming of 1.5°C during the 21st century with a likelihood of greater than 67%. High overshoot refers to temporarily exceeding 1.5°C global warming by 0.1-0.3°C for up to several decades	2030 reductions of total GHG emissions relative to 2019: 23% [0-44 %, 5th-95th percentile range] Timing of net-zero CO2: 2055-2060 [2045-2070] Timing of net-zero GHG : 2070-2075 [2055-...] Cumulative net-negative CO2 after net-zero: 360 $GtCO_2$ [60-680]
Paris Agreement compatible pathways[15]	Pathways that reach or exceed warming of 1.5°C during the 21st century with a likelihood of 67% or less, and simultaneously do not exceed 2°C during the 21st century with a likelihood of 90% or more. Achieve long-term declining temperature by reaching net-zero GHGs. Similar to pathways in category C1a.	2030 reductions of total GHG emissions relative to 2019: 41% [38-44 %, interquartile range] Timing of net-zero CO2: 2050 [2045-205] Timing of net-zero GHG : 2065 [2060-2075] Cumulative net-negative CO2 after net-zero: 453 $GtCO_2$ [127 - 690]

In the following, we provide a comprehensive perspective on future climate outcomes under peak and decline pathways (see Table 1 and Fig 1 for a conceptual overview). In emission space, these pathways are differentiated by the stringency of emission reduction efforts in the near-term and up to achieving net-zero CO2 emissions and the potential of net-negative CO2 emissions in the long term. The former approximately determines the time of peak warming for median climate outcomes, while the latter determines the pace of temperature reversal.[9] Following ref. [12], we separate the dynamics into two phases: the 'warming phase' until around net-zero CO2 emissions, and the 'long-term state' after net-zero CO2.

We first look into uncertainties in global temperature outcomes and their implications for the required net-negative CO_2 emissions to achieve the intended reversal of warming. We then discuss potential feasibility constraints to deploying gigatonne-scale carbon dioxide removal (CDR). Next, we explore if and how global mean temperature reversal translates into reversal of local climatic impact-drivers[18] and subsequent impacts and risks. Finally, we discuss the implications of a potential temperature overshoot for climate change adaptation. Based on this comprehensive perspective, we argue for redirecting the discussion towards managing climate risks both in the near and long-term, and to avoid overconfidence in climate overshoot outcomes.

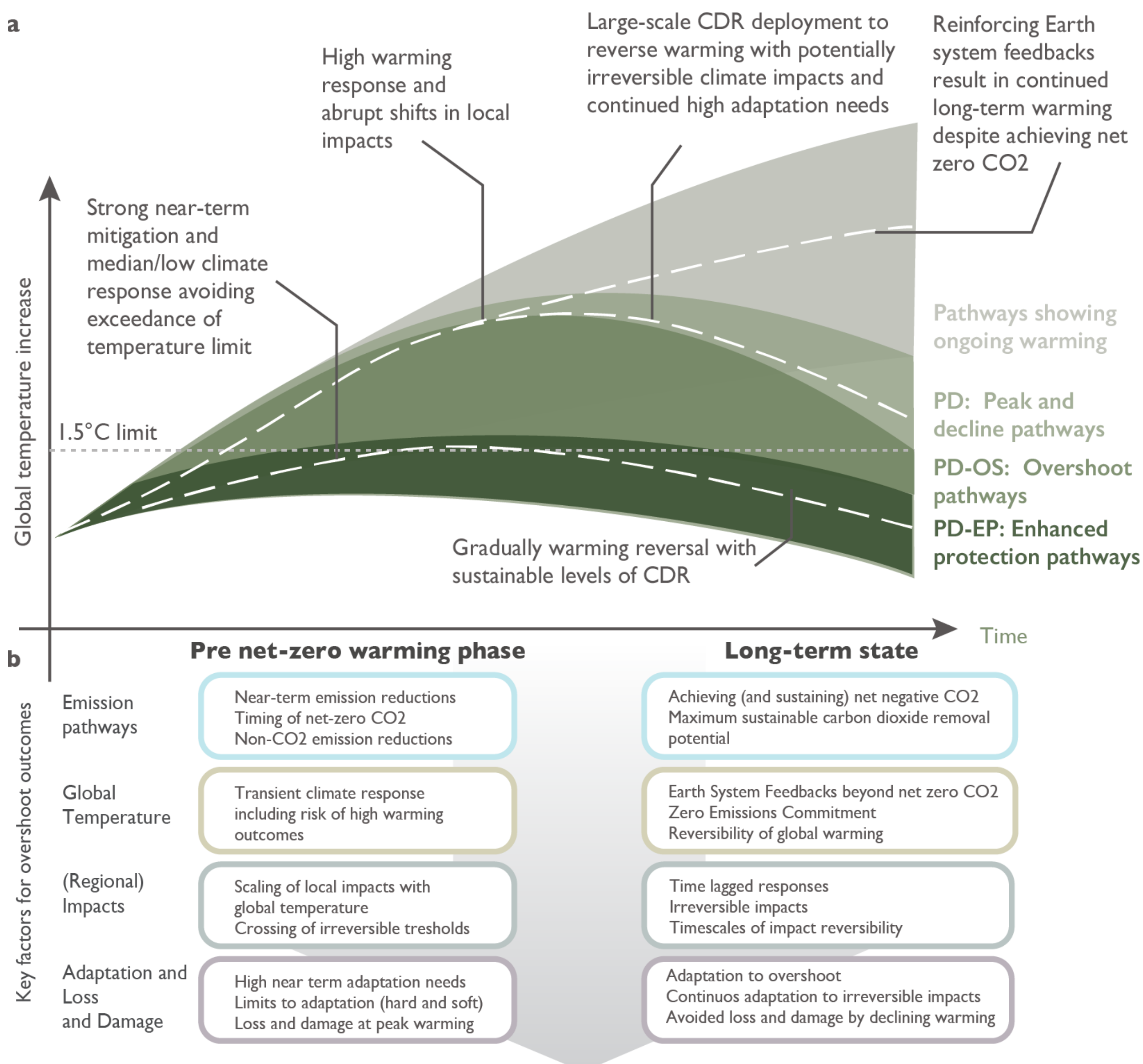

Fig 1 | Illustrative climate outcomes under different conceptual categories of overshoot pathways. **a** Different classes of peak- and decline global mean temperature pathways (compare Table 1). Stylised individual pathways (dashed lines) are highlighted to illustrate specific impact, adaptation and carbon dioxide removal dimensions associated with the different categories. **b,** An overview of key factors affecting pathway and potential overshoot outcomes along the impact chain for the warming phase until net-zero CO2 and for the long term beyond net-zero.

Global climate response uncertainty and reversal

The cumulative CO_2 emissions until net-zero and the level of reduction of non-CO_2 GHGs and other short-lived climate forcers determine the level of peak warming, and the amount of net-negative CO_2 emissions (NNCE) required to reverse global mean temperature to a given level increase under an overshoot pathway[17]. The later peaking of global GHG emissions is achieved, and the less stringent the emission reductions that follow, the higher peak warming will be. Most estimations of the amount of NNCE required to reverse warming under overshoot, including in the IPCC AR6 WG3, focus on median warming outcomes only[19]. A comprehensive appraisal of overshoot risks, however, needs to consider uncertainties in the climate response during the warming phase as well as in the long-term state. Relevant dimensions of uncertainty include: (1) potential high warming outcomes due to strong amplifying climate warming feedbacks up to net-zero CO_2 [20,21], (2) potential continued warming past net-zero, as captured by the zero-emissions commitment (ZEC)[22,23], and (3) the response of the climate system to net-negative CO_2 emissions[24–26]. These geophysical uncertainties are relevant for estimating the net-negative CO_2 emissions necessary to bring down warming in peak and decline pathways.

Even under a stringent emission reduction scenario that achieves net-zero CO2 around mid-century and aims to limit median peak warming close to 1.5°C above pre-industrial levels without relying on net-negative emissions, markedly higher warming outcomes are possible (the PD-EP pathway PROVIDE REN_NZCO2, Fig. 2a). We explore the range of physically plausible warming responses based on 2237 outcomes generated using the simple carbon cycle and climate model FaIR configured to resemble key climate metrics assessed by IPCC AR6 WG1[20] (Methods).

Considering the range of physically plausible outcomes generated by FaIR we identify relatively lower-risk futures, where warming at the time of net-zero is lower than the median estimate and is followed by a further reduction of warming in the long-run (Fig. 2b, bottom left quadrant). In these cases, deployment of net-negative emissions is not strictly necessary, assuming stringent mitigation in line with the assessed pathway.

However, in cases where the warming at net-zero is higher than 1.5°C and when the expected warming after CO_2 emissions cease is either positive (Fig. 2b, top right quadrant) or negative, but not sufficient to reach 1.5°C (Fig. 2b; top left quadrant), net-negative CO_2 emissions may need to be deployed at scale to return warming back below 1.5°C in 2100. In case of a long-term increase in temperatures despite net-zero CO_2 emissions[27], even a lower-than-median near-term warming can imply continued increase of climate risks (Fig. 2b, bottom right quadrant), potentially. Warming outcomes characterised by continued warming after net-zero CO_2 is achieved (Fig. 2b - top right quadrant) are of particular concern.

We estimate the net-negative CO_2 emissions required to return warming for each modelled FaIR GMT outcome to 1.5°C in 2100 (Methods). As a result of the heavy-tailed climate response uncertainty distribution[20], the need for very large net-negative CO_2 deployment cannot be ruled out while net negative CO_2 requirements at the lower end are bound to zero (Fig. 2c). We find that the potential scale implied by geophysical uncertainty (interquartile range: 0 to -400 Gt CO_2 cumulatively, or, 0 to -10 Gt CO_2 per year after 2060) is of the same order of magnitude as the spread of deployed net negative CO_2 across the scenarios assessed in IPCC AR6 WG3 (Fig. 2c)[19,28]. While the dominant contribution to net-negative CO_2 deployment requirements is a consequence of the need for temperature draw-down after high peak warming outcomes, a need for net-negative CO_2 deployment of up to 200 Gt CO_2 (or -5 Gt CO_2 per year, upper 95% quantile, Fig. 2c) to prevent further warming past net-zero cannot be ruled out. These results suggest that a narrow focus on scenario uncertainty and median warming alone is insufficient when assessing potential CDR deployment requirements in the 21st century.

It is important to emphasise that our simple illustrative approach has a number of limitations that should be carefully explored in future research, including dedicated Earth System Model experiments[29]. Of particular relevance would be the exploration of potential asymmetries in the response of the climate system to positive and negative CO_2 emissions (Methods)[25,26]. We note that due to the lack of appropriate training data, the response of the simple climate model FaIR to net negative CO_2 emissions is not well constrained. Moreover, the earth system models used to calibrate FaIR may miss non-linear responses in the climate system including abrupt destabilisation of natural carbon sinks such as permafrost CO_2 and CH_4 release[30], peat carbon loss from climate and anthropogenic land use change[31], extreme fires and drought mortality of forests with high biomass density[32–34]. We explore permafrost and peatland responses to overshoot below (Fig. 4).

Notwithstanding the identified need for further modelling efforts to address this research gap, it is important to consider that such research efforts may not be ultimately conclusive as there is no observational evidence available to constrain the modelled response to net-negative CO_2 emissions. It therefore appears plausible that substantial residual uncertainties about the Earth System response will remain beyond the time net-zero CO_2 is reached, implying the need for a preventive approach to hedge against undesirable warming outcomes in the long term.

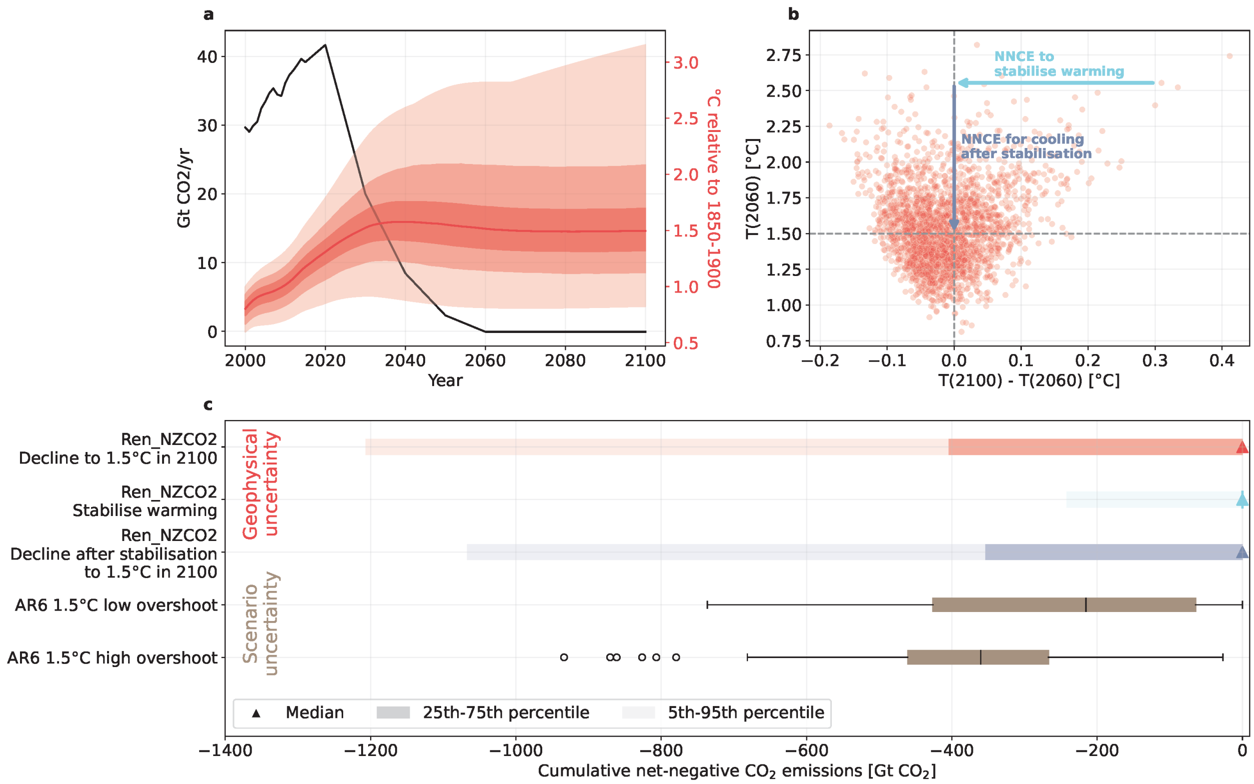

Figure 2: Estimating cumulative net-negative CO_2 emissions (NNCE) needs when accounting for climate response uncertainty. a, Net CO_2 emissions for the PROVIDE REN_NZCO2 pathway (black line) and the warming outcome uncertainty (derived using FaIR v1.6.2[35]). The median warming outcome is the red solid line, with each subsequent plume of varying transparency representing, in order, the 25th - 75th percentile, 5th - 95th percentile, and minimum to maximum ranges respectively. **b**, Peak warming at the time of net-zero CO_2 versus the change in temperature between net-zero CO_2 and 2100. **c**, Estimated net-negative CO_2 emissions to return warming for each peak warming outcome shown in **b** to 1.5°C in 2100 (see Methods). These estimates reflecting net-negative CO_2 emissions implied by geophysical uncertainty of the warming outcome based on the REN_NZCO2 pathway are compared to the scenario uncertainty across the C1 and C2 categories from the IPCC AR6 WG3 report.

Relying on Carbon Dioxide Removal

Achieving net-negative CO_2 emissions will require the deployment of CDR that exceeds residual emissions in hard-to-abate sectors. Scenarios assessed by IPCC WGIII deploy CDR in different ways and to different extents[17]. Near-term scale-up of both conventional methods (i.e., methods that capture and store carbon in the land reservoir) and novel CDR methods[36] is the most rapid in pathways with the lowest peak warming (low or no overshoot 1.5°C pathways, C1). CDR levels by the end of the century tend to be higher in high overshoot C2 pathways (central estimate), but the overall range is relatively similar to the C1 pathways. Also, pathways that are likely below 2°C, but do not limit warming to 1.5°C in 2100 (C3) see a substantial ramp-up of CDR in the second half of the 21st century reaching levels comparable to C1 pathways by 2080 (Fig. S3).

The total amount of removals deployed in emissions reduction pathways depends predominantly on the effective reduction of residual positive CO2 emissions and mitigation of non-CO_2 GHGs by mid-century, rather than on peak warming targets[15].

Reliance on gigatonne-scale CDR deployment in scenarios comes with challenges that strongly affect the overall feasibility of such scale up. There are multiple areas where overshoot scenarios might be overconfident in their use of CDR (Table 2). A myriad of factors ranging from lack of policy support and business models over technological uncertainty to public opposition often connected to external effects may constrain upscaling considerably. For example, insufficient technological readiness may be a critical bottleneck, as current removal rates from CDR methods other than afforestation and reforestation are miniscule (~2 Mt CO_2/yr)[37] and imply a more than 1000-fold increase by 2050[36]. Beyond technological concerns, an array of unintended or unforeseen permanence issues and system feedbacks (Table 2) might reduce or offset CDR's contribution to mitigation[37,38]. Also, under scenarios of future declining CO_2 concentrations, a continuous weakening and eventual reversal of the ocean and land sinks needs to be expected, thereby increasing the need for CDR[39].
This highlights the importance of developing systems for monitoring, reporting, and verification (MRV) of CDR that are genuinely fit-for-purpose. An over-reliance on removals may lead to catastrophic outcomes if CDR fails to deliver at the expected scale. Even if technical removal potentials prove to be large, sustainability and equity considerations may constrain acceptable deployment scales[40]. There is thus a risk of overconfidence and overreliance on both the potential scale-up and effectiveness of CDR to achieve climate objectives.

Squaring these feasibility concerns with the potential need for gigatonne scale CDR deployment to address climate uncertainty (Fig. 2) will be a challenging exercise.
We argue that deployment pathways that address this challenge should be guided by the principle of "harm prevention"[51] . This principled approach requires two complementary actions: (1) reduce gross CO_2 emissions rapidly to reduce the potential CDR needs to address climate uncertainty, (2) address feasibility concerns to facilitate deployment of CDR to hedge against potentially high warming outcomes.

Table 2 | Overview of constraints of large-scale CDR

	Description of constraints and potential for overconfidence
Readiness	Current removal capacities are far from what is required to be compatible with the Paris Agreement. In the coming years, removal scales need to go up while costs need to come down – both at highly ambitious levels. Implementation gaps already arise, potentially precluding reliance on CDR to steer back from overshoot [36].
Permanence & resilience	Permanent and secure storage of removed carbon is key. Overconfidence may arise from neglected uncertainty of the geological storage potential[41] and overestimated storage durability under progressing climate change. Carbon stored in soils and vegetation is especially susceptible to climate or non-climatic impacts, including fires or pest infestation, and may be constrained further by uncertain sink saturation[38,42–44].
System feedbacks	Mitigation effects of CDR may be offset by weakened and potentially reversed land and ocean carbon sinks, and other undesired system feedbacks[39], e.g., unfavorable albedo changes, or emissions due to direct or (unintended) indirect land use change. Carbon uptake potential of land-based CDR is highly uncertain, depending on bioenergy crop yields in the case of bioenergy and carbon capture and storage (BECCS) and soil carbon response to land-use change and the rate of forest regrowth in the case of afforestation[45,46].
Policy response & governance	Betting on CDR effectiveness may lead to insufficient emission reductions if CDR fails, or physical climate feedbacks are stronger than expected. The mere outlook of CDR may evoke a moral hazard, meaning that required gross emission reductions may be delayed and/or weakened[47]. Lacking monitoring and liability of removal additionality and permanence may pose an additional constraint [36].
Sustainability & Acceptability	The extensive land use footprint associated with large-scale CDR may threaten environmental integrity[43,44] and/or agricultural production[42]. However, some types of CDR (for example, via restoration of natural ecosystems and their associated carbon) would be more synergistic. CDR often requires public acceptance – an aspect not reflected in current scenarios. Consensus is critical, as CDR can lead to undesired distributional impacts (e.g., concerning land tenure or food prices if large areas are allocated for CDR). Further constraints arise when considering (transnational) equity criteria, as the burden of CDR may not be evenly distributed between polluters, regions, and generations[40,48]. Even with strong CDR deployment by high-income countries, equitable mitigation outcomes may not be achieved[49,50].

Regional climate change reversibility

The promise of overshoot pathways is to return global warming back below a certain level, i.e. 1.5°C, in the long run. Since the narrative on climate overshoot is focussed on global mean temperature outcomes, it can lead to the impression that achieving a climate objective after an overshoot is just a different trajectory to arrive at the same end-point. Yet this will not necessarily be the case in terms of regional climatic impact-drivers [52].

Even if global warming were to be stabilised at a certain level, the climate system would continue to change as components of the climate system continue to adjust and equilibrate[53–56]. Continued changes in sea-surface temperature patterns, and resulting atmospheric feedbacks will affect regional and potentially also the global temperature trajectory on a multi-century time-scale[27,57].

Comparing climatic impact-drivers before and after overshoot can help to illustrate the implications on the regional level. We provide an analysis for overshoot scenarios from the Coupled Model Intercomparison Project (CMIP6) model simulations (Methods) focussing on annual temperature and precipitation and comparing the differences between spatial patterns before and after peak warming. The most apparent difference in annual mean temperature patterns is a stronger cooling over land after overshoot, as the land-ocean contrast is reduced[58] (Fig. 3a). Furthermore, in the period after peak warming, the fast response to a reduction in atmospheric CO_2 is superimposed on lagged effects of the increase in CO_2 decades earlier. Due to the differences in fast and slow response patterns, a warming of the Southern Ocean relative to the rest of the globe is expected[59,60]. Similarly, a warming signal after overshoot over regions with high present day aerosol loading is apparent (South and East Asia), in line with what would be expected from a reduction in regionally reduced aerosol loadings under stringent mitigation pathways[61]. Strong regional features emerge over the high northern latitude oceans in line with a time-lagged response of the Atlantic Meridional Overturning Circulation[62], although substantial inter-model differences remain over this region. A continued Pacific warming signal is apparent, possibly related to a continuous intensification of extreme El Niño events even under declining temperatures[63]. So even for the regional temperature changes that generally align well with mean temperature at the global scale, some notable differences emerge.
This is even more the case for annual mean precipitation, where even a continuation of regional trends despite declining global temperatures is apparent, such as the Sahel drying and East Asian wetting signals. Some of these changes are related to a shift in the Inter-Tropical Convergence Zone (ITCZ) that could result from a warming of the Southern Hemisphere relative to the Northern Hemisphere after peak warming[64]. On the global scale, the differences between regional precipitation patterns before and after overshoot are comparable in magnitude with the response to a 0.2°C GMT difference. This indicates that changes in regional precipitation cannot be approximated well by GMT change after overshoot.

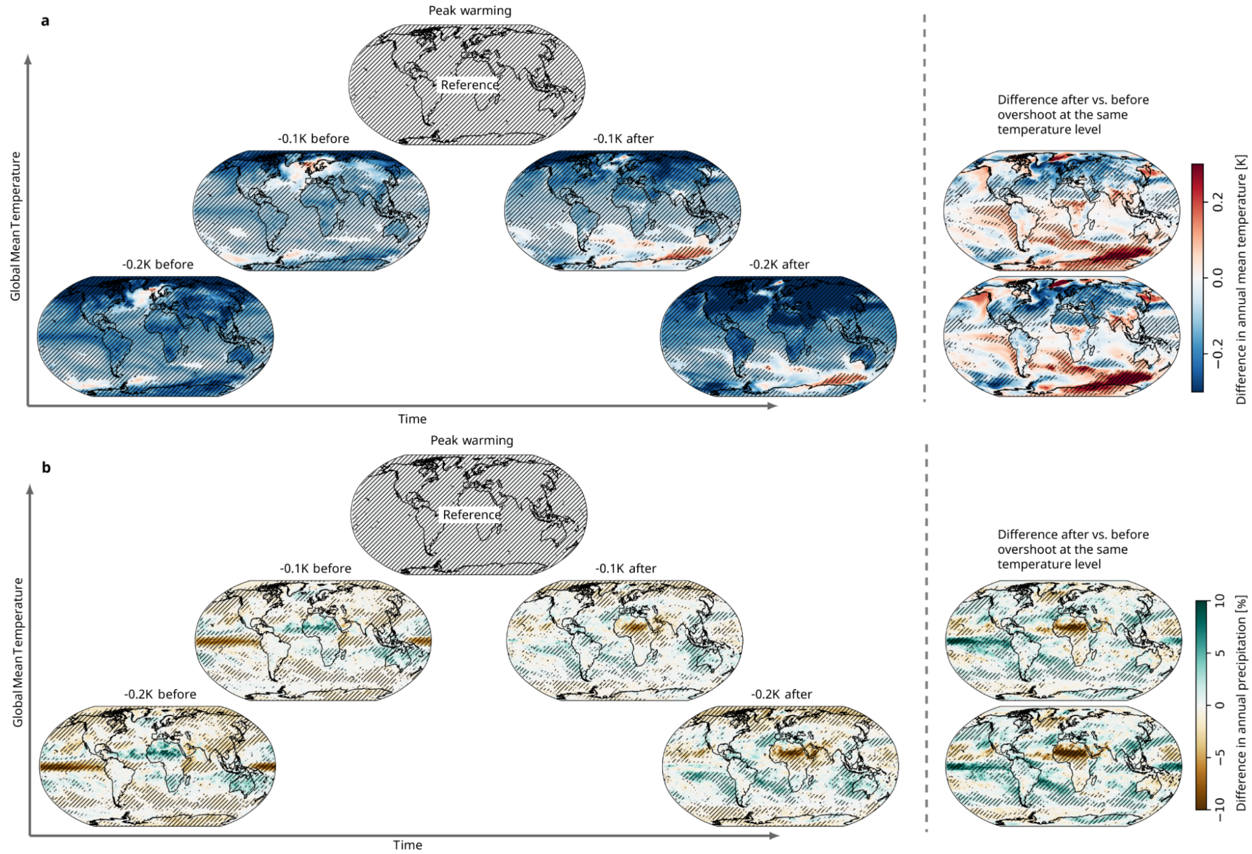

Fig 3| Evolution of regional climate signals before and after overshoot. a 30-year averages of annual mean surface air temperature for different global mean temperatures going from -0.2K below peak warming (before the overshoot) to peak warming to -0.2K below peak warming after the overshoot. Relative differences to peak warming are shown for the ensemble median of 12 CMIP6 Earth system models and the SSP5-34-OS and the SSP1-19 scenarios. On the right-hand side, the difference between after and before peak warming at the same level of Global Mean Temperature is shown. **b** as a but for annual precipitation. Areas where at least three quarters of the ESMs agree on the sign of difference are indicated by black hatching. Adapted from ref. [65].

Time-lagged and irreversible impacts

For a range of climate impact drivers and impacts, there is no expectation of immediate reversibility after overshoot. This includes changes in the deep ocean, marine biogeochemistry, biodiversity and fisheries[66–68], land-based biomes, carbon stocks and crop yields for which CO_2 fertilisation effects play a significant role[69], but also biodiversity impacts including species loss on land[70,71], leading to an erosion of ecosystem services and climate resilience. Overshoot will also increase the probability of crossing stability thresholds of polar ice sheets and other potential Earth System tipping elements[72,73], including risk of large scale forest loss in the Amazon and boreal regions.

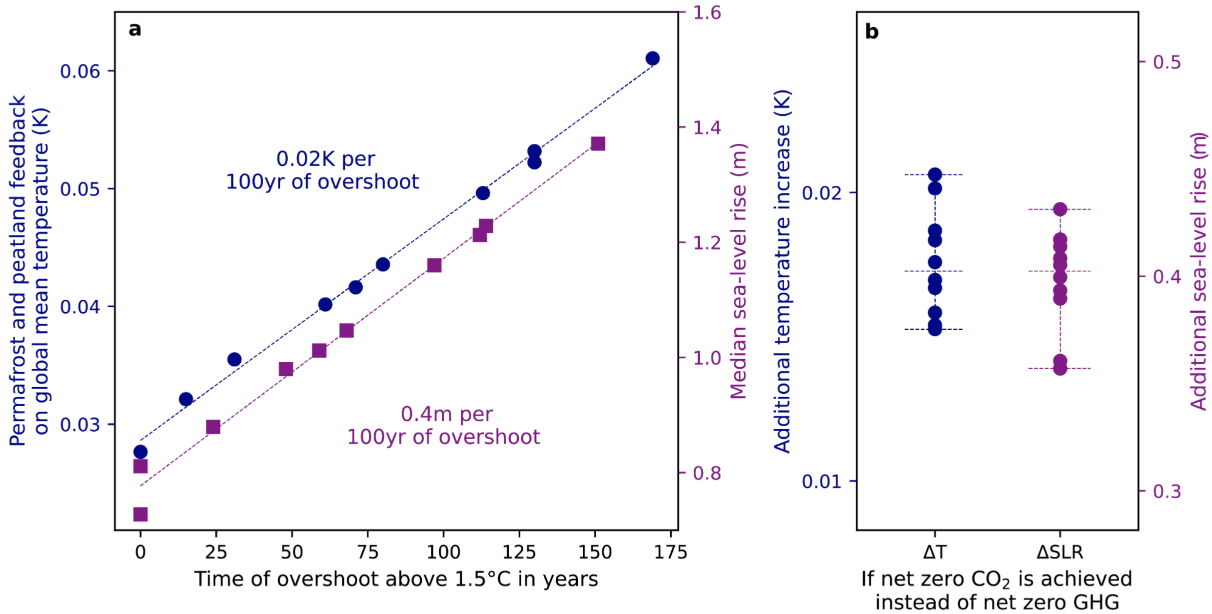

Fig 4| Long-term irreversible permafrost, peatland and sea-level rise impacts of overshoot. a, Feedback on 2300 global mean temperature increase by permafrost and peatland emissions (blue markers and left axis) and 2300 global median sea-level rise (right axis) as a function of overshoot duration. **b,** Additional global mean temperature from warming induced permafrost and peatland emissions and sea-level rise increase implied by stabilising temperatures at peak warming by achieving net-zero CO_2 emissions compared to a long-term temperature decline implied by achieving and maintaining net-zero GHGs.

Global and regional sea levels will continue to rise for centuries to millennia as a result of anthropogenic warming today, even if long-term temperatures are in decline[74,75].

The irreversible nature of many climate impact drivers and impacts poses important questions for research, including the quantification of long-term risks arising from a temporary overshoot. But at the same time, the question of potential benefits of long-term temperature decline compared to stabilisation at higher temperature levels also requires a closer look. For global sea-level rise, we find that every 100 years of overshoot above 1.5°C lead to an additional sea-level rise commitment of around 40 cm by 2300 relative to a baseline of about 80 cm without overshoot (Fig. 4a). Achieving and maintaining net-zero GHGs and thereby long-term temperature decline avoids about 40 cm of 2300 sea-level rise compared to stabilisation at peak warming in the case of net-zero CO_2 (Fig. 4b).
A similar pattern emerges for 2300 permafrost thaw and northern peatland warming leading to increased soil carbon decomposition and CO_2 release (Fig.4). The effect of permafrost and peatland emissions on 2300 temperatures increases by 0.02°C per 100 years of overshoot, while

achieving long-term declining temperatures implied by net-zero GHGs would reduce the additional 2300 temperature effect by about 0.017°C.
Any temperature overshoot will thereby leave a substantial climate impact legacy compared to a no overshoot outcome. However, achieving long-term declining temperatures will also robustly reduce risks for time-lagged processes such as sea-level rise or for triggering irreversible dynamics in large scale tipping elements of the Earth system[73].

Socio-economic impacts

The severity of climate risks for human systems under overshoot will significantly depend on their adaptive capacity[76,77], as well as the potential transgression of limits to adaptation[78]. An overshoot above 1.5°C would likely emerge during the first half of the 21st century, a period still characterised by comparably low adaptive capacity in large parts of the globe even under optimistic scenarios of socio-economic development[76,77]. These temporal dynamics imply that climate risks arising under an overshoot pathway may be amplified by high vulnerability and low adaptive capacity. This has profound consequences for the ability of achieving climate resilient development outcomes under overshoot in particular for the most vulnerable countries, communities and peoples[79].

While geophysical effects of overshoot may be partially reversible, socio-economic impacts are typically irreversible. Climate impacts on health, mortality, ecosystem services, livelihoods, and education typically can leave lasting and intergenerational negative effects on people's well-being[80]. Overshoots might also leave a long-term legacy in the economic performance of countries, at least if impacts of climate change on growth are assumed[81].
Such climate impacts fall most heavily on the poor, while climate change exacerbates poverty[82]. Thus allowing for an overshoot emissions pathway entails deeply ethical questions of how much additional climate-related loss and damage people, and especially the world's poor, would need to endure. Climate justice frameworks offer many ways to consider these questions[83].

Adaptation decision-making and overshoot

In contrast with the prominence of overshoot pathways in the mitigation literature, their implications for adaptation planning have not been widely explored[84]. It poses the question: is overshoot, i.e. the possibility of impact reversal in the far future, relevant for adaptation decisions taken today and in the near future?

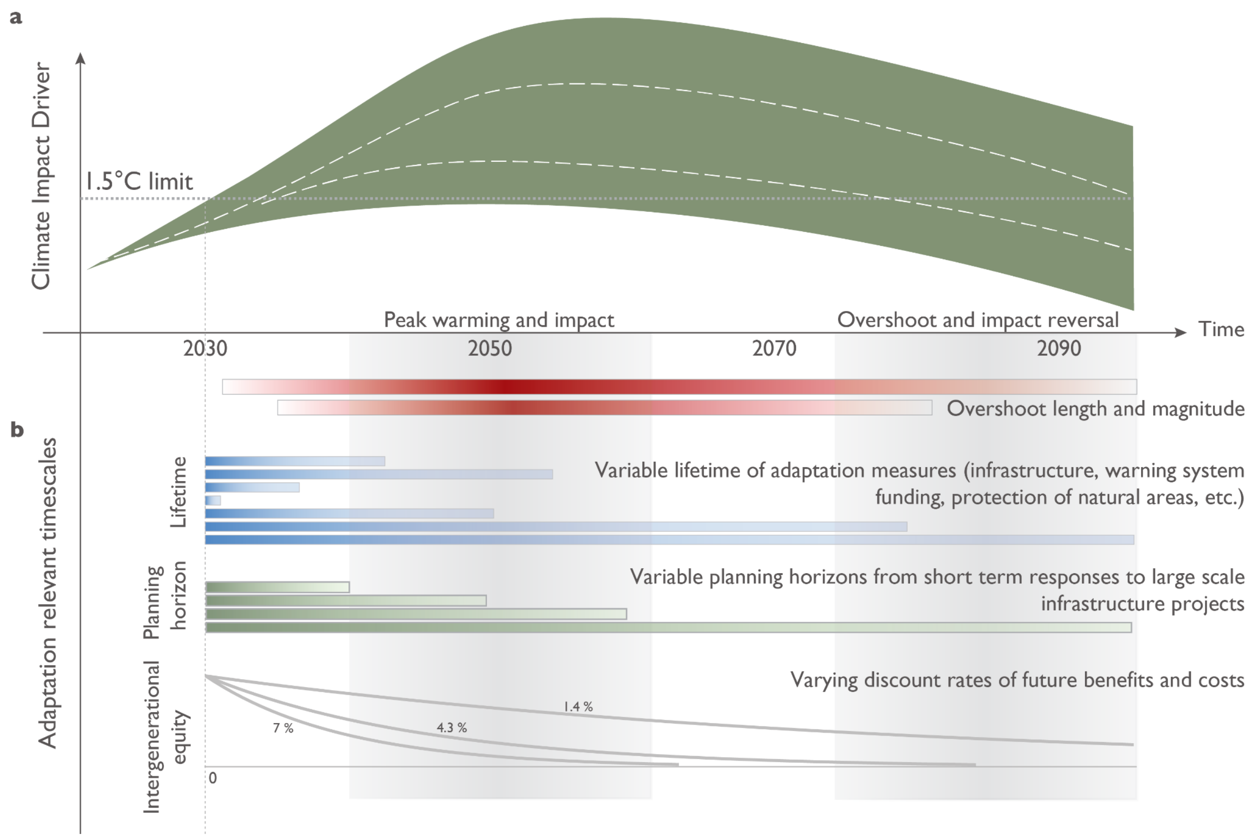

Fig 5| Adaptation relevant timescales and overshoot. a, Stylised temporal evolution of a reversible climate impact driver under a peak-and-decline scenario. Dashed lines indicate a low and high overshoot outcome. **b,** A range of adaptation relevant timescales starting in 2030 illustrating very different lifetimes of individual adaptation measures (from years to decades), the planning horizons for adaptation planning (decades) and the effect of applying discounting (reflecting societal preferences towards intergenerational equity) to future damages and adaptation benefits.

Reversing global temperatures after peak warming would be substantially slower than current warming (across a range of different emission scenarios, median long-term decline would be on the order of around 0.05°C per decade[12], compared to around 0.2°C of recent decadal warming[85]). So even under the optimistic assumption of full reversibility of a climate impact driver, a planning horizon of 50 years or more might be required for the prospects of long-term impact decline to affect adaptation decisions (Fig. 5).
Not many adaptation plans and policies operate on such timescales: for example, the EU Adaptation Strategy spans three decades[86], other national adaptation plans have similar or even shorter time horizons[87]. In practice, infrastructure planning encompasses a wide range of often overlapping time scales; for example, a major hydropower dam may operate for a century or more, while the management of that dam (and whether management should include flood control as an objective) would occur in concession or contract periods (decades) as well as annual and sub-annual budget cycles.

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[88]. Higher discount rates limit the time horizon relevant for economic adaptation decision-making to a few decades (Fig. 5).

We have explored an illustrative example of the implications of incorporating overshoot into adaptation benefit cost analysis under a low and high overshoot pathway (Supplementary Material Section 4, Fig. S4). Our findings suggest that for adaptation measures with higher benefit/cost ratios, adapting to peak warming is preferable to adapting to a lower long-term outcome, making them non-regret options (Fig. S5). We find the magnitude of peak warming to be more important than post-peak reversibility. Our example further supports the conclusion that potential 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) and thereby decision-making under dynamic adaptation pathways[89].

Limits to adaptation, both soft and hard, constrain the option space available for adaptation[78,90]. This includes "hard" limits to adaptation strategies reliant on systems that are themselves negatively impacted by climate change, e.g. ecosystem-based measures reliant on coral reefs or mangroves[91], as well as "soft" limits to the adaptation portfolio due to socio-economic constraints (i.e. lack of resources of governance systems)[77]. Transgressing "hard" limits under overshoot, i.e. the destruction of sensitive ecosystems, implies that these measures may also not be available for implementation under warming reversal, reducing the available pool of adaptation measures compared to a no-overshoot case. It is the risk of transgressing adaptation limits, rather than uncertain prospects of long-term reversibility, that we find to be most consequential for adaptation decision-making.

Reframing the overshoot discussion

We have identified a range of areas where a framing of overshoot as 'another way' to achieve the same (or at least a similar) climate outcome in the long run appears to be misguided. Specifically, there is a risk of overconfidence when focussing on median climate projections alone in particular with the precision of a tenth of a degree.

From a climate impact perspective, it is clear that the world "after" an overshoot will be different from before, and from a no-overshoot world, as impacts' reversibility is not a given. Even if it was, the time scales involved may exceed usual decision-making horizons of adaptation planning. This implies that the expected peak warming, rather than the long-term outlook, will drive most adaptation decisions over the coming decades and should inform estimates of global adaptation needs assessments[92]. From a climate justice perspective, overshoot entails further socio-economic impacts and climate-related loss and damage that are typically irreversible and fall most severely on the world's poor. This ethical dimension should be explicitly discussed when considering overshoot emissions pathways.

As we have shown, whether or not a long-term decline in global temperatures can be achieved depends on uncertain physical climate system feedbacks, but nevertheless needs to rely on large scale carbon dioxide removal. Whether or not the scaling up of such CDR techniques can be achieved sustainably, and at what costs, is an open question. We note that these considerations of both physical and CDR uncertainties also raise questions about proposals of "peak-shaving" of overshoot by deploying hypothetical solar radiation modification intervention techniques[26]. A central motivation to pursue a long-term temperature draw-down is to reduce climate impacts both in the near-term as well as in the long run. We have shown that benefits can be clearly identified for time lagged impacts over centuries including cryospheric changes, sea-level rise, and deep ocean changes. Given the consequences of a potential multimeter long-term sea-level rise commitment for coastal regions globally, drawing down global temperatures is desirable. Similarly, the probability of crossing irreversible thresholds may remain substantial in the long-term unless global mean temperatures are brought back down below 1°C above pre-industrial levels[73].

Based on these insights, we argue for a reframing of the science and policy discourse on overshoot away from a potentially overconfident focus on median outcomes, and rather towards a perspective on minimising climate risks in peak and decline temperature pathways (Table 1). Overshooting of 1.5°C (or even 2°C) is not something that can be planned for with certainty - it is a question of probabilities and might prove impossible due to physical climate system feedbacks under a range of emission pathways.
An *enhanced protection pathway* to limit those risks would thereby first and foremost focus on near-term emission reductions to slow-down warming and reduce peak warming as much as possible, taking into consideration a wide range of physically possible outcomes at peak warming.

After peak warming, a range of new questions arise for the long-term phase. A long-term temperature decline after net-zero CO_2 emissions is a distinct possibility[22]. In a less optimistic case, some level of net-negative CO_2 emissions might be required to even ensure peaking of global temperatures in case of strong climate feedbacks. Similarly, high peak warming outcomes may require significant amounts of net-negative CDR to draw temperatures down again (Fig. 2c). We argue that such high risk outcomes like high peak warming or continued warming after net-zero CO_2, and the resulting net-negative CO_2 emissions required to counter such outcomes, need to be systematically considered in the design of mitigation pathways. This should happen in line with core obligations under environmental law, such as the principle of "harm prevention" that requires taking preventive measures to avoid certain risk outcomes[51].

Based on these considerations, we suggest that there is a need for an environmentally sustainable "preventive CDR capacity" to hedge against long-term high risk outcomes resulting from stronger than expected climate feedbacks. Such a need for a preventive capacity has substantial implications for the use of CDR in stringent emission reduction pathways in light of constraints that limit the overall CDR deployment[93]. Pathways relying on large amounts of CDR to even achieve net-zero CO2 often exhaust or exceed sustainability limits already by design[19], leaving little room for course adjustments in case of high warming outcomes. On the other hand, pathways that deploy very little CDR may fail to build up the technological solutions required to establish a preventive CDR capacity. Incorporating preventive CDR in pathway design requires further reflections, including on avoiding long-term climate risks, and probability levels reflecting risk aversion, policy design[94], but also how responsibilities could be assigned to different emitters for providing for this preventive CDR capacity[40,48]. Finally, it is vital that this preventative capacity be designed to exploit potential synergies with other mitigation strategies and sustainable development goals and reduce competition for resources.

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[95]. 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.

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Methods

Evaluating net–negative CO_2 emissions needs reflecting climate uncertainty

In our illustrative analysis we assess the net-negative CO_2 emissions (NNCE) for the PROVIDE REN_NZCO2 scenario[96]. The REN_NZCO2 scenario follows the emission trajectory of the Illustrative Mitigation Pathway (IMP) "REN" from the IPCC's 6th Assessment Report (AR6)[97,98] until the year of net-zero CO_2 (2060 for this scenario). After the year of net-zero CO_2, emissions (of both GHGs and aerosol precursors) are kept constant.

Deriving climate response metrics

For this analysis we need to derive three metrics that capture different elements of the climate response during the warming phase and the long-term phase. These are:

1. The effective transient response to cumulative emissions (up), or eTCREup: This metric captures the expected warming for a given quantity of cumulative emissions until net-zero CO_2;
2. The effective transient response to cumulative emissions (down), or eTCREdown: This metric captures the expected warming or cooling for a given quantity of cumulative net-negative emissions after net-zero CO_2. This is a purely diagnostic metric and incorporates also the effects of the effective Zero Emissions Commitment (eZEC).
3. The effective zero emissions commitment (eZEC): The continued temperature response after net-zero CO_2 emissions are achieved and sustained[22]. Here, eZEC is evaluated over 40 years (between 2060 and 2100).

To estimate eTCREup (Equation 1), we directly use the warming outcomes reported in the PROVIDE ensemble. The warming outcomes are evaluated using the simple climate and carbon cycle model FaIR v.1.6.2[35] in a probabilistic setup with 2237 ensemble members. Each ensemble member has a specific parameter configuration that allows for the assessment of ensemble member specific properties like the climate metrics introduced above across different emission scenarios. This probabilistic setup of FaIR is consistent with assessed ranges of equilibrium climate sensitivity, historical global average surface temperature and other important metrics assessed by IPCC AR6 WG1[20].

$$eTCRE_{up}(n) = \frac{T_{2060}(n) - T_{2000}(n)}{\sum_{2000}^{2060} E_{t'}} \quad (1)$$

Where, n refers to the ensemble member from FaIR, t′ is the time step, $E_{t'}$ is the net CO_2 emissions in time step t′, and $T_{t'}(n)$ refers to the warming in the time step t′ for a given ensemble member.

We need to take a different approach to estimating the second metric ($eTCRE_{down}$), since the PROVIDE REN_NZCO2 does not have NNCE by design. We adapt this scenario with different floor levels of NNCE ranging from 5 Gt CO_2/yr to 25 Gt CO_2/yr (Fig. S1) that are applied from 2061 to 2100. The scenario is unchanged before 2060. We then calculate the warming outcomes for each of these scenarios applying the same probabilistic FaIR setup and identify the scenario (in this case, REN_NZCO2 with 20 Gt CO_2/yr net removals) for which all ensemble members are cooling between 2060 and 2100 (Fig. S1). This is required to get an appropriate measure of NNCE emissions. From this adapted scenario, we evaluate the eTCREdown for each ensemble member using Equation 2.

$$eTCRE_{down}(n) = \frac{T_{2100}(n) - T_{2060}(n)}{\sum_{2060}^{2100} E_{t'}} \quad (2)$$

Calculating cumulative NNCE for each ensemble member: Each ensemble member demonstrates a different level of peak warming that depends on $eTCRE_{up}$ (Figure 2c). We calculate the cumulative NNCE (per ensemble member) that is necessary to ensure post-peak cooling to 1.5°C in 2100 using Equation 3 depending on the case:

$$NNCE(n) = 0 \text{ if } T2060\,(n) < 1.5 \text{ else } \frac{1.5 - T_{2060}(n)}{eTCRE_{down}(n)} \quad (3)$$

Estimating the effective zero emissions commitment (eZEC) allows us to separate the stabilisation and decline components of $NNCE$. We evaluate eZEC using the post-2060 warming outcome of the original PROVIDE REN_NZCO2 scenario (Equation 4)

$$eZEC(n) = T_{2100}(n) - T_{2060}(n) \quad (4)$$

We assess the component of NNCE(n) to compensate for a positive eZEC using Equation (5).

$$NNCE_{stabilisation}(n) = 0 \text{ if } T2060(n) < 1.5 \text{ else } \frac{eZEC(n)}{eTCRE_{down}(n)} \quad (5)$$

We then assess the component of this NNCE(n) for cooling after stabilisation using Equation (6).

$$NNCE_{decline}(n) = NNCE(n) - NNCE_{stabilisation}(n) \quad (6)$$

Overshoot reversibility for annual mean temperature and precipitation

We analyse climate projections for the SSP5-34-OS and the SSP1-19 scenario by 12 Earth System models of the Coupled Model Intercomparison Project Phase 6[99]: CESM2-WACCM, CanESM5, EC-Earth3, FGOALS-g3, GFDL-ESM4, GISS-E2-1-G, IPSL-CM6A-LR, MIROC-ES2L, MIROC6, MPI-ESM1-2-LR, MRI-ESM2-0, UKESM1-0-LL.

We smooth GMT time series by applying a 31-year running average. In each simulation run we identify *peak warming* as the year where this smoothed GMT reaches its maximum. Next, we select the years before and after peak warming where the smoothed GMT is closest to -0.1 and -0.2 K below peak warming. There is a substantial, model dependent asymmetry in the average time between the rate of change in GMT before and after peak warming[65]. In each run we average yearly temperatures and precipitation for the 31 years around the above described years of interest. Finally, for each ESM these 31-year periods are averaged over all available runs of the ESM and an ensemble median for the 12 ESMs is computed for the displayed differences.

2300 projections for sea-level rise, permafrost and peatland

We project sea-level rise, permafrost and peatland carbon emissions with two sets of scenario ensembles as documented in ref [100]. Both sets of scenarios stabilise temperature rise below 2°C, with one set of scenarios achieving and maintaining the net-zero GHG emission goal of the Paris Agreement and the other set achieving net-zero CO_2 emissions only.

sea-level rise projections are taken from ref [100], based on a combination of a reduced-complexity model of global-mean temperature with a component based simple sea-level model to evaluate the implications of different emission pathways on sea-level rise until 2300. We project carbon dynamics for permafrost and northern peatlands for the aforementioned scenario set using the permafrost module of the compact earth systems model OSCAR[101], and a peatland emulator calibrated on previously published peatland intercomparison project[102]. The forcing data used to drive the permafrost and peatland modules are GMT change and the atmospheric CO_2 concentration change relative to pre-industrial levels. Firstly, we simulated the CO_2 fluxes and CH_4 fluxes from both permafrost and northern peatlands (see Fig S3 for the responses of individual components). Next, we computed the net climate effects of these two systems using the GWP* following the method described in ref [102]. We use Equation 7 to derive the CO_2-warming-equivalent emissions (E_{CO_2-we*}) of the CH_4 emissions, taking into account the delayed response of temperature to past changes in the CH_4 emission rate:

$$E_{CO_2-we*} = GWP_H \times \left(r \times \frac{\Delta E_{CH_4}}{\Delta t} \times H + s \times E_{CH_4}\right) \quad (7)$$

Where ΔE_{CH_4} is the change in the emission rate of E_{CH_4} over the Δt preceding years; is the CH_4 emission rate for the year under consideration; r and s are the weights given to the impact of changing the CH_4 emission rate and the impact of the CH_4 stock. Following ref [102], we use $\Delta t = 20$. Because of the dependency on the emission's historical trajectory and carbon cycle feedbacks, the values of r and s are scenario dependent. Here we use the r = 0.68 and s = 0.32 (the values used in ref [102] for RCP2.6), with H = 100 years, GWP_{100} of 29.8 for permafrost and GWP_{100} of 27.0 for peatland[20].

We then estimate the global temperature change (ΔT) due to permafrost and peatland CO_2 and CH_4 emissions as the product of the cumulative anthropogenic CO_2-we emissions from permafrost and northern peatlands and the TCRE:

$$\Delta T_{permafrost\&peatland} = TCRE \times \left(\sum_{1861}^{2300} \left(E_{CO_2,2300} - E_{CO_2,pre}\right) + \sum_{1861}^{2300}\left(E_{CO_2-we*,2300} - E_{CO_2-we*,pre}\right)\right) \quad (8)$$

Where $E_{CO_2,2300}$ and $E_{CO_2,pre}$ are CO_2 emission rates from permafrost and northern peatlands in 2300 and in the pre-industrial era, respectively; $E_{CO_2-we*,2300}$ and $E_{CO_2-we*,pre}$ are CO_2-we* due to permafrost and northern peatland CH_4 emissions in 2300 and in the pre-industrial era, respectively. For TCRE, we take the median value of 0.45°C per 1000 $GtCO_2$ [20].

Data and Code availability

The scripts to replicate Fig. 2-5 are available here: https://gitlab.com/climateanalytics/2023_overshoot_perspective . The PROVIDEv1.2 scenario data used for Fig. 2 is available at https://zenodo.org/record/5886912. Data required to reproduce Fig. 3 can be found here: https://esgf-data.dkrz.de/search/cmip6-dkrz/. Data required to reproduce Fig. 4 is included in the repository.

Competing interests

The authors declare no competing interests.

Author contributions

CFS and QL conceived the study. CFS designed the study and wrote the first draft. JR and CFS designed Fig. 1, GG performed the analysis underlying Fig. 2 supported by ZN, CJS and JR, PP performed the analysis underlying Fig. 3, BZ, MM and TG performed the analysis underlying Fig. 4. QL and CMK designed the case study presented in Box 1. All authors contributed to the writing of the manuscript.

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