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Overshoot: A Conceptual Review of Exceeding and Returning to Global Warming of 1.5°C

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Abstract

Limited progress with mitigation makes it almost inevitable that global warming of 1.5°C will be exceeded. This realization confronts Parties to the United Nations Framework Convention on Climate Change (UNFCCC) with a choice either to stabilize warming above but as close as possible to 1.5°C or to reverse global warming back to this level. We review core concepts and current knowledge relating to overshoot: an exceedance and subsequent decline back below a specified global warming level. We clarify the concept and origins of overshoot in science and climate policy, discuss the key drivers of climate-related risks and how they might evolve under overshoot trajectories to foster more systematic research into those risks, and consider the role of adaptation. We then consider the feasibility of overshoot in terms of mitigation across the six feasibility dimensions introduced by the Intergovernmental Panel on Climate Change (IPCC) in its sixth Assessment Report. We conclude by discussing critical barriers, challenges, and knowledge gaps related to overshoot.

Contents

1. INTRODUCTION

Earth experienced exceptional temperatures during 2023 and 2024. Global warming[1] will reach 1.5°C by the early 2030s, even in the most ambitious category of mitigation scenarios assessed by the Intergovernmental Panel on Climate Change (IPCC), and rise further to ∼1.6°C by mid-century as the best estimate (3, 4). Such scenarios assume concerted global action from 2020 and

[1]Consistent with the IPCC, we use the term global warming to represent the running 20-year global average surface temperature, relative to the period 1850–1900. Global average temperature may be above or below this 20-year running average in individual years, given internal variability of about ±0.25°C (1, 2).

greenhouse gas (GHG) emissions falling by ∼60% by 2035 (5), but global emissions have continued to increase (6, 7). The remaining carbon budget to limit global warming to 1.5°C with 50% probability from January 1, 2025, is less than 4 years of current emissions (6). There is no historical precedent or scenario from global integrated assessment models wherein emissions would reduce sufficiently rapidly to keep global emissions within this remaining carbon budget (3). Even if global action accelerates rapidly, the question is increasingly not whether global warming will exceed 1.5°C (8), but by how much it will exceed this level and for how long.

These trends are in stark contrast with the Paris Agreement's ambition to "pursue efforts to limit the temperature increase to 1.5°C above preindustrial levels, recognizing that this would significantly reduce the risks and impacts of climate change" (9). The meeting of the Conference of the Parties to the Paris Agreement in Dubai (COP28) further reaffirmed the ambition to "keep 1.5°C within reach" (10).

Reconciling these discordant perspectives relies on a reframing of what "keeping 1.5°C within reach" means: the notion that even though exceeding global warming of 1.5°C is largely inevitable by now, such exceedance would be limited in magnitude and duration and that sustained and concerted global action can bring global warming back down to 1.5°C before the end of the twenty-first century.

The reports of the IPCC's sixth assessment cycle made clear that changes in climate extremes and climate-related risks increase with every increment of warming and that risks will be greater if global warming rises above 1.5°C than if it had been limited to or below that level (2, 11–13). Extreme heat and heavy precipitation events, as well as droughts in some regions, are projected to become more intense and frequent with every increment of global warming, even 0.1°C (13). Warming beyond 1.5°C also increases the likelihood of irreversible losses such as warmwater coral reef collapse (14, 15). Much less clear are (*a*) to what extent bringing warming down again to 1.5°C before the end of the century would limit or reduce climate-related risks compared with global warming stabilizing above 1.5°C, (*b*) how risks incurred after a return to 1.5°C compare to risks incurred had 1.5°C never been exceeded, and (*c*) how feasible such overshoot pathways are in the real world.

Stabilizing global warming at any level relies on at least net-zero global CO_2 emissions alongside deep and sustained reductions in non-CO_2 emissions. Limiting warming anywhere near 1.5°C relies on rapid and transformational changes in all sectors to reach net-zero CO_2 emissions in the 2050s, with every year of delay increasing the amount by which 1.5°C will be exceeded (3, 7). Reversing global warming back to 1.5°C would require even greater mitigation efforts beyond midcentury to achieve a combination of sustained net-negative CO_2 emissions and further reductions in non-CO_2 emissions, which could create additional, uneven risks and pressures on nature and society that compound the risks from climate change itself.

These tensions imply that there is no single answer to the question of whether an overshoot pathway that surpasses 1.5°C of global warming, peaks, for example, at ∼1.7°C, and then reduces global warming again to 1.5°C is preferable to a pathway that surpasses 1.5°C global warming and stabilizes at 1.7°C. Preferences will depend crucially on the distribution and evolution of climate-related risks as well as the distribution and type of additional mitigation efforts that a decline in global warming would require. Policymakers, nongovernmental organizations, and the research community need to open a conversation regarding these choices and trade-offs (16). This conversation will rely on science-based evidence of the implications of overshoot trajectories for climate-related risks, losses, and damages, for near- and long-term adaptation and mitigation measures and efforts, and for distributional aspects, social acceptability, and sustainable development more broadly.

WHAT DOES "OVERSHOOT" MEAN?

"Overshoot" has different meanings in scientific communities, policy, and common languages and is therefore often misunderstood. In common English and many policy uses, overshoot means to exceed or breach a limit, while in the IPCC AR6 it means both to exceed and to decline again below a specified level within a specified time period (see definition in Section 2).

These various interpretations create different connotations: While overshoot in common English simply means a failure to remain within a limit, the IPCC definition implies both a failure and a subsequent corrective action. The corrective action (reversal and decline back below the limit) does not cancel out the failure because overshoot of 1.5°C implies greater climate change impacts than if global warming had remained below the limit throughout; however, overshoot implies fewer and less significant climate change impacts than if global warming exceeds 1.5°C and remains above that level permanently. Whether overshoot as defined by the IPCC is seen mainly as a threat (due to exceedance of a limit) or also as a potentially less detrimental course of action (because it implies more limited climate change impacts than if the limit is exceeded permanently) thus depends on the counterfactual scenario.

We considered alternative terminologies but decided to continue using the IPCC AR6 terminology because other word choices create additional issues. Consistent use of the term will be critical to fostering a common understanding of overshoot in the interface between science and policy.

This review seeks to contribute to and support such conversations by synthesizing the current scientific knowledge about different aspects of overshoot pathways as well as critical research needs. We use the IPCC's sixth Assessment Report (AR6) as a point of departure but expand our discussion with more recent research and insights to build a synthesis of the diverse areas of knowledge and relevant conceptual frameworks and outline some of the critical knowledge gaps and research needs.

2. CONCEPTUAL DIMENSIONS OF OVERSHOOT

Effective climate change mitigation scenarios necessarily fall into one of three categories: (*a*) scenarios that stay below a given warming level, (*b*) scenarios that exceed a given warming level but eventually stabilize at a higher level (permanent exceedance), and (*c*) overshoot scenarios that exceed a given warming level and then return to or below that level within a specified time frame. The full definition of overshoot pathways given in the IPCC AR6 glossary is as follows:

> Pathways that first exceed a specified concentration, forcing, or global warming level, and then return to or below that level again before the end of a specified period of time (e.g., before 2100). Sometimes the magnitude and likelihood of the overshoot are also characterised. The overshoot duration can vary from one pathway to the next, but in most overshoot pathways in the literature and referred to as overshoot pathways in the AR6, the overshoot occurs over a period of at least one decade and up to several decades. (**https://apps.ipcc.ch/glossary/**)

While this definition is general (i.e., applicable for various climate variables), the recent literature uses it mainly for global temperature, which is also how we apply the term in this article. Note that, under this definition, not all scenarios exhibiting a temperature decline would necessarily be labeled as an overshoot pathway because doing so depends on the specific warming level being considered; e.g., a scenario that peaks at 1.8°C and then declines and stabilizes just under 1.7°C would be called an overshoot scenario with respect to 1.7°C but a permanent exceedance (and not an overshoot) scenario with respect to 1.5°C.

Figure 1 illustrates key conceptual characteristics of overshoot pathways; i.e., global temperature crosses a specified warming level and, after peaking, declines again to or below that

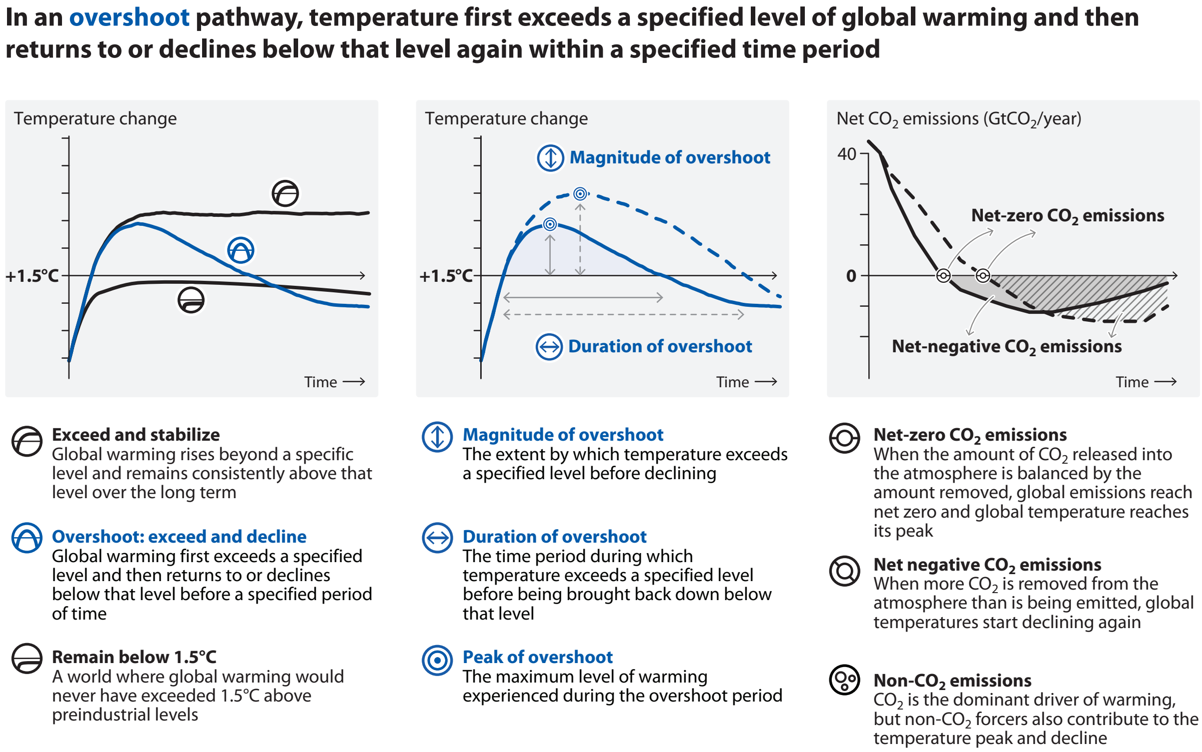


Figure 1

Conceptual dimensions of overshoot. The left panel shows three illustrative temperature pathways relevant for discussion of overshoot: a pathway where warming remains below 1.5°C, a pathway that exceeds and stabilizes warming above 1.5°C, and an overshoot pathway where warming exceeds and declines back below 1.5°C. The middle panel shows the warming for two illustrative overshoot pathways that differ in terms of duration and magnitude of overshoot, shown as solid and dashed lines. The right panel shows the illustrative net CO2 emissions and key emission milestones for the two overshoot pathways in the middle panel, with peak warming approximately correlated with net-zero global CO2 emissions. The overshoot pathway shown as dashed line has a greater magnitude and duration (*middle panel*), with later net-zero and deeper net-negative CO2 emissions (*right panel*) than the overshoot pathway shown as solid line.

originally specified level. The warming level as well as the duration and magnitude of the overshoot can vary. Multi-model studies indicate that peak warming is reached roughly when global net CO_2 emissions from human activities reach zero, and warming declines when CO_2 emissions become net-negative [i.e., when global carbon dioxide removal (CDR) outweighs remaining gross CO_2 emissions (2, 17; see also Section 6, below). Higher emissions in the near term imply higher and longer-lasting overshoot and need to be followed by greater net-negative CO_2 emissions to return to the same warming limit. Sustained emission reductions of short-lived climate forcers (SLCFs) with a warming effect (mainly CH_4) can also contribute to declining temperatures to a limited extent [(18); see also Section 7, below] but are not shown in this conceptual figure.

While the concept of temperature overshoot can be applied to any warming level, a key focus for climate policy and in this review is on overshoot of 1.5°C with a return by 2100. Such pathways still imply urgent near-term mitigation efforts that limit peak warming to less than ∼1.8°C as best estimate (3). Higher global warming limits and magnitudes and durations of overshoot are used scientifically; e.g., model experiments with very high overshoot can help researchers better understand biogeochemical aspects, reversibility/irreversibility, etc. Such experiments can provide further insights on risks and mitigation pathways for overshoot but do not directly address or imply plausibility, let alone desirability from a policy perspective (19).

Other aspects related to the conceptual dimensions of overshoot include the choice of reference level and period for the global surface temperature (i.e., what is considered preindustrial) and the estimation method and averaging period for calculating average global surface temperatures (see 1, cross-chapter box 2.3). The IPCC generally uses 20-year averages for presenting future global warming levels based on modeled scenarios, and the long-term temperature goal (LTTG) of the Paris Agreement "is assessed over a period of decades" (20, building on the structured expert dialogue of the 2013–2015 periodic review of the LTTG). Ongoing work seeks to develop an agreed methodology for more timely updates on current warming levels in relation to normative warming limits such as 1.5°C (e.g., 21).

3. THE CONCEPT OF OVERSHOOT IN THE INTERPLAY BETWEEN THE IPCC AND THE PARIS AGREEMENT

The overarching objective of the UN Framework Convention on Climate Change (UNFCCC) is "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (22). The Paris Agreement (signed in 2015) shifted the focus from GHG concentrations to a long-term temperature goal that sets upper bounds ("holding...to well below 2°C...and pursuing efforts to limit ... to 1.5°C") (9). Subsequent Conferences of the Parties (COPs) to the Paris Agreement strengthened the focus on the 1.5°C end of the LTTG (10, 23, 24).

The Paris Agreement does not refer to temperature overshoot explicitly, but neither does it rule it out (25). Given the proximity to 1.5°C and the already very limited remaining carbon budget at the time the agreement was negotiated, the possibility of exceeding 1.5°C (and hence "pursuing efforts" to limit warming to 1.5°C from above this level) must have already been on the minds of at least some negotiators by then. Furthermore, through agreeing to achieve a "balance of anthropogenic emissions and removals" in Article 4.1 and clarifying subsequently at COP24 to use the Global Warming Potential with a time horizon of 100 years (GWP100) to account for emissions (26), Parties have implicitly already agreed to aim for a long-term decline in temperature; counterbalancing sustained emissions of gases with shorter lifetimes with ongoing removal of long-lived CO_2 gives a net long-term cooling effect. This effect was understood pre-Paris (27), but how much policymakers were aware of it is unclear. The expectation of a decline in global warming under net-zero GHG emissions when using GWP100 was reconfirmed by subsequent studies and noted in the conclusions of AR6 (2, 3, 28, 29).

An explicit acknowledgment of overshoot, and the emission trajectories that it would entail, remains remarkably absent in COP declarations that reconfirm the ambition to "keep 1.5°C within reach." This lack of acknowledgment reflects the political advantage of ambiguity over hard limits: The concept of overshoot allows governments to assert that their actions remain consistent with their ambition to limit warming to 1.5°C even while that warming level is being exceeded (30). The absence of clear science-based limits on how much exceedance of 1.5°C still provides a plausible chance to return to 1.5°C within a meaningful time frame poses significant risks to the actual achievement of the LTTG (31).

In the scientific domain, overshoot emerged as a core topic only over the past decade. Earlier studies constructed temperature and concentration overshoot pathways mostly to illustrate conceptually that "dangerous anthropogenic interference" depends on trajectories as well as long-term outcomes (32, 33), but also to show that overshoot can reduce mitigation costs to achieve a long-term target (e.g., 34). These issues were reflected in the IPCC AR4 but not given prominence, nor was there detailed discussion of the emissions implications (35).

IPCC AR5 established the need for at least net-zero CO_2 emissions to limit warming to 2°C with a probability of greater than 66% (36, 37); however, terms such as "overshoot" and "peak and decline" were used almost entirely with regard to CO_2-equivalent concentrations rather than temperature because concentrations remained the key metric by which mitigation scenarios were categorized (38). AR5 also introduced the representative concentration pathway (RCP) scenarios; even though the lowest scenario (RCP2.6) resulted in a peak and decline in temperature before 2100, this consequence was not highlighted as key characteristic of that scenario and was treated more as incidental outcome (39, 40).

The Paris Agreement's inclusion of 1.5°C in its LTTG sharply increased the scientific focus on temperature overshoot. The IPCC Special Report on Global Warming of 1.5°C (SR15) used the likelihood of exceeding 1.5°C to categorize the most ambitious mitigation scenarios (11, 41). The lowest mitigation category was referred to in the Report's Summary for Policymakers (11) as "pathways that limit warming to 1.5°C with no or limited overshoot," recognizing that very few scenarios remained entirely below 1.5°C and that most of even the most ambitious pathways (with global emissions falling from 2020) exceed 1.5°C as a best estimate for several decades. This categorization choice normalized the notion that "limiting warming to" a given level could be achieved by exceeding that level for some time, provided that warming fell below that level again before 2100. However, climate-related risks and impacts associated with overshoot trajectories were left mainly as a key knowledge gap (42).

AR6 was the first set of IPCC reports to consider overshoot scenarios from the physical science perspective in terms of temperature evolution and the role and feasibility of CDR to achieve net-negative CO_2 emissions, as well as from a mitigation perspective, retaining the overshoot categories used in the SR15 Summary for Policymakers (2, 3). The literature on climate-related risks remained sparse, but the assessment further concluded that risks to natural and human systems, including irreversible impacts, would increase when surpassing 1.5°C and that risks would be less severe for lower and shorter-duration "temporary" overshoot pathways (12). The Synthesis Report (5) combined key physical science, impacts and risks, and mitigation perspectives on overshoot. The "Technical Dialogue of the First Global Stocktake" of the Paris Agreement in turn pointed to the need for more research on overshoot scenarios, potential economic and noneconomic loss and damage, and adaptation options (43).

This brief history shows that climate policy and science relied on an interactive process to engage with the subject of overshoot. Early conceptualization occurred in the science domain, but it became a real-world problem only after an explicit temperature goal was politically set. The pendulum now appears to have swung back into the science domain with an increasing awareness of critical assumptions and knowledge gaps that hamper evidence-informed decision-making on overshoot (19, 44), while climate policy has yet to incorporate overshoot into its agenda. A continuing exchange between those two domains will be necessary for researchers to better understand the knowledge needs of policymakers and how science can be linked with policy narratives that currently focus on loosely defined concepts of "net-zero" (45). The further mitigation actions needed beyond midcentury to achieve a decline in global warming and their feasibility need to become a central part of that dialogue, and policymakers and research funders need to ensure that relevant knowledge gaps can be addressed.

4. A CONCEPTUAL FRAMEWORK TO UNDERSTAND CLIMATE-RELATED RISKS UNDER TEMPERATURE OVERSHOOT

The IPCC AR6 concluded that impacts of recent climate trends, including extremes, are already being felt in all regions of the world, with those most vulnerable being affected the most, and that for every increment of warming, climate-related risks[2], and related losses and damages, increase in severity and become more complex to manage (2, 12, 13). These findings imply urgency and a clear desirability to ensure that warming exceeds 1.5°C by as little as possible to limit risks and the potential for irreversible impacts (12).

The IPCC assessment expressed high confidence that overshoot of 1.5°C would result in additional severe risks compared with if global warming had remained below 1.5°C (12), but scarce attention has been given to how risks would evolve in an overshoot pathway when global warming first exceeds 1.5°C but then declines again (16, 46, 47). Understanding the evolution of risks in overshoot pathways is necessary to make a case for the additional mitigation efforts needed to achieve a decline in global temperature rather than stabilizing at whatever above-1.5°C level global warming might peak. It is also important to inform robust adaptation strategies, to manage complex and cascading risks including those arising from additional mitigation efforts, and to build long-term resilience in the context of sustainable development.

No decline in temperature can undo irreversible harm, i.e., it will not bring back people or species that were lost while limits of adaptation were exceeded. We therefore address two core questions: to what extent could declining temperature reduce future climate-related risks, i.e., what future potential impacts could yet be avoided if global warming falls below 1.5°C again, rather than remaining elevated above this level; and, equally, how might risks in a world that has exceeded and returned to 1.5°C differ from a world that had remained below 1.5°C throughout. Further questions include how risks evolve if the overshoot period is prolonged beyond the twenty-first century and the implications for risks related to the rate of temperature change.

The literature currently lacks robust evidence and a coherent framework to consider these questions. This section therefore sets out some core elements that could guide systematic research within the broader context of socioeconomic drivers, mitigation, (mal)adaptation, and other policies or actions that may also influence risk.

Risks in overshoot pathways will depend largely on how the three core determinants of risk—hazard, exposure, and vulnerability (48)—evolve during the period of overshoot. AR6 broadened the definition of risk to include responses, in recognition that adverse consequences can also arise from actions taken to respond to climate change (49–51). The potential for these latter interactions increases in overshoot scenarios, e.g., from the widespread demand for land for CDR that could compound risks to ecosystems and food security (52–55) and from the prioritization of finance for mitigation to achieve even deeper reductions that could limit the support to least-developed countries to adapt to climate change [(56); see also Section 5, below]. The interplay of these four determinants of risk is dynamic and will occur through complex and cascading processes that can propagate risk among systems, sectors, and regions.

Many hazards, or adverse climatic impact-drivers (57), scale roughly with global warming in projections with increasing temperatures (13). These changes are therefore expected to be largely reversible if global warming declines, e.g., regional temperature and precipitation means and extremes, Arctic sea ice coverage, and some derivative hazards such as drought (although the response will not necessarily be linear with global average temperature). However, responses after overshoot have been less investigated, and some variables could exhibit inertia and hysteresis effects, especially at regional scales (58; see also Section 6). Furthermore, even if a hazard is reversible, this does not imply that associated risks would also decline. This is because changes

[2]Risk is defined by the IPCC in its AR6 as "[t]he potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change" (**https://apps.ipcc.ch/glossary/**).

in risk depend not only on changes in hazards but also on concurrent changes in exposure and vulnerability as well as on risks from (mal)adaptation and mitigation.

Figure 2 illustrates conceptually some of the potential interplays of these determinants of risk in an overshoot world (i.e., where warming has exceeded to 1.5°C and then declined back), compared with a world where global warming of 1.5°C had not been exceeded, and an alternative world where global warming exceeds and stabilizes above 1.5°C. The figure shows four illustrative examples; these are intended not as projections but as illustrations of the different trajectories that the four key drivers of climate-related risk (i.e., hazards, exposure, vulnerability, and risks arising from mitigation responses to achieve the decline in global temperature) could take. **Figure 2** illustrates that the different ways in which those drivers evolve and interact will shape the degree to which an overshoot world would still suffer worse consequences than a world that avoided global warming of 1.5°C outright; it also illustrates the extent to which a return to 1.5°C could reduce harm compared with a world in which warming remained above that level permanently. We emphasize that the examples shown in **Figure 2** are conceptual only (see **Supplemental Data** for additional details) and that future research will need to address the determinants of risks in different real-world overshoot contexts.

In the most optimistic case, risks could be lower in some sectors and regions once global warming has declined again than when 1.5°C was first exceeded (**Figure 2*d***). This scenario could be achieved if the overshoot period prompted the implementation of effective adaptation measures and broader policies that close adaptation deficits and build resilience in the longer term by reducing vulnerability (e.g., reducing precarious socioeconomic conditions and distributional inequity and improving health status) and/or exposure (e.g., widespread implementation of improved building designs to reduce heat stress or managed retreat from areas that are at high risk of river flooding). Nonetheless, from the perspective of accumulated losses and damages, even in this most optimistic scenario, the time period with overshoot will lead to irreversible impacts that would not have occurred without global warming exceeding 1.5°C (e.g., human deaths from heat waves, irreversible damages to ecosystems).

In other contexts, however, risks could remain elevated or increase further, even after hazards have declined again, particularly where vulnerability and exposure increased as a result of the intervening temperature exceedance or other nonclimatic drivers (46, 59–61). For example, food insecurity arising from successive droughts during the period of temperature exceedance could result in undernutrition, child stunting and impaired development, increased child mortality, and deepening rural poverty (60, 62–64) (**Figure 2*a***). The reversibility of hazards is thus only a small part of understanding the evolution of climate-related risks in overshoot scenarios.

Furthermore, not all hazards will reverse proportionately to global average temperature: Some hazards, particularly those related to a cumulative response to increasing temperature, such as sea-level rise, would continue to increase even if global warming declines again or stabilizes (19) (**Figure 2*b***). Reducing global warming would only reduce the rate at which such hazards increase, but it would not be able to reverse the committed trend in the hazard. Risks related to such hazards are therefore expected to continue to increase, even if global warming declines again, but increase less than if global warming remains elevated (53, 65, 66).

Other hazards or impacts, even though reversible in principle, could experience a substantial lag between a decline in global warming and an eventual reversal. Key examples include shifts in ecosystems and food webs, where multiple interacting components imply that recovery, if possible at all, would take many decades to centuries (46, 67–69). Some impacts that occur at peak warming will be irreversible (e.g., species extinctions, ecosystem transformation), as biophysical and socioecological limits to adaptation are passed, and thus result in permanently altered states compared with preovershoot conditions (46, 47, 53, 70, 71). In the case of ecosystems, the demand for land

Climate risk will differ, and mostly be higher, in an overshoot world where global warming exceeds 1.5°C and then declines below that level, compared with a world where warming never exceeds 1.5°C

PROPELLER DIAGRAM
Each risk propeller diagram illustrates how climate risk may differ in a 1.5°C world (left side) versus an overshoot world and a world with permanent exceedance (right side).

Drivers of climate risk
The four blades on each side represent the drivers of climate risk:
- Hazard
- Exposure
- Vulnerability
- Responses to climate change

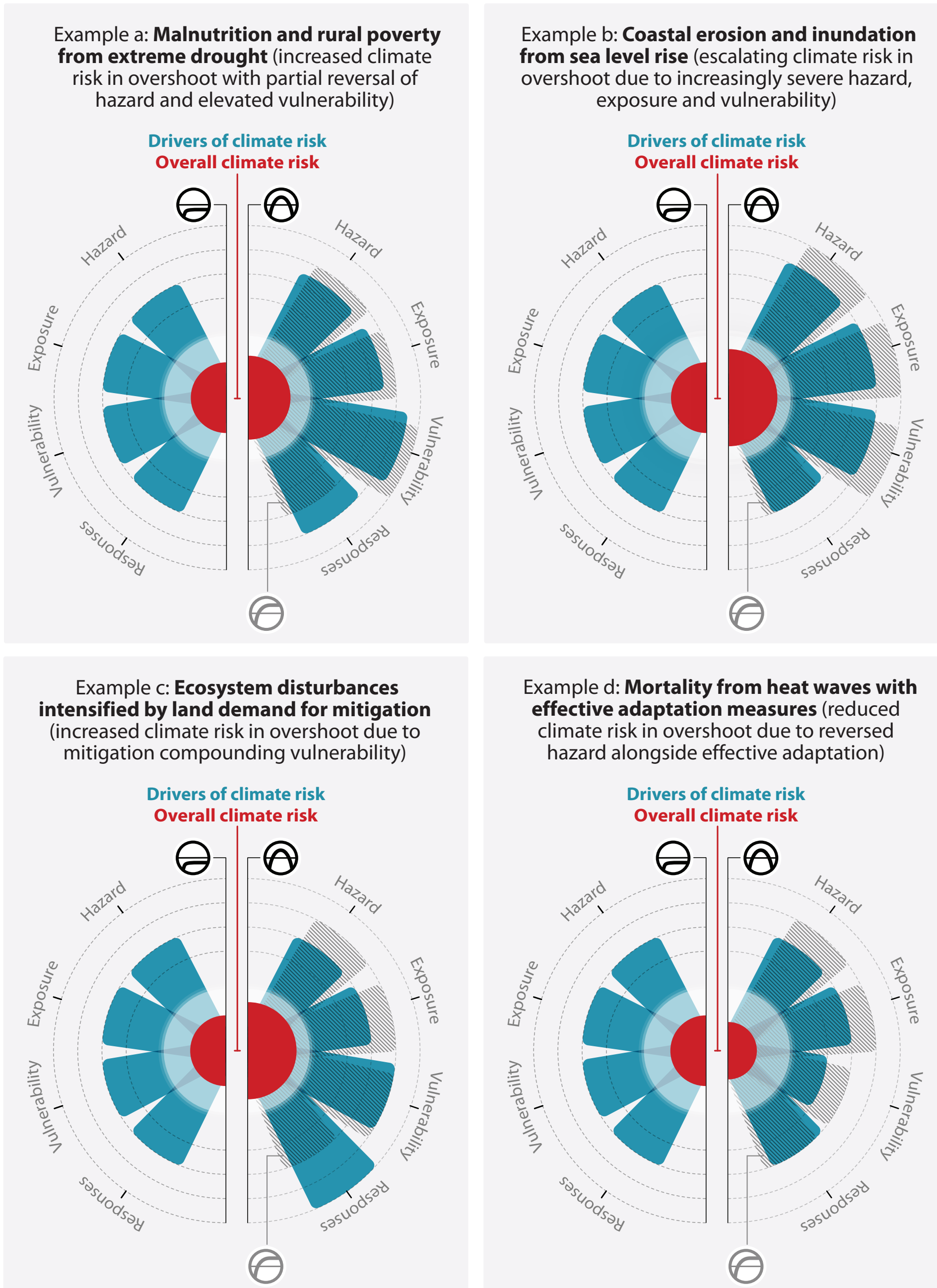
The height of each blade illustrates the contribution of each driver to the overall climate risk.

Overall climate risk
The center semicircles of each propeller illustrate the overall risk size, resulting from the dynamic interactions among the risk drivers in a 1.5°C world (left side) versus an overshoot world (right side).

1.5°C world
Drivers and overall climate risk in a world that could have been, where the global temperature increase never exceeded 1.5°C above pre-industrial levels (left side).

Overshoot world
Drivers and overall climate risk in an overshoot world, where global warming exceeds 1.5°C and then declines below it (right side).

Exceedance world
Drivers of risk in a world where global warming permanently exceeds 1.5°C (right hatched shadows).



The four examples of climate risks (a, b, c, d) are not predictions or projections, but conceptual illustrations of how risk could evolve. The data may vary depending on context, like location.

(Caption appears on following page)

Figure 2 (*Figure appears on preceding page*)

Illustrative changes in the risk drivers in an overshoot world compared with worlds where warming remained below 1.5°C or where warming exceeded 1.5°C permanently. This figure illustrates conceptually that climate-related risks in a world where global warming exceeded 1.5°C and then declined below that level again will be different (and in most instances higher) than the risks in a world where warming never exceeded that level, but also that risks would (in most instances) be lower than if warming remained above 1.5°C permanently. Panels *a–d* illustrate that the reasons for these differences can vary significantly, depending on specific systems, sectors, and regions, using four contrasting hypothetical examples and building on the commonly used risk propeller diagram (12, 50). In each panel, the four blades on the left-hand side indicate the key drivers of climate risk (hazard, exposure, vulnerability, and responses to climate change) in a below-1.5°C world, while the four blades on the right-hand side indicate how those risk drivers might have changed after an overshoot. The indicative magnitudes of resulting risks for the below-1.5°C and the overshoot worlds are indicated by red semicircles on a white canvas. The gray hashed blades on the right-hand side of each panel illustrate the change in the risk drivers in a world that exceeds and remains above 1.5°C permanently, without showing the resulting risk. The magnitude of each blade has been set to a uniform level in the below-1.5°C world, such that the overshoot and permanent exceedance worlds illustrate the relative change in the risk drivers compared to these drivers in the below-1.5°C world.

- Panel *a* illustrates that risk after overshoot could remain higher than if warming had remained below 1.5°C, even if hazards largely decline again, if vulnerability has increased due to impacts during the overshoot period; a possible example for this scenario would be malnutrition and rural poverty from extreme drought.
- Panel *b* illustrates that risk after overshoot could also remain higher than if warming had remained below 1.5°C because some hazards will continue to increase even if global temperature declines again, which can also increase vulnerability and exposure; a possible example for this scenario is coastal erosion and inundation from sea-level rise.
- Panel *c* illustrates that risk after overshoot could also remain higher than if warming had remained below 1.5°C, even if hazards fully decline again, if mitigation responses that aim to reduce global temperature increase pressure on already vulnerable and impacted systems; a possible example for this scenario would be ecosystem disturbances from climate change compounded by land demand for large-scale afforestation and biomass production for bioenergy.
- Panel *d* illustrates that risk after overshoot could, in principle, be lower than if warming had remained below 1.5°C if hazards fully decline again and if the overshoot period prompted effective enhanced measures to reduce vulnerability and close existing adaptation gaps; a possible example for this scenario would be reduced mortality from heat waves if comprehensive and effective adaptation occurred during the overshoot period. Further details on the narratives underlying these conceptual illustrations can be found in the **Supplemental Data**.

Note that this figure shows hypothetical examples intended to illustrate conceptually the different ways in which the four key risk drivers could change as a result of overshoot and to demonstrate the issues that will need to be addressed by dedicated research and assessment; they are not projections or predictions of actual risk for these systems, since those will depend on specific context, will vary by region, and will depend on location-specific adaptation and mitigation responses.

from CDR could further compound risks from climate change itself and thus result in materially higher risks in a world that returns to global warming of 1.5°C compared with a world that avoids exceeding that level through rapid near-term reductions in gross emissions (**Figure 2*c***).

Applying this conceptual framework of risks under overshoot to specific areas of impacts is beyond the scope of this review, as there is insufficient evidence in the literature to allow meaningful projections or to provide best estimates. Rather, we demonstrate this framework by characterizing the potential evolution of the five "reasons for concern" (RFCs) in the context of overshoot. RFCs have been used routinely by the IPCC for aggregating and communicating risks at global scales (59).

- RFC1: Unique and threatened systems. Species extinctions (53) and loss of cultural sites (72) will be irreversible even if global temperature declines again. Nevertheless, limiting the period of overshoot would reduce the likelihood of further impacts being realized compared with warming stabilizing at higher levels. Limiting the period of overshoot could lead to, for example, a more limited loss of ecosystem goods and services (**Figure 2*a***).
- RFC2: Extreme weather events. The hazard component of risks related to extreme weather is generally expected to decrease if global temperature declines. Effective and proactive adaptation during the overshoot period could, in principle, reduce vulnerability and hence lower overall risk levels (**Figure 2*b***). However, impacts during the overshoot period could

also erode resilience and increase vulnerability, especially if adaptation was absent or ineffective; the risks associated with extreme weather could therefore remain high postovershoot, even after hazards have decreased (**Figures 2*a*,*c***).

- RFC3: Distribution of impacts. The uneven distribution of risks across sectors and regions would be expected to shift further as global temperature declines. Regional climate changes can diverge over time, even if global warming stabilizes, due to the redistribution of heat around the globe (73, 74); such adjustments are likely to continue to occur at different regional rates, causing the distribution of hazards to be different after overshoot compared with before (75). Moreover, sectors, systems, and regions most at risk might see their adaptive and institutional capacities erode and remain at elevated risk due to increased vulnerability, even if global warming is reduced (see RFC2 above). If some regions or groups were able to adapt effectively while others became even more exposed or vulnerable during the overshoot period, global inequality would increase and the global benefits of declining temperature would be felt unevenly (**Figures 2*c*,*d***).
- RFC4: Global aggregate impacts. Broadly, global aggregate impacts can be expected to be smaller if warming returns to lower levels compared with if warming remains high**,** as the worldwide hazard level would be comparatively smaller with reduced warming. However, the global aggregate impacts would not be expected to scale with cooling in a simple manner due to cascading risks and shifting heterogeneities of regional risks, as discussed above for RFC3, and continuously growing pressure from sea-level rise (**Figure 2*b***). Global aggregate impacts in a post-overshoot world will depend critically on impacts and adaptation during overshoot and on the resulting socioeconomic, institutional, and governance systems.
- RFC5: Large-scale singular events. This concern refers to Earth system tipping points or critical thresholds, beyond which the world experiences abrupt and sometimes irreversible changes, e.g., ice sheet collapse, thermohaline circulation shift, Amazon forest dieback, and permafrost thaw (76). The likelihood of triggering most tipping points can be broadly expected to decrease if global temperature declines again rather than remaining elevated, such that the hazard component of risk associated with singular events would decline. Some large-scale singular events may also depend on nonclimatic factors; e.g., the risk of abrupt transitions in the Amazon depends on land-use change and direct forest degradation as well as climate change (77). The comparative risk of Amazon forest dieback before and after overshoot may therefore depend on the levels of direct human-induced deforestation and degradation in each period.

This section has provided a conceptual framework for investigating implications and consequences of overshoot trajectories for climate-related risks. We emphasize that this synopsis is not exhaustive; the scientific literature does not currently allow for robust projections of risk under overshoot, and outcomes will depend critically on sectoral and local contexts. Our goal here has been to demonstrate that the level and nature of risk in a world that returns to global warming of 1.5°C after an overshoot period will depend not only on the reversal of climate-related hazards, but also on how the exposure of society and ecosystems and their capacity to cope with and respond to climate-related stresses have been affected by the period of temperature overshoot as well as the impact of mitigation responses. This more comprehensive understanding of climate-related risk under overshoot signals the high potential for regionally divergent and potentially inequitable outcomes and sets out the issues that research will need to address systematically to enable a more robust characterization and assessment in future IPCC reports. The scarce evidence base and related knowledge gaps for the determinants of risk in an overshoot context, including risk transmission pathways and losses and damages, are currently significant barriers for assessment, particularly for the most vulnerable regions, communities, and ecosystems.

5. KEY CONSIDERATIONS FOR ADAPTATION AND CLIMATE RESILIENCE IN THE CONTEXT OF OVERSHOOT

The preceding section demonstrates that the implications of global temperature overshoot will depend strongly on the effectiveness of adaptation strategies for reducing (or limiting the increase in) exposure and vulnerability to climate change risks as well as for managing risks that arise from mitigation strategies. However, adaptation policies and actions to date continue to be insufficient to secure a livable future for multiple regions around the world. Even in the face of emerging transboundary, complex, and cascading risks, most current adaptation actions continue to be sector specific and unevenly distributed across regions, small in scale, fragmented, incremental, and short term, and they often prioritize immediate risk reduction with a significant potential for maladaptation (5, 78, 79). The demand for land and water for land-based CDR, which is a key element of strategies to reverse global warming, will increase these pressures (52, 54, 80).

Highly exposed and vulnerable peoples and regions already experience large gaps between current levels of adaptation action and what is needed to effectively respond to, and reduce, worsening adverse impacts (81). An estimated 3.3–3.6 billion people live in settings that are highly vulnerable to changing climate conditions (12). In addition, climate justice remains, for the most part, more of a conceptual objective than a reality within today's adaptation planning and implementation efforts (82, 83), and evidence of just outcomes from adaptation strategies and plans remains limited and ambiguous (e.g., 84).

The disparity in adaptation planning and effectiveness, both within and across regions, is likely to result in a continued widening of adaptation gaps under overshoot scenarios, with increasing adverse climate impacts, risks, and losses and damages. These widening gaps are compounded by the uneven distribution of adaptation finance (85). Globally tracked adaptation finance is currently unevenly distributed across regions and sectors; this uneven distribution, in conjunction with political framework and incentive paucities, is a key cause of existing adaptation implementation gaps (81). Addressing these gaps will require not only a dramatic scale-up of grant-based and other highly concessional finance and nondebt instruments, but also the transfer of technology and capacity building. An increased political focus on reversing global warming could exacerbate the inequitable allocation of adaptation finance, not only because of additional and competing investment needs for mitigation but also because a decline in global warming could be construed as effectively addressing climate-related risks, hence reducing the need for adaptation finance. Our conceptual framework of risks in overshoot pathways, and the contingency of those risks on adaptation, suggests that an approach that trades off resourcing for adaptation with mitigation could instead further deepen global inequalities.

Given that the next few decades will almost certainly see continuing increase in risk due to increasing global temperature, it may not be realistic to develop adaptation strategies explicitly for overshoot trajectories that rely on the reversal of some adaptation limits and climate-related risks with a future decline in global temperature (19). Adaptation responses that remain robust to a continued increase in global warming and stabilization well above 1.5°C are likely to yield significant benefits even if global warming declines again subsequently, e.g., by reducing exposure to hazards, strengthening early-warning systems, and ensuring that institutions are resourced to strengthen their resilience across scales and despite uncertainties in local climate projections.

Given that most adaptation actions require medium-to-long periods of time to deliver benefits, prompt implementation of effective adaptation is likely to be key to addressing increasing risk and, at its best, would outpace a slower reversal of hazards. This effort would require flexible strategies to increase resilience and deal with compound events, address increasing losses and damages, and accommodate shifting priorities in the face of irreversible impacts. Given the near ubiquity of soft limits and existing financial, governance, policy, and institutional constraints, initial entry points to enable such transformative action would urgently require bridging the adaptation finance gap to address factors that contribute to soft adaptation limits (79). Adaptation strategies that are contingent on a future decline in global temperature, and hence rely on yet-to-be-realized global cooperation, would carry a high risk.

6. EARTH SYSTEM RESPONSES AND GEOPHYSICAL FEASIBILITY OF OVERSHOOT

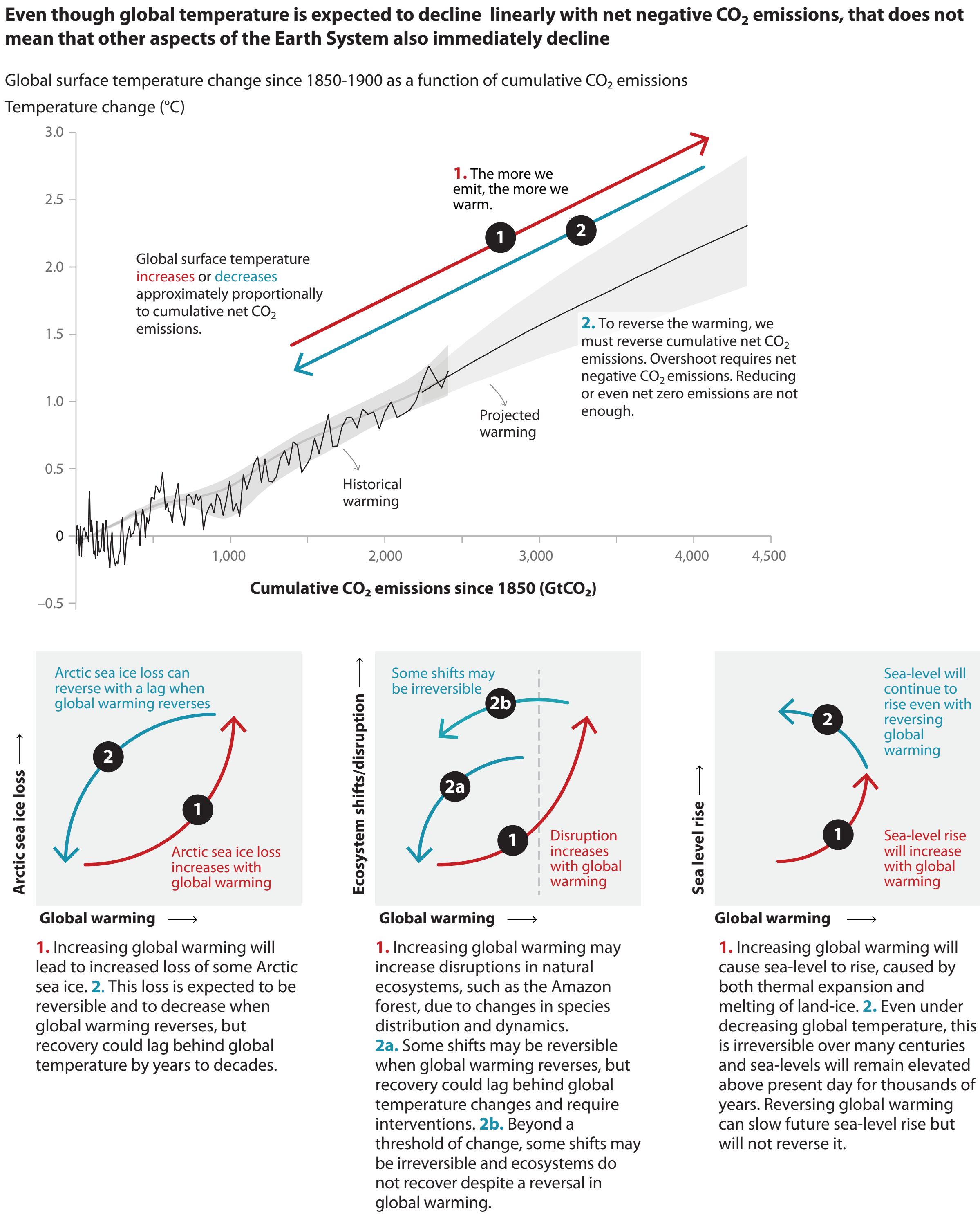
The magnitude of global warming scales almost linearly with cumulative CO_2 emissions (86, 87), and reaching net-zero global CO_2 emissions[3] would approximately stabilize CO_2-induced global warming over centuries to millennia (2). This stabilization is approximate as residual further warming or cooling under net-zero CO_2 emissions could be up to ±0.3°C over the following half-century (94, 95).

Reducing CO_2-induced global warming therefore requires net-negative global CO_2 emissions, i.e., a situation where anthropogenic permanent CDR outweighs any residual anthropogenic CO_2 emissions. The IPCC AR6 quantified that every 1,000 $GtCO_2$ results in warming of 0.45 [0.27–0.63]°C (2). Assuming symmetry of the global temperature response, a decline of 0.1°C in global warming could thus be achieved by net-negative emissions of 220 [160–370] $GtCO_2$ (see **Figure 3*a***). The total amount of CDR will need to be greater than this amount to compensate for any residual gross CO_2 emissions; achieving a decline in global warming through net-negative CO_2 emissions thus depends not only on large-scale CDR but also on the amount of residual gross CO_2 emissions (see also Section 7).

Some studies have questioned the symmetry of the temperature response to positive or negative net CO_2 emissions (96, 97), but other studies have found no discernible difference in global average surface temperature when the same cumulative CO_2 emissions are reached with or without overshoot (98). Any asymmetry is likely to be small and likely part of the uncertainty in residual warming or cooling under net-zero CO_2 emissions (99). Note that reversibility of global temperature with net-negative CO_2 emissions does not imply that global temperature would reverse with declining CO_2 concentrations because CO_2 concentrations would decline over time already even before net-zero CO_2 emissions. Most aspects of the climate system, including global temperature, will therefore exhibit a significant hysteresis relative to a reversal in CO_2 concentrations (e.g., 75), but this hysteresis does not imply that they are irreversible under overshoot of global temperature.

While net CO_2 emissions are the primary driver of global warming, non-CO_2 forcing can also play a significant role. Many non-CO_2 forcers, known as short-lived climate forcers (SLCFs), have a significantly shorter atmospheric lifetime than does CO_2, and, in contrast with CO_2 emissions, the contribution of SLCFs to global warming depends largely on their recent rate of emissions not on their cumulative emissions. A sustained decline in SLCF emissions with a warming

[3]The definition of "anthropogenic" here is based on bookkeeping models for CO_2 emissions and removal from land-use change, but national GHG inventories under the UNFCCC also include passive uptake of CO_2 on managed land, arising, e.g., from CO_2 fertilization and nitrogen deposition, as part of anthropogenic CDR (88–91). Under that accounting convention, net-zero CO_2 emissions would not lead to stabilized global temperature, and net-negative CO_2 emissions may not lead to a temperature decrease (92, 93). Throughout this article, we use the definition from bookkeeping models for anthropogenic CDR.



(*Caption appears on following page*)

Figure 3 (*Figure appears on preceding page*)

Reversibility of different aspects of the Earth system with global net CO_2 emissions and global temperature. The figure illustrates changes to global temperature and components of the Earth system during a period of global warming (*red arrows*) compared with changes associated with a decline in global average temperature (*blue arrows*). Global surface temperature change since 1850–1900 as a function of cumulative CO_2 emissions. The top panel illustrates that global surface temperature increases approximately proportionally to cumulative global CO_2 emissions, which is expected to reverse concurrently with global net-negative CO_2 emissions, using data from Reference 2. The bottom panels show examples of other Earth system components that may not reverse fully or concurrently with global temperature. Left panel: loss of Arctic sea ice reverses with a lag when global temperature decreases. Middle panel: disruptions to natural ecosystems are expected to increase with global warming; some shifts may be reversible, albeit with a substantial lag, while others may be irreversible beyond some thresholds of global warming (*vertical dashed line*). Right panel: sea-level will continue to rise in a warmer world, caused by both thermal expansion and melting of land ice; reversing global warming can slow future sea-level rise but will not reverse it for thousands of years.

effect, particularly CH_4, would therefore also contribute to declining global temperature, but the maximum decline that can be achieved is limited by the total warming from SLCF emissions at the time of peak temperature. Anthropogenic removal of non-CO_2 gases, particularly CH_4, has also been proposed (100, 101) and could further reduce net CH_4 emissions by compensating for emissions from natural sources that may also increase in a warming climate (18).

The literature on climate reversibility has generally focused on the reversibility of global average temperature, which does not necessarily imply a concurrent return of regional temperatures or other key aspects of regional climate. Some components of the Earth system may reverse quickly, such as rainfall over land (102), or with a lag of years to decades, such as Arctic sea ice amount (103, 104) (**Figure 3*b***). Some studies have shown that long-term regional climate continues to adjust for decades after global average temperature has stabilized (73, 74) and that precipitation changes may not fully reverse in some regions (58). In addition, regional climate can exhibit changes that are disproportionate and occur over slower timescales than global temperature due to the response of the North Atlantic circulation under negative emissions (105) or as CO_2 concentration decreases (75, 106). The limited evidence from existing studies collectively suggests that a decline in global average temperature is feasible from a geophysical perspective but that, at regional scales, key climate variables, such as temperature and precipitation extremes, may not decline concurrently with global average temperature and could exhibit a significant time lag of decades to centuries.

Moreover, slow components of the climate system (e.g., deep ocean heat uptake, land ice loss, and sea-level rise) will continue to change for centuries to millennia while warming remains above preindustrial levels, although the rate of change will be lower if global warming declines again (e.g., from 2°C back to 1.5°C) than if it stabilizes at a higher level (5, 103) (**Figure 3*d***). Similarly, shifts in species distribution and resulting changes in ecosystem composition will continue for decades to centuries, even if global warming declines again, and some transformations could result in alternative stable states rather than reversal (46, 68) (**Figure 3*c***). Risks driven by long-term integrated climate responses and ecosystem changes may thus continue for centuries, even if global warming levels decline again, and will require continued adaptation responses.

7. ILLUSTRATIVE OVERSHOOT PATHWAYS AND ENVIRONMENTAL, TECHNOLOGICAL, AND ECONOMIC ASPECTS

The feasibility dimensions of a broad suite of mitigation actions consistent with pathways that limit warming below 2°C have been assessed in the IPCC AR6 (see 107, figure TS.31). However, this feasibility assessment did not separate actions that can help limit peak warming (e.g., by reaching net-zero global CO_2 emissions) from the additional actions required to achieve a subsequent temperature decline.

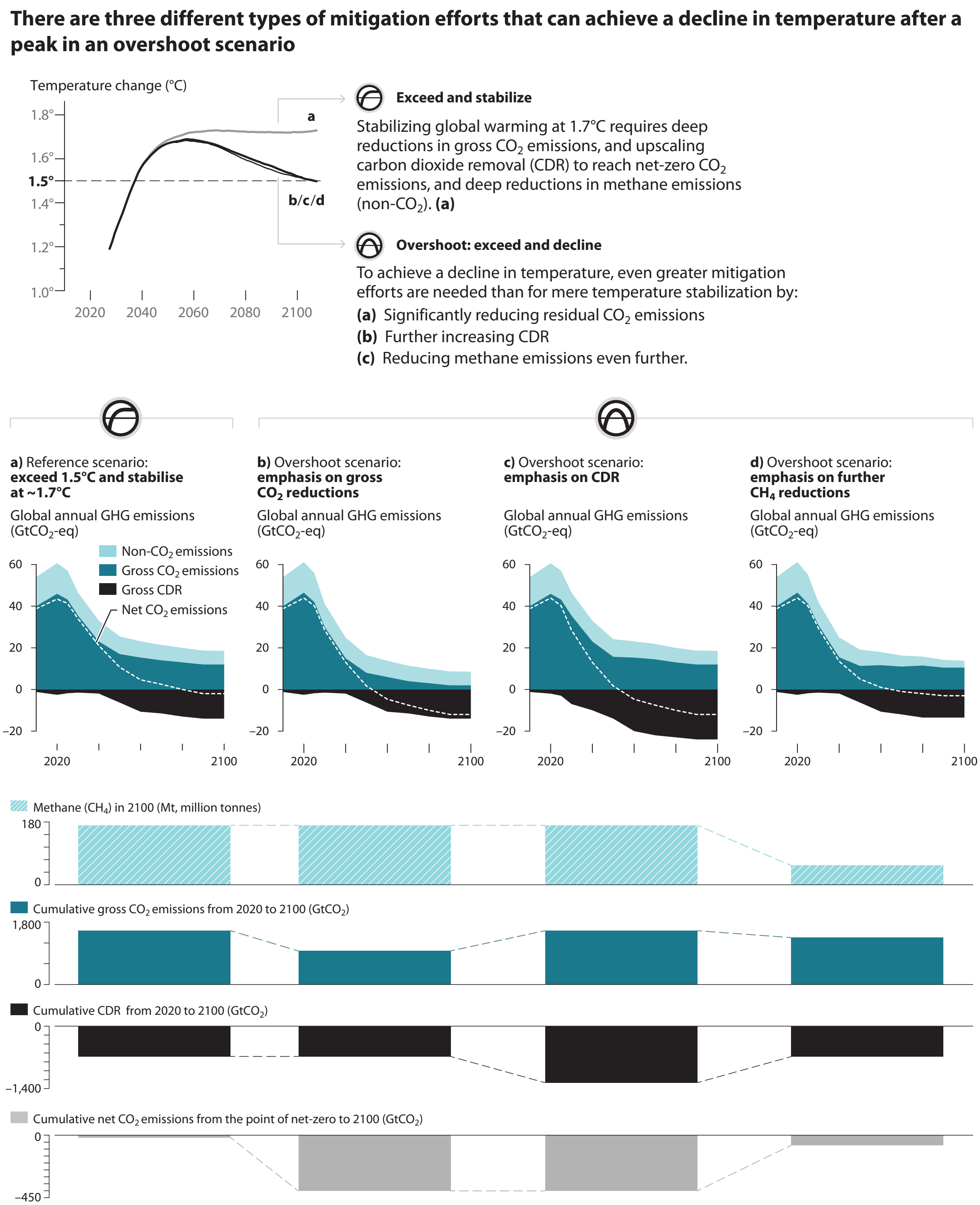
As discussed in Section 2, global warming will peak roughly when global CO_2 emissions reach net zero. Halting global warming anywhere below 2°C already assumes rapid and major reductions in global gross CO_2 emissions this decade, global deployment of CDR at the scale of gigatonnes per year within the next few decades, and concurrent deep reductions in global non-CO_2 emissions.

A subsequent decline in global warming can be achieved by one or a combination of three archetypal strategies (16) that go beyond what is needed to merely halt the rise in global warming: (*a*) further reducing residual gross CO_2 emissions, (*b*) further increasing CDR, and (*c*) further reducing SLCF (especially CH_4) emissions. The first and second archetypes achieve sustained net-negative global CO_2 emissions by either further gross emission reductions or further increases in CDR, while the third archetype prioritizes further reducing CH_4 emissions while approximately maintaining net-zero emissions of long-lived GHGs. All three components could, in principle, reduce the level of global warming by at least 0.1°C or more and play complementary roles to achieve an overall temperature decline. In general, the lower the level of peak warming and hence the smaller the necessary decline to return to 1.5°C, the lower the environmental, technological, and economic barriers to such a return. Rapid reduction of emissions in the near term to minimize the level of peak warming is therefore a key prerequisite for any overshoot strategy to remain feasible and to keep associated losses and damages to a minimum.

In **Figure 4**, we illustrate options for achieving a decline in temperature through three archetypal illustrative overshoot pathways. These pathways all reach global warming of almost 1.7°C around 2050 and then decline again by ∼0.2°C to return to 1.5°C by the end of the century. Such a temperature trajectory is consistent with pathways assessed in the IPCC AR6 as "limiting warming to 1.5°C with high overshoot" (108) and which, although challenging, are not yet precluded by current global emission trends. Each pathway prioritizes a particular mitigation strategy to achieve a decline in temperature, i.e., a set of actions that would be needed in addition to a reference scenario that limits warming to ∼1.7°C but then stabilizes around that level. This counterfactual stabilization scenario approximates the most optimistic interpretation of current long-term pledges and targets (109), which already rely on a significant and rapid upscaling of mitigation efforts through a combination of supply- and demand-side measures. All three illustrative overshoot pathways would face substantial but different challenges to their environmental, technological, and economic feasibility, as discussed below, from mitigation efforts going beyond those reductions.

The first archetype focuses on substantial further reductions of gross CO_2 emissions to achieve net-negative global CO_2 emissions without increasing reliance on CDR. However, achieving further gross emission reductions, down to ∼2 $GtCO_2$ by 2100 in this illustrative pathway, could increase costs and create challenges, especially for industry, aviation, and long-distance heavy transport whose emissions are considered hard to abate and where current policies show limited ambition (110, 114). Addressing these limitations would require an increased emphasis on demand-side measures and system changes to achieve deep reductions (115), which, despite their large mitigation potential, have been underutilized in current policy and rely on increased policy coordination to avoid inequitable outcomes (116, 117). Depending on policy sequencing and national priorities, the potential from demand-side interventions might already be partly deployed to reach net-zero CO_2 emissions. For some sectors, such as international aviation, deep reductions based on currently envisaged technologies would imply an increased reliance on biofuels that have the potential to increase pressure on food security if deployed at large scales (54).

The second archetype relies on increased CDR not only to counterbalance continued considerable residual CO_2 emissions but also to achieve large-scale net-negative CO_2 emissions. As assessed in the IPCC AR6, this reliance on CDR, reaching a scale of more than 20 $GtCO_2$ per



(Caption appears on following page)

Figure 4 (*Figure appears on preceding page*)

Global GHG emissions and temperature under three archetypal illustrative overshoot pathways and a reference stabilization pathway. The top panel shows global warming under a pathway that exceeds 1.5°C permanently and stabilizes at ∼1.7°C and for illustrative overshoot pathways that peak at ∼1.7°C and then return global warming to 1.5°C by 2100. The middle panels show global gross CO_2 emissions and removals, net CO_2 and other GHG emissions for the above-1.5°C stabilization, and three illustrative overshoot pathways. The level of emissions and removals at the time of net-zero CO_2 is within the range of values found in integrated assessment models assessed in the IPCC AR6 to limit warming to 1.5°C with limited or high overshoot (108, 110). The bottom panels show key differences in those illustrative pathways for global emissions of methane (CH_4) in 2100, cumulative gross CO_2, and cumulative CDR between 2020 and 2100 and cumulative global net-negative CO_2 emissions from the point of net-zero CO_2 emissions (i.e., approximately when peak warming is reached) in each pathway until 2100. See the text for details on assumptions of CO_2 and CH_4 emissions and removals in the different pathways. Individual pathways are illustrative and intended to demonstrate key alternative potential mitigation strategies to achieve a decline in temperature; they are created by the authors and are not the result of detailed economic modeling. Emissions of gases other than CO_2** and CH_4 follow the SSP1–1.9 pathway in all cases for these illustrative pathways. Temperature outcomes shown in the top panel were modeled using the climate emulator FaIR (111), calibrated (version 1.3.1) to emulate the climate response to emissions as assessed in the IPCC AR6 (112, 113). Abbreviations: CDR, carbon dioxide removal; GHG, greenhouse gas; IPCC AR6, Intergovernmental Panel on Climate Change Sixth Assessment Report; Mt, million tonnes; SSP, shared socioeconomic pathway.

year in this illustrative pathway, could create major risks to food security and biodiversity if the main CDR methods are afforestation or bioenergy combined with carbon capture and storage (BECCS) (19, 52–54, 118). Furthermore, the efficacy of CDR approaches based on afforestation may also be threatened due to increases in climate extremes (e.g., fire weather index) with increasing global warming (119). Other CDR methods face very high economic costs [e.g., direct air capture and carbon storage (DACCS)], have limited scientific understanding in terms of permanence and potential side effects (many ocean-based methods), or are at high risk of reversal (e.g., soil carbon) (118, 120). Apart from afforestation/reforestation, no CDR method has been implemented at scale to date (118, 120). Scaling up CDR to the extent required under the second archetype would rely on extensive and urgent government and industry support for research, development, and deployment (118, 121).

The third archetype achieves a temperature decline mainly through further deep reductions in CH_4, with much lower levels of net-negative CO_2 emissions. This illustrative pathway faces feasibility challenges that are similar to those in the first archetype but arise in different sectors. Residual CH_4 emissions are expected to come mainly from agriculture because CH_4 emissions from fossil fuel exploration and use and from landfills can typically be abated at much lower costs; therefore, those emissions are expected to be reduced substantially already in the reference scenario that limits warming to ∼1.7°C (108). Substantial further reductions in residual agricultural emissions, beyond those in integrated assessment models, would rely on demand-side measures that reduce the production and consumption of ruminant livestock products within globally highly uneven capacities and baselines and/or the introduction of novel technologies, such as methane inhibitors or a vaccine (115, 122, 123). Demand-side dietary change, despite its health benefits in regions with current high meat consumption, presents major challenges for policy and equity, given the diversity of diets and the social and economic importance of livestock for rural poverty alleviation (55, 124–127).

Further reducing residual gross emissions of CO_2 or CH_4 could achieve at most a decline of ∼0.2°C by 2100 without increasing CDR, depending on the level of residual emissions at the time of peak temperature. While the amounts of CDR and residual CO_2 reductions in our illustrative overshoot pathways fall within the range of reductions found in the integrated assessment scenario literature (108, 110, 128), the additional CH_4 reductions go beyond the literature range. This does not mean that such CH_4 reductions are infeasible; rather, it reflects the limited incorporation of future technologies and food system changes to address these hard-to-abate emissions in integrated assessment models and the limited exploration of CH_4 removal that could also support deeper net emission reductions (129–131).

While these archetypes illustrate three distinct strategies to reduce global warming, in practice they are likely to be deployed in combination. Interactions among the different strategies could result in significant synergies and trade-offs, which will need careful further exploration to allow governments to chart the most feasible and sustainable pathways. A key synergy is that dietary change to achieve deeper CH_4 reductions would reduce demand for grazing land, which in turn would enable significant additional land-based CDR without increasing risks to food security (55, 132). An example of trade-offs is that rapid upscaling of DACCS would entail additional energy demand, which could increase energy prices and hence make further electrification of industry to achieve deep reductions in gross CO_2 emissions more challenging, and it could increase fugitive losses of CH_4 if direct air capture is powered by natural gas (133). The systematic exploration of synergies and trade-offs across mitigation strategies to achieve a decline in global warming, including the interplay between supply- and demand-side options to maximize their feasibility, has only begun to be considered (134).

In summary, a decline in global warming back to 1.5°C after a midcentury peak could be achieved through three complementary archetypal mitigation strategies, provided that overshoot is limited to a few tenths of a degree; overshoot does not necessarily imply an even greater reliance on CDR. However, each strategy faces substantial but distinct environmental, economic, and technological barriers. Challenges to the feasibility and scale of deployment needed to achieve the necessary decline increase the higher the temperature peak. Our illustrative overshoot pathways suggest that, if peak warming exceeds about 1.7°C, mitigation strategies based solely on either additional gross reductions in CO_2 or additional reductions in CH_4 post-2050 could no longer achieve a return to 1.5°C by 2100. Higher peak warming therefore increases reliance on CDR, reduces the feasibility of a return to 1.5°C, and increases risks arising from mitigation responses and the need for a combination of overshoot strategies. In the IPCC AR6 scenario database, a peak warming of ~1.8°C is the upper limit for scenarios that still manage to return to 1.5°C by 2100 (3).

8. POLICY OPTIONS AND THE SOCIOCULTURAL AND INSTITUTIONAL ASPECTS OF OVERSHOOT

The IPCC AR6 included sociocultural and institutional dimensions in its feasibility assessment of mitigation. However, an assessment of these aspects with respect to policy options to govern a post-peak return to 1.5°C by 2100 is constrained in three dimensions. First, there is no political or public debate on such a trajectory yet and therefore no empirical data to analyze how sociocultural (e.g., values and norms, behavioral choices) and institutional (e.g., administrative capacity, political preferences) factors could enable or constrain a collective project of a managed temperature decline. Second, once such debates emerge and evolve, feasibility frontiers can be expected to be dynamic, for instance in response to technological and economic developments but also to accelerating climate change impacts and societal risk perceptions. Third, at least in the institutional dimension, feasibility is specific to actors, options, scale, and time (135, 136). Model-based assessments indicate institutional constraints as a significant limiting factor but generally adopt more generic and static definitions (137, 138). Taken together, these limitations allow us to anticipate some likely key barriers and enabling aspects for overshoot from a sociocultural and institutional perspective in only a limited number of areas.

On the global level, the Parties to the Paris Agreement would need to reach a shared understanding that returning to 1.5°C after reaching peak temperature is indeed a core target of global climate governance. This consensus could happen tacitly, if the exceedance is limited, simply by pursuing global net-zero GHG emissions based on Article 4.1 of the Paris Agreement and the implied gradual decline in temperature (28, 139, 140). But a shift in focus could result from a deliberate decision, for example preceded by a discussion in the format of a "structured expert dialogue" as part of a UNFCCC periodic review of the LTTG (141). In such deliberations, options for a post-peak return to 1.5°C by 2100 would be assessed against pathways that exceed 1.5°C permanently with only a slight decrease in temperature, given the social, financial, and ecological pressures that could arise from very high levels of CDR deployment and additional measures to further reduce hard-to-abate emissions. A deliberate decision on pursuing a peak-and-decline pathway and its reliance on CDR would likely be made conditional on respecting high-level sustainability principles (142).

However, whether the UNFCCC will—either implicitly or explicitly—opt for getting back to 1.5°C is not a given. A consensus outcome could also be to stabilize global warming at some level between 1.5°C and (the rather ambiguously defined) "well below" 2°C. A further option could be to simply to focus on halting global warming and defer a decision about a managed temperature decline until closer to the time when net-zero CO_2 emissions are achieved globally and Parties have gained more experience with implementing the CDR needed even just to reach net zero (30).

If the UNFCCC develops a common understanding to pursue a getting back to 1.5°C strategy, it will come with distributional considerations stemming from the UNFCCC's principle of common but differentiated responsibilities and respective capabilities and the issue of fair burden-sharing. The latter has been prevalent not only in the UN climate regime but also in the research literature on mitigation pathways, albeit with a wide range of different interpretations (137, 143, 144). If the UNFCCC starts considering global net-negative emissions benchmarks for the second half of the century, then developed countries will be seen as front-runners again (145) and expected to explore "negative territory" (146) first, given their higher capability and higher responsibility for historical emissions. This effort would need to translate sooner or later into net-negative emissions targets for developed countries and a societal willingness to incur the associated costs for further reductions in hard-to-abate residual emissions and/or a further increase in annual CDR volumes. Agreeing on this approach in principle is likely to be feasible, at least for some, given that, for example, the European Union as a whole and many European Union member states already have an (unquantified) vision to aim for net-negative GHG emissions after reaching net zero (147). But even the European Union would presumably want to clarify the relative contribution of emerging economies (particularly China) toward achieving a global net-negative CO_2 emissions target (148, 149).

Aiming for modest levels of net-negative CO_2 or even GHG emissions in advanced economies is achievable in principle, if the deployment of CDR increases and/or levels of residual emissions decline further from the point of net zero. But aiming for a national net balance of, say, −110% GHG emissions by 2060 is different from aiming for −130% or more by 2070 in that it requires a sustained societal commitment to deliver a significant volume of net-negative emissions over multiple decades and to support the ongoing efforts that these targets would require. While such levels might meet global fairness norms (i.e., paying back historical carbon debt), it is not a given that even promising such levels of ambition will prove to be politically feasible in developed countries, especially if such reductions are based on domestic action alone (150). If seriously attempted, this effort will entail decisions on which economic sectors might remain net emitters and which sectors need to deliver the net-negative emissions (5). Integrated assessment models indicate that both the agricultural sector and the energy sector will be at the heart of this debate: the former as the major source of residual non-CO_2 emissions that could be reduced through further demand shifts, and the latter as a potential key provider of additional CDR in conjunction with agriculture, for example, via BECCS (120).

Because an uneven sectoral distribution of burdens to deliver net-negative emissions will also be perceived through the lens of domestic (un)fairness, instruments for financial redistribution will need to be refined. Achieving net-negative emissions at scale will eventually rely not only on public money, but also on the willingness of governments (and societal support for governments) to organize the delivery of CDR at very large scales themselves, if necessary. If ambitious climate policy until net zero is mainly about controlling emissions, this goal can be achieved by revoking noncompliant companies' licenses to operate or requiring them to compensate for residual emissions with CDR. But once a country reaches net-negative territory, relying on a polluter-pays model will no longer drive the desired volume of sustained removals, as it would imply a negative cap in emissions trading schemes, and annual state revenues from carbon pricing will also become net-negative (151, 152).

Achieving globally net-negative CO_2 emissions could be considered feasible only if at least some major emitters—among them developed countries in the Group of 7—take the lead in entering net-negative territory at national levels. But while in recent years such demands have sporadically been made by large developing countries (148, 153), these efforts have not captured much attention in the public climate policy debate nor have major historical emitters—such as the United States, United Kingdom, or European Union—presented robust plans or clear commitments for going net-negative.

9. CONCLUSIONS AND OUTLOOK

The concept of overshoot—that is, to exceed a specified global warming level and to return to that level within a specified time period—is becoming increasingly relevant to keep 1.5°C within reach. However, this situation is still not given attention by policymakers and is only starting to be addressed by science. This article seeks to initiate and support a conversation on the various elements of overshoot across disciplines and communities and the conceptual frameworks that underpin these discussions (**Figure 5** illustrates relevant dimensions and tensions).

We have applied the climate risk framework in terms of the interplay of its drivers—climate-related hazards, exposure, and vulnerability, as well as responses to address climate change—to understand the evolution of risk in overshoot scenarios. Current evidence suggests that a reversal of global warming is feasible from a geophysical perspective, but understanding about the behavior of relevant hazards at regional scales is more limited. Even where hazards can be reversed or substantially reduced again through a decline in global temperature after a peak, this reversal alone does not ensure a reduction in the level of risk because a reduction of risk depends on the concurrent evolution of the other drivers, particularly vulnerability and the consequences of compounding and cascading risks. A decline in temperature is therefore unlikely to return risks to what they would have been if 1.5°C had never been exceeded: A world that returns to 1.5°C after decades above that level will potentially be a very different world from the one before exceedance.

At the same time, a decline in global temperature will generally result in lower risks than if global warming remains elevated above 1.5°C permanently. However, we find that the current scientific literature is not able to provide a clear evidence base of how much lower and how this risk level might differ, depending on the system at risk, regional and contextual differences, and the effectiveness and management of both adaptation and mitigation during the period of overshoot.

Mitigation pathways with a return to 1.5°C exist in theory and models, but large knowledge gaps exist with regard to their feasibility, efficacy, and consistency with sustainable development needs. Furthermore, the necessary governance mechanisms and institutional arrangements do not

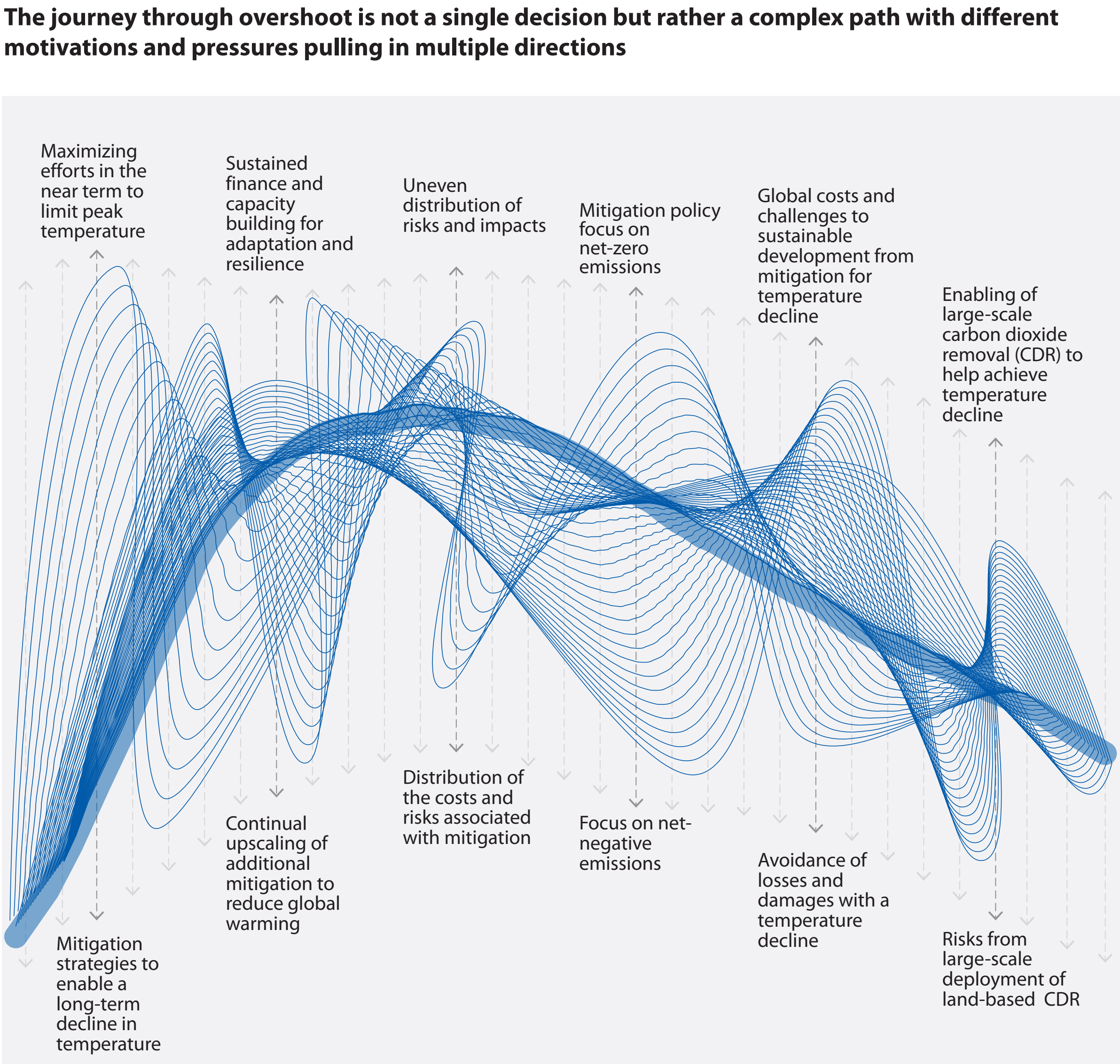


Figure 5

Competing drivers along an overshoot pathway. Figure illustrates the multiple competing drivers, trade-offs, and synergies that decision-makers will need to navigate when considering whether and how quickly to bring global temperature back down below 1.5°C after that level has been exceeded (shown as *vertical dashed arrows*) The drivers listed are not an exhaustive list, and while they signal potential tensions in the decision-making process, they do not necessarily imply simple either/or decisions. The journey along an overshoot pathway will require simultaneous and integrated decisions on adaptation, mitigation, and resilience while accounting for differing preferences, capacities, and responsibilities for action. Abbreviation: CDR, carbon dioxide removal.

exist and need to be developed in the context of the burden-sharing principles embedded in the Paris Agreement.

Regardless of whether the world will decide to bring warming back down to 1.5°C before 2100, strengthening adaptation and resilience to climate change in the near term will be a priority to face the consequences of increasing temperatures. This approach is needed to minimize losses and damages and also to maximize the benefits that an eventual reduction in temperature would bring. An overshoot trajectory is a distinctly second-best option to not exceeding 1.5°C in the first place. Given the ambitions of the Paris Agreement, the challenge is to ensure that the overshoot is as short and as small as possible while also closing adaptation finance gaps and building capacity to enable communities to adapt to the warming in the near term. A robust evidence base and broad assessment of the elements of overshoot addressed here are needed to inform the collective need to move into the new uncharted policy territory of successfully bringing temperatures back down.

SUMMARY POINTS

1. Exceeding global warming of 1.5°C is, by now, almost inevitable, but actions by governments and other actors will determine by how much and for how long this level will be exceeded.
2. IPCC's definition of overshoot means to exceed and decline again to a specified warming level within a specified time period; it represents both a failure and a subsequent corrective action.
3. Climate-related risks will be greater if global warming exceeds 1.5°C than if it had remained below this level; understanding is much more limited about how risks will evolve if global warming returns again to 1.5°C and how those risks compare to risks if warming stabilizes above 1.5°C.
4. The evolution of climate-related risks will depend on changes in all four components of risk—hazards, exposure, vulnerability, and responses—during the period of overshoot, which depend on the system at risk, local and regional characteristics, and adaptation and mitigation responses. Understanding and systematic assessment of risks under overshoot are major knowledge gaps.
5. Global warming can be reversed in principle through sustained net-negative global CO_2 emissions, but a reversal of global warming would not reduce all climate-related hazards; sea-level rise would continue to increase, and some hazards may not return to their original state, even if global temperature declines.
6. A decline in global temperature relies on additional mitigation measures beyond the net-zero CO_2 emissions needed to halt global warming: further increase in CDR deployment, further reductions in residual CO_2 emissions, and further deep reductions of residual CH_4 emissions. All three types of action face substantial but different barriers, and the feasibility of returning to 1.5°C by 2100 therefore declines as peak warming increases.
7. Making an overshoot trajectory, i.e., a managed future temperature decline, a reality faces major institutional barriers. These include bringing net-negative emissions into geopolitical as well as national policy conversations and adjusting policy tools to move beyond a polluter-pays principle to enable countries to achieve net-negative emission targets.
8. Building resilience to climate change through adaptation, including through finance and capacity building, is critical, even if there were a plan to reverse global warming; this

effort would also reduce inequities that could result from variation in the abilities of different regions to cope with excess warming.

FUTURE ISSUES

1. A concerted effort is needed to understand the evolution of climate-related risk under overshoot pathways for a range of systems and local and regional contexts, with differing assumptions about adaptation and mitigation responses, and the IPCC's assessment of this knowledge.
2. We need to better understand mitigation strategies to achieve a global temperature decline through a combination of further CDR and further reduction in residual CO_2 and CH_4 emissions through additional demand-side and supply-side interventions and to understand their feasibility, costs, synergies, and trade-offs, in the context of sustainable development.
3. A more comprehensive assessment of the feasibility of temperature decline could help set an upper limit for peak global warming that still enables a return to 1.5° by 2100.
4. Countries need to consider including net-negative emission targets in their long-term goals, rather than treating net zero as a natural end point for climate policy.
5. Researchers and policymakers will need to find opportunities to begin regular conversations about overshoot to refine knowledge needs, research gaps, and windows of opportunity for a post-peak return to 1.5°C.

DISCLOSURE STATEMENT

All authors have had previous and, in some cases, current roles in IPCC assessment cycles. These roles are a key source of insights and problem areas covered in this article. The authors are not aware of any other affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

AUTHOR CONTRIBUTIONS

A.R., J.S.F., and A.P. conceptualized the review and coordinated the writing and internal review process. A.M. and T.G.J. led the conceptualization and design of the figures with input from all authors. A.R. led Section 1; J.S.F. led Sections 2 and 3; A.P., E.P., and S.M. led Section 4 with contributions from R.A.B., S.I.S., and C.A.; S.M. led Section 5; C.D.J. led Section 6; A.R. led Section 7; O.G. led Section 8; and A.P., J.S.F., and A.R. led Section 9. A.R. performed FaIR calculations to support Section 7 and provide data for **Figures 1** and **4**. All authors contributed to discussions, drafting, and review of the article.

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