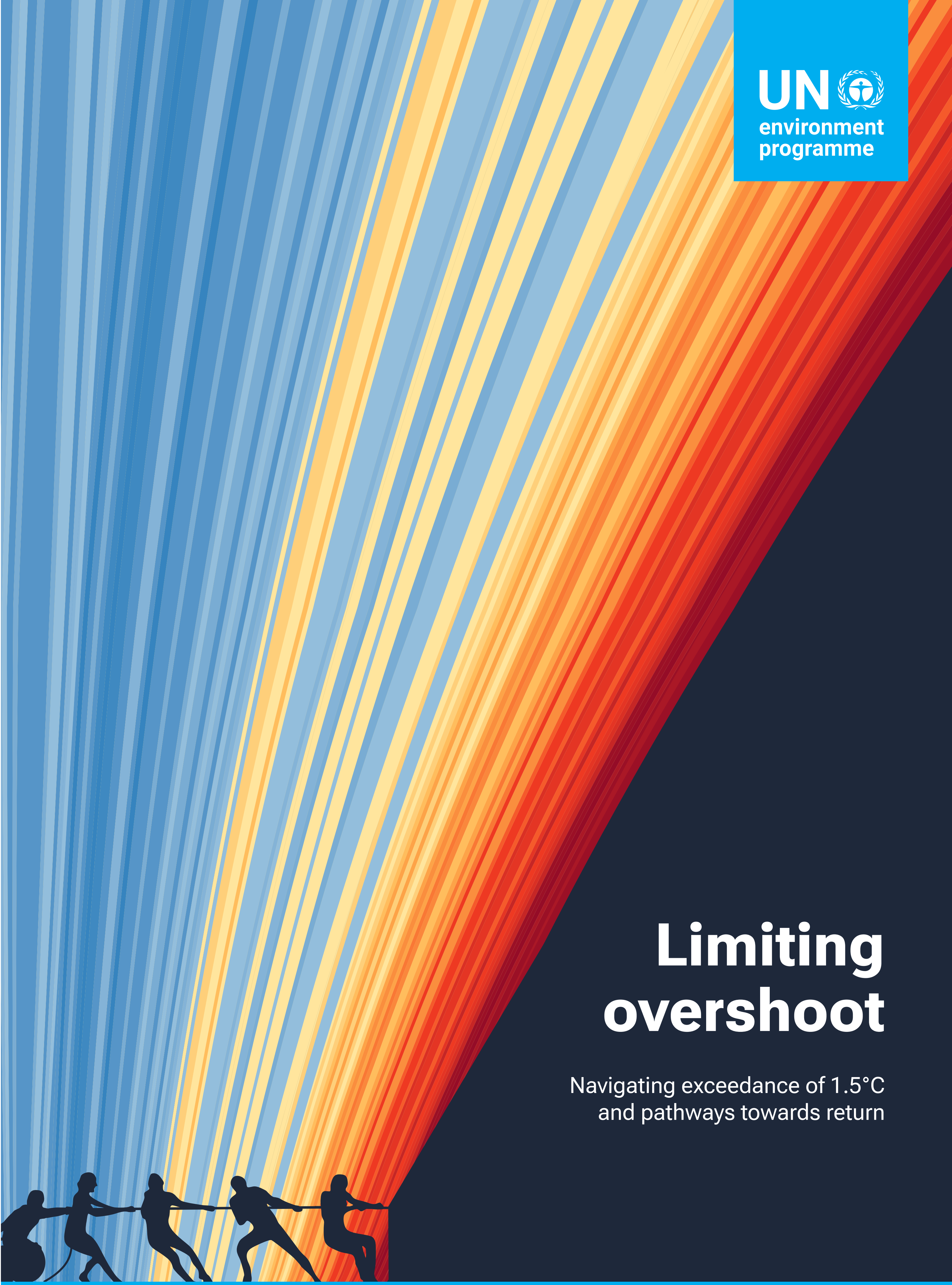

UN environment programme

Limiting overshoot

Navigating exceedance of 1.5°C
and pathways towards return

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Abbreviations and Acronyms

AMOC	Atlantic Meridional Overturning Circulation
AR6	Sixth Assessment Report of the Intergovernmental Panel on Climate Change
BECCS	Bioenergy with carbon capture and storage
C3S	Copernicus Climate Change Service
CBD	Convention on Biological Diversity
CBDR-RC	Common but differentiated responsibilities and respective capabilities
CCAC	Climate and Clean Air Coalition
CDR	Carbon dioxide removal
CH_4	Methane
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
COP 28	the twenty-eighth session of the Conference of the Parties to the United Nations Framework Convention on Climate Change
COP 27	the twenty-seventh session of the Conference of the Parties (COP 27) to the United Nations Framework Convention on Climate Change
COVID-19	Coronavirus disease 2019
DACCS	Direct air carbon capture and storage
EbA	Ecosystem-based Adaptation
EEA	**European Environment Agency**
ESM	Earth System Models
FAO	Food and Agriculture Organization of the United Nations
GCA	Global Center on Adaptation
GDP	Gross Domestic Product
GHGs	Greenhouse gases
GMSL	Global Mean Sea Level
GMST	Global Mean Surface Temperature
$GtCO_2$	billion tons of carbon dioxide
GWP	Global Warming Potential
IAM	Integrated Assessment Model
ICJ	International Court of Justice
ICRI	International Coral Reef Initiative
ICT	Information and Communication Technology
IEA	International Energy Agency
IMF	International Monetary Fund
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence Zone
ITLOS	International Tribunal for the Law of the Sea
LDC	Least Developed Country
LULUCF	Land Use, Land-Use Change and Forestry
NAPs	National Adaptation Plans
NASA	National Aeronautics and Space Administration
NCP	Nature's Contributions to People
NDCs	Nationally Determined Contributions
NGOs	Non-Governmental Organizations
NOAA	United States National Oceanic and Atmospheric Administration
NOx	Nitrogen Oxide
OECD	Organisation for Economic Co-operation and Development
OED	Oxford English Dictionary
PAs	Protected Areas
PADDD	Protected area downgrading, downsizing and degazettement
SDGs	Sustainable Development Goals
SEI	Stockholm Environment Institute
SIDS	Small Island Developing States
SLR	Sea-level rise
SO_2	Sulphur Dioxide
SSP	Shared Socioeconomic Pathway

TCRE	Transient Climate Response to Cumulative Emissions of CO_2
TWh	terawatt-hours
UN	United Nations
UN DESA	United Nations Department of Economic and Social Affairs
UNGA	United Nations General Assembly
UN Women	United Nations Women
UNCTAD	United Nations Conference on Trade and Development
UNCLOS	United Nations Convention on the Law of the Sea
UNDP	United Nations Development Programme
UNDRR	United Nations Office for Disaster Risk Reduction
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UNICEF	United Nations Children's Fund
WAF	World Agriculture Forum
WGI	Working Group I
WHO	World Health Organization
WMO	World Meteorological Organization
WWA	World Weather Attribution

Glossary

In this glossary, selected key terms used in this report are defined. The terms in this glossary are taken from the online glossary of the Intergovernmental Panel on Climate Change (IPCC) https://apps.ipcc.ch/glossary/ unless otherwise indicated.

Adaptation: In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.

Adaptation limits: The point at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions.

Hard adaptation limit: No adaptive actions are possible to avoid intolerable risks.

Soft adaptation limit: Options may exist but are currently not available to avoid intolerable risks through adaptive action.

Transformational adaptation: Adaptation that changes the fundamental attributes of a socio-ecological system in anticipation of climate change and its impacts (Möller *et al.* 2022) — a fundamental, system-wide reorganization that reaches beyond technology and economic structures to paradigms, goals and values (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES] 2024b), and that addresses the underlying drivers of climate risk in inclusive ways, enhances the capacity to cope with and recover from future impacts, and guards against maladaptive outcomes now and in the future (Biesbroek *et al.* 2026).

Afforestation: Conversion to forest of land that historically has not contained forests.

Bioenergy: Energy derived from any form of biomass or its metabolic by-products.

Bioenergy with carbon dioxide capture and storage (BECCS): Carbon dioxide capture and storage (CCS) technology applied to a bioenergy facility. Note that, depending on the total emissions of the BECCS supply chain, carbon dioxide (CO_2) can be removed from the atmosphere.

Carbon budget: The maximum amount of cumulative net global anthropogenic CO_2 emissions that would result in limiting global warming to a given level with a given probability, considering the effect of other anthropogenic climate forcers. This is referred to as the Total Carbon Budget when expressed starting from the pre-industrial period, and as the Remaining Carbon Budget when expressed from a recent specified date.

Carbon dioxide removal (CDR): Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical CO_2 sinks and direct air carbon dioxide capture and storage (DACCS) but excludes natural CO_2 uptake not directly caused by human activities.

Cascading impacts: Cascading impacts from extreme weather/climate events occur when an extreme hazard generates a sequence of secondary events in natural and human systems that result in physical, natural, social or economic disruption, whereby the resulting impact is significantly larger than the initial impact. Cascading impacts are complex and multi-dimensional, and are associated more with the magnitude of vulnerability than with that of the hazard.

Earth system: The Earth system is a complex social-environmental system of interacting physical, chemical, biological and social components and processes that determine the state and evolution of the planet and life on it; The Earth´s interacting physical, chemical and biological processes. The system consists of the land, oceans, atmosphere and poles. It includes the planet's natural cycles—the carbon, water, nitrogen, phosphorus, sulphur and other cycles—and deep Earth processes (UNEP 2025f)

Earth System Model (ESM): A coupled atmosphere–ocean general circulation model (AOGCM) in which a representation of the carbon cycle is included, allowing for interactive calculation of atmospheric carbon dioxide (CO_2) or compatible emissions. Additional components (e.g. atmospheric chemistry, ice sheets, dynamic vegetation, nitrogen cycle, but also urban or crop models) may be included.

Hysteresis: The dependence of the state of a system on its history (so-called path-dependency). In the Earth system, hysteresis behaviour is often caused by system time lags (e.g. due to inertia) and non-linear processes. Jeltsch-Thömmes *et al.* (2020)

Impacts: The consequences of realised risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather/climate events), exposure and vulnerability. Impacts generally refer to effects on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ecosystem services) and infrastructure. Impacts may be referred to as consequences or outcomes and can be adverse or beneficial. (IPCC AR6, WGI definition)

Specifically in this report, the impact can be at different timescales: current impacts, impacts under exceedance, peaking, reversal or stabilization; and broader, projected impacts under overshoot and the mitigation and adaptation responses required. (expanded from IPCC by the authors of this report)

Irreversibility: A perturbed state of a dynamical system is defined as irreversible on a given time scale if the recovery from this state due to natural processes takes substantially longer than the time scale of interest.

Loss and Damage, and losses and damages: Research has taken Loss and Damage (capitalised letters) to refer to political debate under the United Nations Framework Convention on Climate Change (UNFCCC) following the establishment of the Warsaw Mechanism on Loss and Damage in 2013, which is to 'address loss and damage associated with impacts of climate change, including extreme events and slow onset events, in developing countries that are particularly vulnerable to the adverse effects of climate change.' Lowercase letters (losses and damages) have been taken to refer broadly to harm from (observed) impacts and (projected) risks and can be economic or non-economic.

Maladaptation: Actions that may lead to increased risk of adverse climate-related outcomes, including via increased greenhouse gas (GHG) emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, or diminished welfare, now or in the future. Most often, maladaptation is an unintended consequence.

Mitigation (of climate change): A human intervention to reduce emissions or enhance the sinks of greenhouse gases.

Mitigation potential: The quantity of net GHG emission reductions that can be achieved by a given mitigation option relative to specified emission baselines. [Note: Net GHG reductions are the sum of reduced emissions and/or enhanced sinks]

Net-zero CO_2 emissions: Condition in which anthropogenic carbon dioxide (CO_2) emissions are balanced by anthropogenic CO_2 removals over a specified period.

Net-zero GHG emissions: Condition in which metric-weighted anthropogenic GHG emissions are balanced by metric-weighted anthropogenic GHG removals over a specified period. The quantification of net-zero GHG emissions depends on the GHG emission metric chosen to compare emissions and removals of different gases, as well as the time horizon chosen for that metric.

Net-negative CO_2 emissions: Condition in which anthropogenic CO_2 removals exceed anthropogenic CO_2 emissions over a specified period. (IPCC AR6)

Net-negative GHG emissions: A situation of net negative GHG emissions is achieved when metric-weighted anthropogenic GHG removals exceed metric-weighted anthropogenic GHG emissions. Where multiple GHG are involved, the quantification of net emissions depends on the metric chosen to compare emissions of different gases (such as the global warming potential), as well as the chosen time horizon. (adapted from IPCC AR6 by the authors of this report)

Pathways: The temporal evolution of natural and/or human systems towards a future state. Pathway concepts range from sets of quantitative and qualitative scenarios or narratives of potential futures to solution-oriented decision-making processes to achieve desirable societal goals. Pathway approaches typically focus on biophysical, techno-economic and/or socio-behavioural trajectories and involve various dynamics, goals and actors across different scales.

Emissions pathways: Modelled trajectories of global anthropogenic emissions over the 21st century.

Overshoot, peak and decline pathways, sometimes abbreviated as **Overshoot pathways**. Pathways that first exceed a global warming level (e.g. 1.5°C) and then return to or below that level again before the end of a specified period (e.g. before 2100). Sometimes the magnitude and likelihood of the overshoot are also characterized. The overshoot duration can vary but typically lasts for at least multiple decades. (adapted from IPCC AR6 by the authors of this report)

A 1.5°C overshoot, peak and decline pathway comprises a multidecadal sequence involving four distinct stages:

- **Exceedance of 1.5°C:** the period in which global warming surpasses 1.5°C but before it reaches its peak.
- **Plateauing stage:** the period when global warming reaches and plateaus at its maximum level above 1.5°C for a period before starting to decline. The maximum level is called **peak warming**.
- **Decline stage:** the period in which global temperatures begin to decline from their peak level.
- **Stabilization stage:** reached once global temperatures return to or below 1.5°C after peak and reversal, and stabilize at this level.

For the purpose of this report, **Overshoot,** when mentioned alone refers to exceedance of a specified global warming level. The world is considered in overshoot when the multidecadal average global surface air temperature increase exceeds a specified warming level (e.g. 1.5°C), not when the global temperature in a single year exceeds that warming level temperature. (Further explained in Chapter 1, following the introduction) (Rogelj *et al.* 2026)

Reasons for concern (RFCs): Elements of a classification framework, first developed in the IPCC Third Assessment Report, which aims to facilitate judgements about what level of climate change may be dangerous (in the language of Article 2 of the UNFCCC; IPCC 2023a) by aggregating risks from various sectors, considering hazards, exposures, vulnerabilities, capacities to adapt and the resulting impacts.

Climate resilient development: a process of implementing GHG mitigation and adaptation options to support sustainable development for all. (adapted from IPCC AR6 by the authors of this report)

Risk: The 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. Relevant adverse consequences include those on lives, livelihoods, health and well-being, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species. In the context of climate change impacts, risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards. Hazards, exposure and vulnerability may each be subject to uncertainty in terms of magnitude and likelihood of occurrence, and each may change over time and space due to socio-economic changes and human decision-making. In the context of climate change responses, risks result from the potential for such responses not achieving the intended objective(s), or from potential trade-offs with, or negative side-effects on, other societal objectives, such as the Sustainable Development Goals (SDGs). Risks can arise for example from uncertainty in the implementation, effectiveness or outcomes of climate policy, climate-related investments, technology development or adoption, and system transitions.

Tipping element: A component of the Earth system that is susceptible to a *tipping point*.

Tipping point: A critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly.

Transition: The process of changing from one state or condition to another in a given period. Transition can be in individuals, firms, cities, regions and nations, and can be based on incremental or transformative change.

Just transitions: A set of principles, processes and practices that aim to ensure that no people, workers, places, sectors, countries or regions are left behind in the transition from a high-carbon to a low-carbon economy. It stresses the need for targeted and proactive measures from governments, agencies and authorities to ensure that any negative social, environmental or economic impacts of economy-wide transitions are minimized, while benefits are maximised for those disproportionally affected. Key principles of just transitions include: respect and dignity for vulnerable groups; fairness in energy access and use, social dialogue and democratic consultation with relevant stakeholders; the creation of decent jobs; social protection; and rights at work. Just transitions could include fairness in energy, land use and climate planning and decision-making processes; economic diversification based on low-carbon investments; realistic training/retraining programmes that lead to decent work; gender-specific policies that promote equitable outcomes; the fostering of international cooperation and coordinated multilateral actions; and the eradication of poverty. Lastly, just transitions may embody the redressing of past harms and perceived injustices.

Vulnerability: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

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Foreword

Even though global warming is set to cross 1.5°C above pre-industrial levels, likely within the next few years, the goal remains limiting warming to this level. However, the goal must now be approached from above while the world adapts to intensifying climate impacts. Every fraction of a degree avoided and every year by which overshoot is shortened will save lives, protect ecosystems and reduce economic losses.

As the UNEP Limiting Overshoot report shows, there are no good outcomes above 1.5°C. Extreme weather, glacier melt, ecosystem loss and sea-level rise will intensify. Some Small Island Developing States and low-lying coastal cities could be partially or completely submerged. Risks of tipping points will grow. Human health, food and water security, cities and infrastructure will come under increasing strain. These impacts will not be distributed equally, and some losses will be irreversible even if global temperatures eventually decline.

So, we must hold fast to global commitments under the Paris Agreement, try to return to below 1.5°C by the end of the century and adapt to the impacts of climate change. Prepared with the contribution of leading experts from across climate science, adaptation, mitigation, governance and sustainable development, Limiting Overshoot examines how we might achieve this.

We must deliver rapid and deep cuts to CO_2, methane and other greenhouse gases immediately, working towards net-zero – with governments sending the right policy signals to financial institutions and the private sector. As net-zero is merely a milestone, we must follow a long-term path to net-negative emissions – while delivering transformational adaptation and resilience. As mitigation and adaptation are interconnected, measures should target both for the greatest impact. Carbon Dioxide Removal (CDR) – the process of removing carbon from the air and storing it through reforestation or other means – will be needed to bring temperatures back down, so we should research these approaches – while being aware of the risks, trade-offs, limits and need for strong governance.

To succeed, we need stronger political will and multilateralism, and more agile and inclusive governance, with equity and justice at the core of all action. Countries with greater historical responsibility for climate change should act the fastest and with the greatest ambition. And, as many nations and communities will likely face permanent changes, we will require a fundamental rethink to long-term governance to ensure that those who have contributed least to global warming are not left to bear its greatest burdens.

Efforts will need to evolve over the years to address many unknowns, but decisions taken now and in the next few years will determine whether viable options remain to reverse warming towards 1.5°C. So, I call on governments—and on everyone with the power to effect change—to act with urgency and determination. This is not the future we sought. A return to 1.5°C is not assured. But limiting the magnitude, duration and consequences of overshoot, while preserving the possibility of bringing temperatures back down, is the best remaining option to protect vulnerable people, reduce losses and secure a livable future for all.

Inger Andersen,
UNEP Executive Director

Executive summary

1. While the international community has made progress on climate change, global action to cut greenhouse gas emissions has not been fast enough to avoid global warming crossing 1.5°C above pre-industrial levels in the next few years.

This means surpassing the multi-decadal global warming level of 1.5°C, the central long-term temperature goal of the Paris Agreement, as affirmed by the International Court of Justice and backed by a UN General Assembly resolution. Even an optimistic scenario of current government pledges (full implementation of all national climate plans plus meeting additional net-zero targets) puts expected peak temperature rise at 1.8°C.

2. Exceedance of 1.5°C should not be interpreted as safe or acceptable; there are no benign scenarios with global temperature rise above this level.

Risks and impacts include faster sea-level rise, a higher likelihood of collapse of ecosystems such as coral reefs, more extreme heat and wildfires, and profound changes to the cryosphere (ice sheets, sea ice, glaciers, permafrost and snow). For example, glaciers could lose more than a quarter of their mass by 2100, which could raise sea levels by 9 to 12.5` cm (for warming up to/less than +3°C) and permanently alter water availability in many places. There is also a higher risk of irreversible tipping points to global systems such as the West Antarctic and Greenland ice sheets, the Atlantic Meridional Overturning Circulation (AMOC) and the Amazon rainforest — which would reshape the world forever.

While there are uncertainties around the timings and strength of these impacts and tipping points, it is clear they will harm people, societies and economies, particularly in Small Island Developing States (SIDS) and low-lying cities, some of which face partial or complete submersion. Food security and water supplies will be hit — for example, projections indicate declines of up to 14 per cent in global food production by 2050 in the absence of effective adaptation. More frequent and intense heatwaves, more nutrition-related diseases and greater risks of pathogen spillover will increase illnesses and deaths.

Cities and infrastructure will be at greater risk from stronger and longer heatwaves and flooding. Warming oceans, declining oxygen levels and rising acidity will make it harder for marine life and the communities that depend on it to survive. Higher energy demand, consumer costs, and insurance and financial system stress will pose risks to all nations.

3. The global goal remains limiting long-term average warming to 1.5°C.

However, overshoot means this goal must now be approached from above, while simultaneously adapting to the impacts of climate change. This means meeting and exceeding, not rescinding, existing commitments and concurrently delivering faster mitigation and adaptation.

With unprecedented action it is possible to minimize and adapt to the impacts of exceedance and return to 1.5°C — which would keep options open to protect the poor and vulnerable, minimize harm to infrastructure and livelihoods, and support people and nature. To do so, the world must get onto an 'overshoot, peak and decline' pathway that holds temperature rise to the lowest level possible, then brings it down by the end of the century, all while taking adaptation actions that reduce vulnerability to the current or expected impacts of climate change.

This is by no means an acceptable or preferred pathway; it is simply the best remaining option.

4. Avoiding every additional fraction of a degree of global warming and reducing the time in overshoot decrease risks and damages and increase the chances of bringing temperatures back down.

The duration and severity of the overshoot, peak and decline pathway, and the ability of communities to cope, will depend on how fast emissions are cut and how quickly transformational adaptation measures are implemented. Reductions in methane and other short-lived climate pollutants are particularly important in the immediate term. Enhancing adaptive and mitigation capacity requires strong political will, urgent multilateral action, effective policies and finance — with equity, justice and differentiated responsibilities serving as guiding principles.

5. The global response needs to encompass three interconnected phases: immediate response, coping and containment, and long-term resilience.

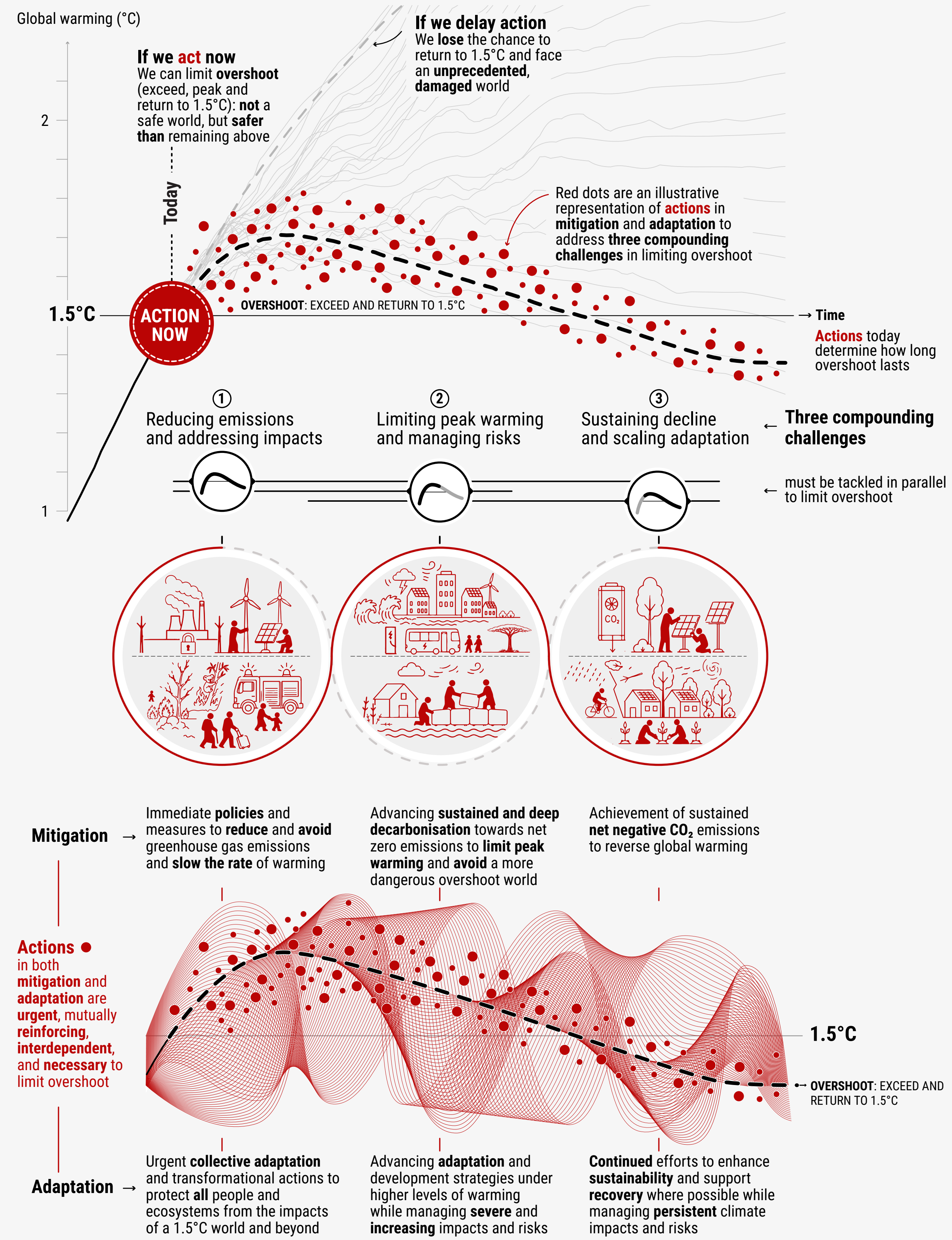
- **Immediate response phase (as temperatures approach, then exceed, 1.5°C)**: Slow warming quickly through deep emissions cuts, including to methane and other short-lived climate pollutants. Adopt urgent adaptation measures that protect the most-vulnerable people and ecosystems.
- **Coping and containment phase (as temperatures peak)**: Advance deep and sustained decarbonization that achieves at least net-zero emissions. Develop societal resilience, while managing severe impacts and risks.
- **Long-term resilience phase (as temperatures decline and stabilize)**: Deliver sustained net-negative carbon dioxide (CO_2) emissions. Enhance sustainability and resilience. Ensure lasting adaptation where irreversible limits have been reached.

Figure ES 1: Temperature overshoot: actions and challenges *(See next page)*

Description: This is an illustrative depiction of temperature overshoot and the actions and challenges associated with limiting its magnitude, duration and consequences. The visual features in the **top panel** are indicative and do not represent precise warming magnitudes, rates or probabilities. The black dashed line represents an overshoot pathway adapted from an SSP2-4.5 pathway based on IPCC (2021), while the light grey dashed line represents a high-overshoot pathway adapted from Reisinger *et al.* (2025). The horizontal line marks the 1.5°C global warming level, relative to 1850–1900. The light grey trajectories in the background are illustrative and are informed by visual interpolation across an ensemble of SSP scenarios and tipping-point peaks, depicting a world that may become increasingly challenging depending on the actions we take. The red dots are an illustrative representation of actions in mitigation and adaptation to limit overshoot. (See Conclusion for full description)

TEMPERATURE OVERSHOOT: EXCEED AND RETURN TO 1.5°C

Decades of **insufficient** action have locked us into **three compounding challenges** to limiting **temperature overshoot**, with an **urgent** need for **action** now



In practice, multiple phases will coexist across time and across and within regions. Impacts are expected to accumulate dynamically across the overshoot, peak and decline pathway, with each phase inheriting the legacies of those that preceded it.

6. Mitigation and adaptation are fundamentally interconnected and must advance together throughout all phases.

Mitigation and adaptation are both critical to address the climate challenge and protect human and natural systems. Many interventions can achieve adaptation and mitigation goals at once — increasing urban tree canopy coverage, for example, lowers heat-related morbidity and mortality while reducing the need for energy intensive and polluting cooling approaches.

Weak mitigation will increase impacts and potentially divert funds to emergency responses instead of needed climate action, creating a feedback loop. Yet even the most successful mitigation efforts will not eliminate the need for adaptation: 1.5°C is not considered safe for most nations, communities, ecosystems and sectors. Meanwhile, current adaptation plans and their implementation often overlook links to mitigation, neglect inequalities and insufficiently address loss and damage and adaptation limits. Without proper adaptation, the assets built to cut emissions are themselves at risk. Therefore, actions to reduce and manage the risks of climate change will need to be radically re-thought, re-imagined and re-calibrated under the overshoot, peak and decline pathway.

7. To navigate an overshoot, peak and decline pathway, the world must adopt proactive approaches that deploy flexible, multi-level governance, particularly when it comes to adaptation.

Such approaches are necessary to anticipate coming risks, integrate new knowledge, reduce and adapt to climate impacts before they arrive with full force, and allow enough agility to adjust to uncertainties associated with the decline to 1.5°C. Adaptation set up now forms the foundation for all efforts to come, but it must become transformational and responsive to evolving non-linear and abruptly arising risks, recognizing these will occur unevenly across regions or systems. Expected profound shifts—such as submersion of SIDS or low-lying coastal cities and uninhabitability across the world—mean that incremental adjustments are not enough.

Transformational adaptation must embed flexibility, learning and continual revision of baselines across all phases.

8. Conventional and novel Carbon Dioxide Removal (CDR) will be needed in addition to, not instead of, sustained reductions in residual greenhouse gas emissions, but CDR methods come with risks and trade-offs that could limit their potential — calling for strong governance frameworks that ensure responsible and appropriate deployment of CDR.

CDR comes in two forms: conventional, such as afforestation and ecosystem restoration, and novel, such as bioenergy combined with carbon capture and storage, and direct air carbon capture and storage. However, CDR can only contribute credibly to a return to below 1.5°C within the 21st century if peak warming remains well below 2°C and all remaining emissions of CO_2, methane and other greenhouse gases are reduced. Beyond around 1.8°C, decline to 1.5°C during the 21st century becomes increasingly challenging. In a warmer future, nature's removal and carbon retention capacity will likely be eroded, while competition between sustainable development goals and CDR can limit the feasibility of land-intensive mitigation strategies.

It would take over 100 years of afforestation and forest management at the current scale, and zero residual CO_2 emissions, to bring warming back by 0.1°C. Meanwhile, the temperature reduction achievable through novel CDR that relies on geological carbon storage is also constrained. Just maintaining net-zero CO_2 emissions could exhaust current estimated storage capacity in sedimentary basins by 2200.

While rapid upscaling of CDR is critical, alongside urgent and accelerated emission reductions, strong governance frameworks on CDR are needed to manage implications for equity, scale and uptake — and to provide guardrails for the exploration of new and uncertain technologies that could have unintended negative consequences.

Overall, even optimistic CDR scaling is unlikely to deliver a temperature reversal beyond a few tenths of a degree this century. This emphasizes the importance of focusing on reducing greenhouse gas emissions now.

9. Equity and justice must be the core of effective strategies to protect the vulnerable, create a just transition for communities and workforces, and secure a liveable future for coming generations.

Countries with greater historical responsibility for climate change and capability to address it should act the hardest and fastest. Countries disproportionately impacted by climate change must be an integral and respected part of the global decision-making process; they should take an active role in implementation of mitigation and adaptation, based on science and the principles of equity, as a matter of survival.

10. Even if a return to below 1.5°C is secured, many nations and communities will face irreversible losses and permanently changed conditions.

Impacts such as continued sea-level rise, species extinctions and ecosystem regime shifts may continue far beyond peak temperatures. Many communities may have relocated or changed livelihoods. Societies will face the challenge of readjustment: agricultural systems reconfigured for higher temperatures may need to be readapted; infrastructure designed for climate extremes may become mismatched; communities weakened by decades of crisis will face a second transition capacity; and maladaptation from mitigation may be an issue.

11. The legacy consequences of overshoot raise issues of justice, power and political legitimacy, which will require inclusive governance arrangements far beyond what most current climate governance envisions.

Governance arrangements at all scales will have to evolve to resolve difficult issues, such as deciding what gets rebuilt, how livelihoods are reconfigured, how loss and damage is addressed, and how the sovereignty and entitlements of SIDS and their peoples are respected even as their territories face increasing risk of uninhabitability.

12. Rapid, collective and global action is vital — with stronger political will, multilateralism and governance as key enabling conditions for all efforts.

Across both mitigation and adaptation, countries will need to strengthen international cooperation, align policies and institutions with the realities of overshoot, and substantially increase finance, technology transfer and capacity-building. Effective multilateralism will be essential to coordinate action across borders and generations, manage shared risks and ensure that countries with the least responsibility and capacity are not left to face the greatest burdens alone.

13. As an overshoot, peak and decline pathway could unfold over decades to centuries, subject to many unknowns, the discussion and efforts initiated by this report will need to evolve alongside the challenge.

The prospect of an overshoot pathway points to new frontiers for research and science to underpin and support better understanding, policy setting, governance and decision-making. The science, policies and institutions needed to navigate this pathway must therefore evolve as knowledge and conditions change. Particular attention is required to the poorly understood decline stage, the durability and equity of carbon removal, persistent and irreversible impacts, and adaptation as temperatures peak and later recede.

This report is not a definitive prescription, but a foundation for sustained research, learning, action and inclusive decision-making across generations.

The issues of equity and trade-offs require further research, learning and shaping as the baton is passed from generation to generation, across different geographies, and within countries and communities.

Introduction

Why this report?

The long-term objective of limiting warming to 1.5°C remains the foundation of international climate policy. For more than a decade, the global response to climate change has been organized around a shared objective: holding global warming "well below 2°C" above pre-industrial levels and pursuing efforts to limit it to 1.5°C (UNFCCC 2015a; UNFCCC 2015b). This objective, embedded in Article 2(a) of the Paris Agreement and reaffirmed in subsequent international decisions, remains the central benchmark for climate ambition. The goal of limiting global warming to 1.5°C has been further reinforced by international law. The International Court of Justice (ICJ) considers the "'1.5°C threshold to be the parties' agreed primary temperature goal for limiting the global average temperature increase under the Paris Agreement" (ICJ 2025). The United Nations General Assembly (UNGA) resolution adopted in 2026 (UNGA Res A/RES/80/L.65 2026) further reaffirmed this legal obligation.

The policy challenge has shifted from avoiding overshoot to navigating it. Scientific assessments (IPCC 2023a; UNEP 2025b) indicate that temporary exceedance of 1.5°C is inevitable under current emissions trajectories and policy settings. Therefore, the challenge confronting policymakers is no longer solely how to avoid exceedance, but rather how to understand, prepare for and navigate a future in which global temperatures exceed 1.5°C. Most importantly, society is now faced with the task of limiting exceedance through unprecedented action, for an overshoot, peak and decline pathway to be possible. In this pathway, the world faces the reality of global temperatures going beyond 1.5°C and collectively working towards limiting a temporary overshoot to well below 2°C so as to still make a decline feasible.

The decline stage depends on decisions made and actions taken today. This report does not assume that future outcomes are predetermined. Rather, it emphasizes that a 'decline' is not a given. Every fraction of a degree matters: the magnitude of peak warming, the duration of how long we stay above 1.5°C and the scale of resulting impacts remain strongly influenced by present actions. Every fraction of a degree avoided reduces risks. Every year by which overshoot duration is shortened reduces exposure. Every investment in resilience preserves future options.

Box 1: Overshoot terminology

The term ‘overshoot’ has a variety of meanings. In everyday usage, overshoot refers to “the action or result of exceeding a limit or target” (Oxford English Dictionary [OED] 2024) or crossing a limit. However, in the scientific literature the shorthand term ‘overshoot pathway’ has been used to refer to a pathway that returns global warming below a specified limit after first having exceeded it for a certain amount of time (IPCC 2018b; IPCC 2022a; Schleussner *et al.* 2024; Reisinger *et al.* 2025). This poor alignment between the scientific and public understanding of the term overshoot is confusing. Therefore, a framing that distinguishes two separate challenges of scientific ‘overshoot pathways’ has been suggested (Schleussner *et al.* 2024): (i) halting global warming so that a peak in global warming is achieved; and (ii) reversing global warming until it returns back below the target level (in this case 1.5°C). This framing is referred to as an overshoot, peak and decline pathway.

Such pathways can be segmented in four stages. When pursuing efforts to limit warming to 1.5°C, an overshoot, peak and decline pathway is characterized by: first, a time when 1.5°C is crossed; second, the plateauing of global warming at a level above 1.5°C (and thus defining a peak in global warming); third, a period of global warming decline; and fourth, a period of global warming stabilization at a level below 1.5°C. Each of these stages comes with different implications for mitigation, adaptation, resilience and their associated challenges (see Section 1.6).

Throughout this report, the term overshoot in isolation refers to the crossing of 1.5°C of global warming, but more specific terms such as exceeding or crossing are preferred for clarity. Meanwhile, pathways that return global warming to or below 1.5°C after first having overshot are referred to in more explicit terms as ‘overshoot, peak and decline pathways’, sometimes abbreviated as ‘overshoot pathways’.

Based on ‘Practical guidance towards consistent use of overshoot terminology’ (Rogelj *et al.* 2026)

Understanding overshoot pathways

Overshoot is a process, not a single threshold. An overshoot pathway that includes overshoot, peak and decline is often discussed as a physical climate phenomenon — as a threshold crossing. In reality, it is part of a dynamic process that will unfold over decades and involve several stages. Climate risks are shaped not only by global temperature outcomes, but also by how high temperatures rise, how long they remain elevated and how ecosystems and societies respond throughout the process (see Chapter 1).

Climate risks evolve differently across the stages of overshoot pathways. Peak warming matters because many climate impacts increase non-linearly with temperature. Duration matters because prolonged exposure compounds stress on ecosystems, infrastructure, institutions and communities with direct implications on how and whether they can rebound. Decline matters because some impacts may gradually lessen while others may persist for decades or centuries. Stabilization matters because future societies will inherit a world that will remain fundamentally altered even after temperatures begin to fall.

Planning must account for the full overshoot pathway. An overshoot pathway comprises four distinct but interconnected stages: exceedance, peak warming, decline and stabilization. Recognizing overshoot as a dynamic process rather than a single event is therefore essential for effective planning and decision-making.

Many existing planning assumptions no longer hold. Policies, institutions, finance and planning systems were designed around assumptions of gradual change, relative climatic stability and reliance on historical data for physical factors and projections for human factors. These assumptions cannot hold in a world in overshoot that introduces a different reality characterized by accelerating impacts, increasing uncertainty, threshold effects and growing interactions between environmental, social and economic risks. Some populations, ecosystems and sectors are also exposed to impacts driven by development elsewhere, without adequate capacity, skills, resources or financing to respond (O’Neill *et al.* 2022; Lamptey *et al.* 2024; Venner, García-Lamarca and Olazabal 2024). These distributional dimensions must be central to planning for the exceedance, peak, decline and stabilization stages and not treated as equity considerations to be addressed after the primary technical response (Birkmann *et al.* 2022; Mycoo *et al.* 2022; O’Neill *et al.* 2022).

Adaptation must become iterative rather than static. As temperatures rise and impacts intensify, many planned and established measures may become ineffective, pushing systems toward soft and hard adaptation limits and increasing the likelihood of crossing critical tipping dynamics associated with exceedance and response actions. Without redesign, current adaptation pathways risk widespread maladaptation and the reinforcement of existing, or introduction of new, vulnerabilities and inequities. In a world in overshoot and decline, decision-makers will increasingly confront situations in which historical experience provides limited guidance for future conditions (Milly *et al.* 2008). Adaptation and mitigation decisions may need to be revised repeatedly, at different levels of governance as infrastructure lifetimes may exceed the validity of current design assumptions (Milly *et al.* 2008; Hallegatte *et al.* 2012; Theokritoff *et al.* 2026).

Overshoot is as much a governance challenge as a climate challenge. Its implications extend far beyond the climate system itself to governance, planning, finance, development pathways and intergenerational responsibility. In the 1980s, there was already an indication of the negative impacts of anthropogenic climate change and political priorities then could have averted the damage that is currently locked in (Stoddard *et al.* 2021). The trajectory from exceedance to stabilization will likewise depend on policy choices made today. Infrastructure, food systems, human settlements, ecosystems and public investment have traditionally been designed around assumptions of relative climatic stability and historical experience. Overshoot challenges those assumptions and requires institutions capable of operating under increasing uncertainty, changing risks and evolving climate conditions.

The stages of overshoot provide a temporal thread across the report. The chapters therefore return at several points to impacts, mitigation, adaptation and governance — not as discrete or sequential agendas, but to examine how their roles, constraints and interactions evolve through exceedance, peak warming, decline and stabilization. This deliberate recurrence reflects the need to revisit decisions and response options as climatic, ecological and societal conditions change.

Every fraction of a degree matters, every investment matters

Overshoot reinforces the need for climate action. The inevitable overshoot of 1.5°C should not be interpreted as justification for reduced ambition. On the contrary, it reinforces the urgency of accelerated climate action. The lower the peak warming reached, and the shorter the duration of exceedance, the lower the risks faced by people and ecosystems.

Mitigation and adaptation are complementary, not sequential. Mitigation remains essential because it determines the scale and duration of future climate risks. It also limits the magnitude and duration of overshoot. Adaptation remains essential because climate impacts are already occurring and additional warming is unavoidable. Neither can substitute for the other. Effective responses require mitigation, adaptation and resilience-building efforts to advance together.

Overshoot pathways inform decisions under uncertainty. While the pathways examined in this report should not be interpreted as predictions of a predetermined future, they represent scientifically informed scenarios that illuminate potential risks, opportunities and decision points. Although uncertainty remains regarding the timing, magnitude and distribution of future impacts, the evidence consistently indicates that higher peak warming and longer durations of exceedance are associated with greater risks for people and nature. For example, adaptation and mitigation decisions may need to be revised repeatedly, at different levels of governance as infrastructure lifetimes may exceed the validity of current design assumptions (Milly *et al.* 2008; Hallegatte *et al.* 2012; Theokritoff *et al.* 2026).

Even 1.5°C carries substantial risks. A key point often underemphasized is that 1.5°C global warming (IPCC 2018a) is not considered safe for most nations, communities, ecosystems and sectors, and still poses significant risks to natural and human systems (Chapter 2 and 4). Global warming beyond 1.5°C is expected to amplify non-linear increases in impacts, compounding their complexity and disproportionately affecting Least Developed Countries, (LDCs) SIDS, the poor and vulnerable (see Chapter 2). This means that even if warming eventually returns to or below 1.5°C, substantial adaptation needs will remain.

Today's decisions determine tomorrow's risks. These challenges reinforce the importance of accelerating mitigation. The lower the peak warming reached, the lower the risks faced by people, societies, economies and ecosystems. The shorter the duration of overshoot, the lower the probability of crossing irreversible thresholds and adaptation limits. The sooner emissions decline, the greater the opportunities to reduce future losses and damages (Chapter 3). Mitigation therefore remains indispensable because it determines the scale and duration of future climate risks (Chapter 3).

The central lesson throughout this report is that mitigation and adaptation should not be sequenced; they must advance together. Overshoot is therefore not an argument for resignation, but for urgency.

In a world where temporary exceedance is inevitable, every fraction of a degree avoided, every year by which overshoot is shortened and every investment in mitigation, adaptation and resilience helps keep the goals of the Paris Agreement within reach and protects human, economic and environmental health.

01 Entering an era of 1.5°C overshoot

Impacts of a world at and beyond 1.5°C are already emerging. These include: accelerating ecosystem and cryosphere loss, intensifying extreme weather and increasing harms to vulnerable populations. The evidence indicates that 1.5°C cannot be considered safe, and that even temporary exceedance will result in substantial and often irreversible impacts.

Reversing global warming after exceeding 1.5°C is theoretically possible. However, it would require sustained net-negative carbon dioxide (CO_2) emissions at globally relevant scales over decades to centuries, supported by deep reductions in methane. Achieving the former would require avoiding CO_2 emissions as much as possible while scaling CO_2 removal methods. Achieving the latter would require substantial advances in reducing 'hard-to-abate' methane emissions, particularly from agriculture. The feasibility of achieving both at the required scale remains uncertain. As any global warming reversal would unfold only gradually over multiple decades, adaptation decisions are most sensibly guided by climate risks between 1.5°C exceedance and expected peak warming. However, achieving reversal would bring important long-term benefits, especially for reducing risks from sea-level rise and potential destabilization of tipping elements such as the Greenland and West Antarctic ice sheets.

Responding to overshoot of 1.5°C requires action across three response phases. The first is an immediate response phase, requiring urgent measures to protect vulnerable populations from foreseeable impacts of the imminent exceedance of 1.5°C while rapidly reducing emissions to slow warming. The second, a coping and containment phase—beginning in parallel—focuses on advancing climate resilience in a world above 1.5°C alongside sustained deep decarbonisation towards net zero in which global warming is halted. The third, a long-term resilience phase, follows net-zero CO_2 and peak warming, combining sustained net-negative CO_2 emissions and further methane reductions with continued adaptation and broader efforts to strengthen sustainability and societal resilience. Across all three response phases, mitigation and adaptation are deeply interdependent and must advance together to deliver climate resilient development.

1.1 Global warming approaching 1.5°C

Staying below 1.5°C is the preferred outcome. The long-term temperature goal of the Paris Agreement and the Climate Change Convention refers to two global warming limits (Mace 2016; Rajamani and Werksman 2018). The 2021 Glasgow Climate Pact focused attention more firmly onto pursuing efforts to limiting warming to 1.5°C (UNFCCC 2021) and, most recently, the International Court of Justice in its Advisory Opinion on the Obligations of States in Respect of Climate Change stated that it "considers the 1.5°C threshold to be the parties' agreed primary temperature goal [...] under the Paris Agreement" (ICJ 2025, para. 224) (See In Focus: Legal implications of 1.5°C overshoot pathways).

However, exceedance of 1.5°C is coming in the next few years.

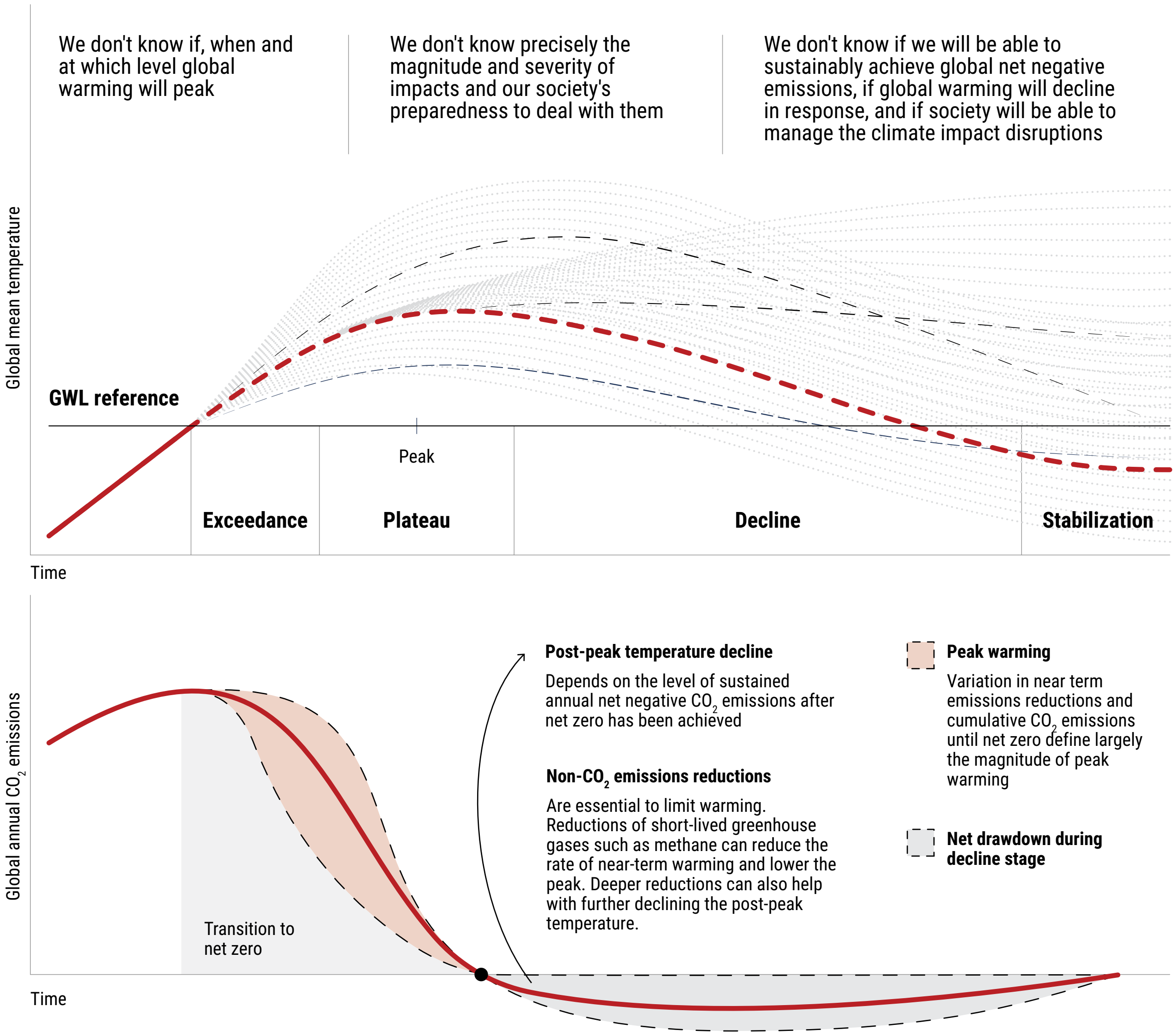
Human-induced global warming is nearing 1.4°C above pre-industrial levels, and observed global temperatures have been increasing at about 0.25°C per decade (Forster *et al.* 2026), with some recent studies showing an even higher rate (Foster and Rahmstorf 2026). Extrapolating current trends, global warming may reach 1.5°C around the end of this decade. A recent operational decadal forecasts (WMO 2026) assigned 3-in-4 chance that the 2026–2030 five-year mean in global temperatures (reflecting the combined effect of human-induced warming and natural variability) will exceed 1.5°C. Taken together, the available evidence suggests that the central estimate of human-induced global warming will be crossing 1.5°C above pre-industrial levels in the next few years. The remaining carbon budget—the total amount of CO_2 that can still be emitted while meeting a specified temperature goal—continues to be revised downward as global emissions continue to consume it, and science is updated. To have a 50 per cent chance of limiting global warming to 1.5°C, only about 130 billion tons of CO_2 ($GtCO_2$) can be emitted from 2026 onwards (Forster *et al.* 2026). However, emissions remain at record highs. In 2024 alone, fossil fuels and industry produced around 40 $GtCO_2$ (Friedlingstein *et al.* 2025). At this rate, the remaining carbon budget for staying within 1.5°C would be exhausted in roughly three years. Put differently, to remain within this budget, global CO_2 emissions would need to decline linearly from 2025 levels to zero in just over six years.

Every year of high emissions makes limiting overshoot more difficult. Global mean temperature increase is approximately linearly proportional to cumulative CO_2 emissions (Canadell *et al.* 2021), and temperatures stabilize when net CO_2 emissions reach zero (IPCC 2021). The earlier net-zero CO_2 is achieved—and the fewer CO_2 emissions emitted until that point—the lower the eventual peak temperature. Concurrent reductions in non-CO_2 greenhouse gases (GHGs), particularly of short-lived methane emissions, can further limit peak warming and affect the timing of net-zero CO_2 aligned with a given temperature outcome (Rogelj *et al.* 2014; Reisinger *et al.* 2021; Ou *et al.* 2021a; Riahi *et al.* 2022).

Every five years of high emissions adds 0.1°C to peak warming. The Intergovernmental Panel on Climate Change (IPCC)'s quantification of the relationship between cumulative CO_2 emissions and global warming means that each additional five years of sustained high emissions adds approximately 0.1°C to peak warming[1] (Canadell *et al.* 2021; UNEP 2025b). Consequently, the more than 400 $GtCO_2$ of cumulated CO_2 emitted since 2015 (Friedlingstein *et al.* 2025) have already increased the lowest achievable warming by about 0.2°C.

1 This value of a 0.1°C increase per five years of delay is based on the central estimate of the transient climate response to cumulative emissions of CO_2 (TCRE), which indicates the amount of global warming that is caused per unit of CO_2 that human activities add to the Earth's atmosphere. The IPCC AR6 WGI reports a ***likely*** (>66 per cent) range of 0.27–0.63°C per 1000 $GtCO_2$ for the TCRE with a best estimate of 0.45°C (Canadell *et al.* 2021). These values indicate that a best estimate of 220 $GtCO_2$ causes 0.1°C of global warming. Current global CO_2 emissions exceed 40 $GtCO_2$ (UNEP 2025b), and more than 200 $GtCO_2$ will therefore be emitted over the course of five years.

Figure 1.1: Key pathway concepts



- Dotted lines illustrate alternative futures from different starting points
- Global annual CO_2 emissions refer to net emissions.

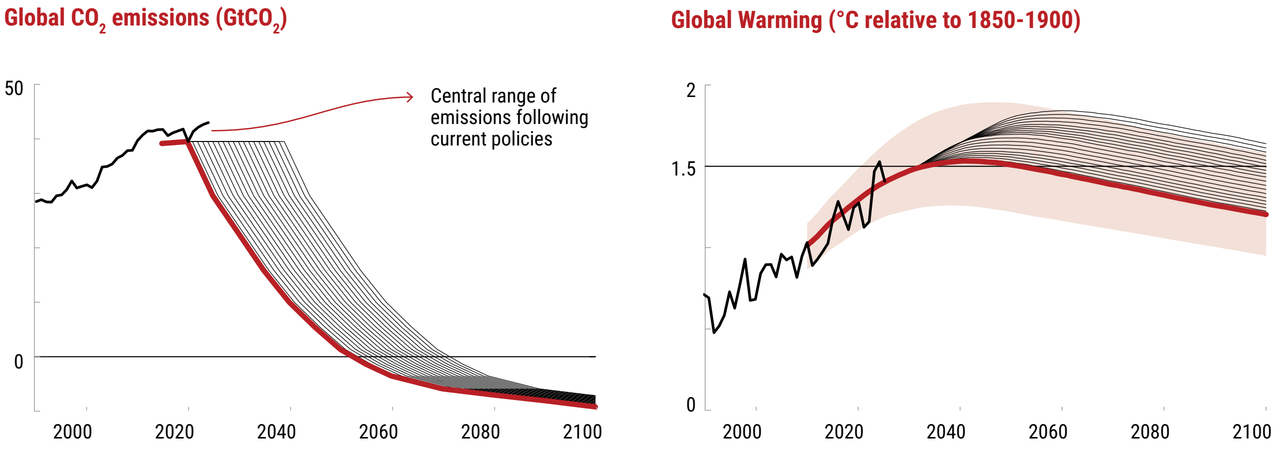
1.2 Futures lost and futures still available

Inadequate action means that emissions trajectories are inconsistent with 1.5°C. Emissions have continued to rise towards historically high levels (UNEP 2022; UNEP 2025b). Although emissions dipped temporarily during the COVID-19 pandemic, they have since rebounded as expected (UNEP 2022; UNEP 2025b). Current policies and emissions reduction targets in place as of the mid-2020s are projected to result in emissions in 2030 substantially above levels required for 1.5°C-consistent pathways, leaving a pronounced "emissions gap" (UNEP 2025b). Under current policies and alternative near-term trajectories, exceedance of 1.5°C is now widely assessed as unavoidable. Key concepts related to the exceedance of a temperature target and possible pathways thereafter are presented in Figure 1.1.

Immediate and deep cuts to greenhouse gases are needed. Pursuing efforts to limit warming to 1.5°C—while minimizing the magnitude and duration of overshoot—requires immediate and deep emissions reductions across all sectors**.** Even before 1.5°C was formally part of an international climate target, both UNEP and the

IPCC had already identified emissions pathways and GHG benchmarks consistent with low-temperature stabilization and with keeping 1.5°C within reach (UNEP 2013; IPCC 2014; UNEP 2014; UNEP 2015). These benchmarks have evolved as the evidence base has expanded and definitions have been refined. However, they have consistently implied strong GHG emission reductions relative to recent levels, with 2030 GHG benchmarks of 40 $GtCO_2e$/yr or lower[2] (Rogelj *et al.* 2018a; UNEP 2018; UNEP 2019; UNEP 2020; UNEP 2021; Riahi *et al.* 2022). Beyond 2030 benchmarks, studies have emphasized the importance of longer-term GHG reductions, including achieving net-zero CO_2 emissions around mid-century and net-zero GHG emissions in the second half of the century (Rogelj *et al.* 2015; Rogelj *et al.* 2018a; Riahi *et al.* 2022).

Figure 1.2: Futures available and futures lost



Every year of delay in emissions reductions (left) adds to the magnitude of overshoot of 1.5°C (right). Central projections of global greenhouse gas emissions under current policies do not yet indicate a clear decline and continue to exacerbate overshoot of 1.5°C.

Illustration of how delays in global reductions of greenhouse gas emissions increase the magnitude of overshoot. Bold red lines show data for emissions reductions starting in 2020, the thin black lines show the outcome of delay.

2 Global Warming Potentials over a time horizon of 100 years (GWP-100) are used to aggregate GHG emissions into CO_2 equivalence (CO_2e), consistent with reporting requirements under the UNFCCC and the Paris Agreement (UNFCCC 2018).

National climate pledges are nowhere near sufficient. Analysis of mitigation pledges submitted as part of countries' nationally determined contributions (NDCs) under the Paris Agreement reveals a substantial emission gap. Both the first and second round of NDCs submitted since the Paris Agreement's entry into force were projected to result in a continued increase in global GHG emissions[3] (Rogelj *et al.* 2016; UNEP 2016; Ou *et al.* 2021b; UNEP 2021). Assuming full implementation of the most recent, third-round NDCs as submitted by September 2025, global GHG emissions are projected to decline slightly from their record 2024 levels to around 51 $GtCO_2e$/yr in 2030, but still leaving a substantial emissions gap (UNEP 2025b).

Implementation of existing pledges is weak. A further challenge is the persistent implementation gap between pledged emission reductions and policies currently in place to deliver them. Under currently implemented or planned policies, global emissions are projected not to decline but to remain broadly stable through 2030 (UNEP 2025b). In both cases, the outlook to 2030 remains markedly above levels consistent with pathways that limit warming below 2°C, let alone return it to 1.5°C by 2100 after a limited overshoot. The existence of both ambition and implementation gaps has been consistently highlighted in scientific assessments over many years (UNEP 2015; UNEP 2016; UNEP 2017; UNEP 2018; UNEP 2019; UNEP 2020; UNEP 2021; UNEP 2022; UNEP 2023; UNEP 2024b; UNEP 2025b).

The persistence of this gap comes with three consequences:

First, recent UNEP estimates indicate that 1.5°C will be exceeded across all central estimates. Under current policies, median projected global warming reaches around 2.6°C by 2100 (range 1.9–3.6°C).[4] Even under one of UNEP's most optimistic scenarios, which assumes implementation of all NDCs and long-term net zero targets, central global warming estimates peak at around 1.8°C (range 1.7–2.2°C). In all cases, central estimates indicate that global warming will cross 1.5°C within the next decade.[5]

Second, the most stringent emission reduction pathways that were available around the time of the Paris Agreement are no longer feasible (Figure 1.2). Such pathways required immediate, deep and sustained global GHG emissions reductions to start as early as 2015 or 2020, included rapid declines in both CO_2 and non-CO_2 GHG emissions and reached global net-zero CO_2 around mid-century (UNEP 2015; Rogelj *et al.* 2018a). Even under these conditions, most studies indicated that warming would temporarily exceed 1.5°C before being reversed back below 1.5°C by 2100 (Rogelj *et al.* 2018a; Rogelj *et al.* 2018b; Riahi *et al.* 2022; Tavoni *et al.* 2026).[6] More recent studies that account for delayed action over the past ten years, institutional constraints and technological feasibility show that even stringent mitigation pathways starting around 2025 result in best-estimate peak warming exceeding 1.5°C by about 0.2°C (Bertram *et al.* 2024; Hooijschuur *et al.* 2025; Riahi *et al.* 2026). Strengthening near-term ambition therefore remains central to limiting both peak warming and the duration of overshoot (Rogelj *et al.* 2019; Iyer *et al.* 2022).

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3 NDC targets are typically categorised in unconditional and conditional targets. Conditional targets are targets that are accompanied by certain conditions that need to be met first, such as ensuring the availability of finance or technology transfer. Full implementation of NDCs means that both unconditional and conditional targets in NDCs are implemented.

4 These estimates refer to central (median) global warming projections, with the range illustrating the indeterminacy in estimating how emissions will evolve beyond the years for which there are explicit assessments (e.g. 2030). Note that for ease of communication, the median estimates of global warming for each case are referred to here, while the UNEP Emissions Gap reports focus their reports on the level of global warming that would be avoided with a greater than 66 per cent probability.

5 In the more optimistic UNEP case, highlighted in the main text, projection uncertainty still encompasses 1.5°C, but only with a low (~20 per cent) probability.

6 These pathways were referred to as pathways limiting warming to 1.5°C with no or limited overshoot in the IPCC Special Report on Global Warming of 1.5°C (Rogelj *et al.* 2018a) and as C1 pathways in IPCC AR6 (Riahi *et al.* 2022).

Third, delayed action has pushed the lowest avoidable peak warming above 1.5°C. While options for deep emissions reductions from 2025 onwards remain available, a decade of insufficient action and persistently high emissions has increased the minimum level of peak warming.

1.3 The climate impacts of entering a 1.5°C world

A temperature rise of 1.5°C is already dangerous. A 1.5°C world is already associated with high to very high risks across natural and human systems**.** In its Sixth Assessment Report (AR6), the IPCC provided a comprehensive assessment of the key risks and "Reasons for Concern" for a global warming level of 1.5°C that serves as the point of departure for this report. Specifically, it identified high to very high risks for unique and threatened systems including coral reefs and other biodiversity hotspots as well as the cryosphere, including the Arctic and mountain glaciers. In the IPCC's assessment, very high risks imply "severe impacts and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risk". At the time of the IPCC AR6, the 1.5°C global warming level—defined as a 20-year average—had not yet been reached. After the first individual year with a global mean temperature above 1.5°C in 2024, the world has now entered a 20-year period with mean warming of 1.5°C (Bevacqua, Schleussner and Zscheischler 2025).

Many of the impacts assessed in AR6 are beginning to unfold. Between 2023 and 2025, more than 80 per cent of tropical coral reefs experienced bleaching events and mass coral bleaching has been documented in at least 83 countries and territories (National Oceanic and Atmospheric Administration [NOAA] 2025b). Climate change-driven global biodiversity loss is also accelerating (Urban 2024). In February 2025, combined Arctic and Antarctic sea ice reached a new all-time minimum (Copernicus Climate Change Service [C3S] 2025), and the oldest and thickest multi-year ice has decreased by over 95 per cent since the 1980s (NOAA 2025a). Of total global glacier loss since the 1970s, more than 40 per cent occurred in the last decade (2015–2024), with 6 per cent lost in 2023 alone (Dussaillant *et al.* 2025).

Extreme weather is already intensifying. The IPCC AR6 assessed the risks posed by extreme weather events to be high at 1.5°C, with unprecedented events emerging that would have been virtually impossible without global warming (Philip *et al.* 2022). Such events are becoming more frequent, intense and widespread. Over the past two decades, more than 50 unprecedented, high impact heatwave events have been documented (Quilcaille *et al.* 2025). Simultaneously, global warming has increased the likelihood and intensity of tropical cyclones, as well as many flood, drought and wildfire events (Otto, F. *et al.* 2025). From May 2024 to May 2025, about half of the world's population experienced at least 30 days of extreme heat — defined as days hotter than 90 per cent of temperatures observed in their local area over the 1991–2020 period (Giguere *et al.* 2025). As a consequence, heat-related mortality is rising globally (Matthews *et al.* 2025). For example, heat-related deaths during a European summer heatwave in 2025 were estimated to have tripled with this increase being attributed to global warming (Clarke *et al.* 2025).

Limits to adaptation are being reached. The IPCC AR6 also identified soft limits to adaptation that are already being reached, particularly for the most vulnerable communities. Escalating ecosystem impacts—such as the documented widespread bleaching of tropical coral reefs—indicate that in a 1.5°C world, some ecosystem-based adaptation measures will increasingly reach hard adaptation limits (IPCC 2022c). Chapter 2 of this report further assesses the impacts of exceeding 1.5°C and the extent to which they may be reversible during a subsequent period of temperature decline.

1.4 Global warming reversal after overshoot

The goal remains 1.5°C. The pursuit of 1.5°C endures as a legal and ethical imperative (Rogelj and Rajamani 2025). However, as global warming exceeds 1.5°C, efforts to limit warming to this level from above necessarily include an element of global warming reversal (cf. Section 1.1).

Net-zero is a necessary milestone to returning below 1.5°C. Under the Paris Agreement, countries aim to collectively achieve a balance of emissions and removals of all GHGs in the second half of this century — that is, net-zero GHG emissions.[7] Following the GHG aggregation method under the Paris Agreement framework, this implies net-negative CO_2 emissions and is therefore expected to result in a gradual decline in global warming (Fuglestvedt *et al.* 2018; IPCC 2021).

The contribution of non-CO_2 GHGs is time-bound. Reductions in methane—the most important short-lived GHG—are a key part of deep mitigation strategies (IPCC 2018a; IPCC 2022b). Cost-effective near-term methane reductions can lower both the rate of warming over the next decades and the warming peak (Rogelj *et al.* 2014; CCAC and UNEP 2021) while delivering gains for air quality and public health (CCAC and UNEP 2021). However, if this near-term mitigation potential is effectively utilized, further contributions from methane emission reductions to the reversal of global warming are limited and would require addressing 'hard-to-abate' methane emissions, particularly in the agricultural and waste sectors (see Chapter 3).

Carbon Dioxide Removal (CDR) will be needed to offset remaining emissions. The physics of a global warming decline are similar to the physics governing our current increase in warming: anthropogenic GHG emissions alter the Earth's radiative balance. When net CO_2 emissions reach zero, CO_2-induced warming is expected to stabilize (IPCC 2021). Achieving this balance requires carbon dioxide removal (CDR) to offset any remaining CO_2 emissions (IPCC 2022b). To reverse warming requires CDR to exceed residual CO_2 emissions resulting in sustained net-negative CO_2 emissions that may gradually lower global temperatures (IPCC 2021; see also Chapter 3).

CDR deployment is needed to reach even net-zero, but faces challenges. IPCC AR6 highlighted that any strategy to reach net-zero CO_2 emissions relies to some degree on CDR, often in the order of several billion tons of CO_2 removed per year (IPCC 2022b).[8] In these strategies, CDR is primarily used to balance residual emissions and must be scaled further to achieve net-negative CO_2 emissions and enable temperature decline. However, CDR methods vary in durability, resource requirements and scalability (Smith *et al.* 2024), and are often considered as a portfolio of approaches. Their deployment is shaped by biophysical, economic, governance and societal factors, including public perceptions related to their feasibility, legitimacy and potential mitigation deterrence. CDR deployment can also result in trade-offs with sustainable development goals, and sustainability limits to their deployment over the course of this century have been identified in the literature (Deprez *et al.* 2024), as well as legal and governance constraints (Stuart-Smith *et al.* 2023).

7 This expectation is captured in Paris Agreement article 4.1 which sets out that "In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty."

8 IPCC AR6 WG3 highlights in its Summary for Policymakers that "C.3.3 In modelled pathways that reach global net zero CO_2 emissions: at the point they reach net zero, 5–16 $GtCO_2$ of emissions from some sectors are compensated for by net negative CO_2 emissions in other sectors."

Reversing global warming will be a slow and difficult process. Approximately 220 $GtCO_2$ of cumulative net-negative emissions are required to lower global temperatures by around 0.1°C (UNEP 2025b). Consequently, the sustainable rate at which CO_2 can be removed from the atmosphere is a key determinant of the net-negative CO_2 emissions achievable, which in turn determines the pace of temperature decline (cf. Chapter 3). Even under scenarios where net-negative CO_2 emissions reach 10 $GtCO_2$ per year, or around a quarter of present-day CO_2 emissions, warming may only reverse by about 0.05°C per decade (Rogelj *et al.* 2019). In other words, a decade of global warming at the current rate of about 0.25°C per decade (Forster *et al.* 2026) may take about 50 years to reverse, even under optimistic CDR assumptions. Current deployment remains well below these levels: over the past decade, durable land-based CDR averaged about two $GtCO_2$ per year, while novel CDR methods, which use technologies to capture and store carbon, removed amounts around one-thousandth of that amount (Smith *et al.* 2024).


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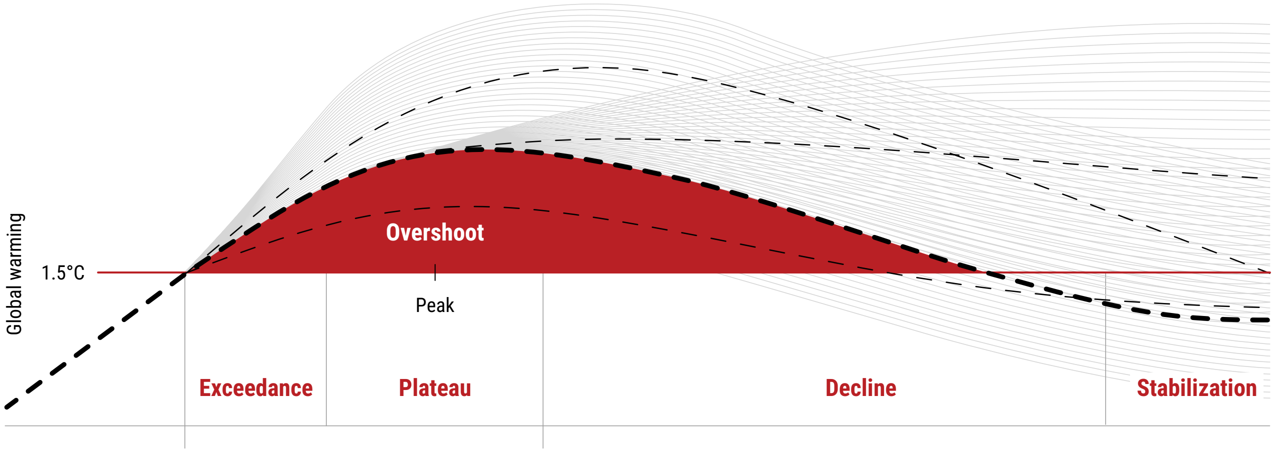
A return to below 1.5°C is deeply uncertain. These various challenges in achieving a reversal in global warming have led the scientific literature to highlight uncertainties and potentially optimistic assumptions in current overshoot discussions (Schleussner *et al.* 2024). In addition to CDR scale-up challenges, net-negative emissions may be less effective in reversing global warming than central estimates suggest. Numbers cited previously in this section assume a symmetric climate response to emissions and removals, yet this assumption might not hold in a warmer and more impacted world. While warming is expected to stabilize when net-zero CO_2 emissions are reached (IPCC 2021), additional warming under certain Earth system feedbacks cannot be excluded (Palazzo Corner *et al.* 2023). Uncertainty also remains as to whether the cooling effect of CO_2 removals matches the warming caused by comparable CO_2 emissions: earlier studies suggest it may be less (Zickfeld *et al.* 2021), while preliminary recent findings indicate that it could also be more (Chimuka and Zickfeld 2026).

Emissions reductions are the priority. The uncertainties above can increase the challenge of achieving an overshoot, peak and decline pathway when they rely on increasing amounts of CDR for warming stabilization and reversal. For instance, if the climate response is at the higher end (around the 75th percentile), several hundred gigatons of additional net CDR may be required to achieve the same temperature outcome as under median-response assumptions for the same emissions pathway (Schleussner *et al.* 2024). Given limits on sustainable annual CDR deployment (Deprez *et al.* 2024), this would likely extend the duration of temperature overshoot rather than be met through higher annual deployment rates. A prudent response therefore anticipates potential adverse outcomes (Ganti *et al.* 2025), clarifies the required scale and portfolio of responsibly deployed CDR, and prioritises rapid near-term emissions reductions—including limiting 'hard-to-abate' emissions—to minimize climate harm. Limiting the magnitude of overshoot is critical to ensure warming reversal remains feasible on timescales shorter than a century.

In conclusion, coming back is possible, but uncertain and complex. Reversal of global warming after an overshoot is possible but would require sustained net-negative CO_2 emissions over extended periods. Its effects remain contingent not only on Earth system responses but also on governance capacity, institutional coordination and the practical conditions shaping large-scale CDR deployment. The pace of temperature reversal therefore remains uncertain and constrained. The most effective risk management strategy is to reduce emissions rapidly in the near term and progress towards net zero as early as possible, thereby limiting peak warming and the duration of exceedance. Proactive adaptation is equally essential – not only to reduce harms but also to maintain capacity to sustain mitigation efforts under the increasing pressures associated with overshoot.

Figure 1.3: Key determinants of overshoot peak and decline pathway outcomes down to the impact chain



Key determinants of overshoot, peak and decline pathway outcomes

Global temperature outcomes	• Near-term emission reductions • Non-CO_2 emission reductions • Timing of net-zero CO_2	• Achieving (and sustaining) net negative CO_2 • Maximum sustainable carbon dioxide removal potential
Climate impacts and risks	Earth system feedbacks and transient climate response	• Earth system feedbacks beyond net-zero CO_2 • Zero Emissions Commitment • Reversibility of global warming
Adaptation and loss and damage	• Scaling of climate impact drivers with global warming • Crossing of irreversible thresholds	• Time lagged responses • Irreversible impacts • Timescales of climate impact driver reversibility
Adaptation and loss and damage	• Urgent near-term adaptation needs • Limits to adaptation (hard and soft) • Loss and damage at peak warming	• Continuous adaptation needs to irreversible changes • Avoided loss and damage by declining warming

Source: Adapted from Schleussner *et al.* 2024

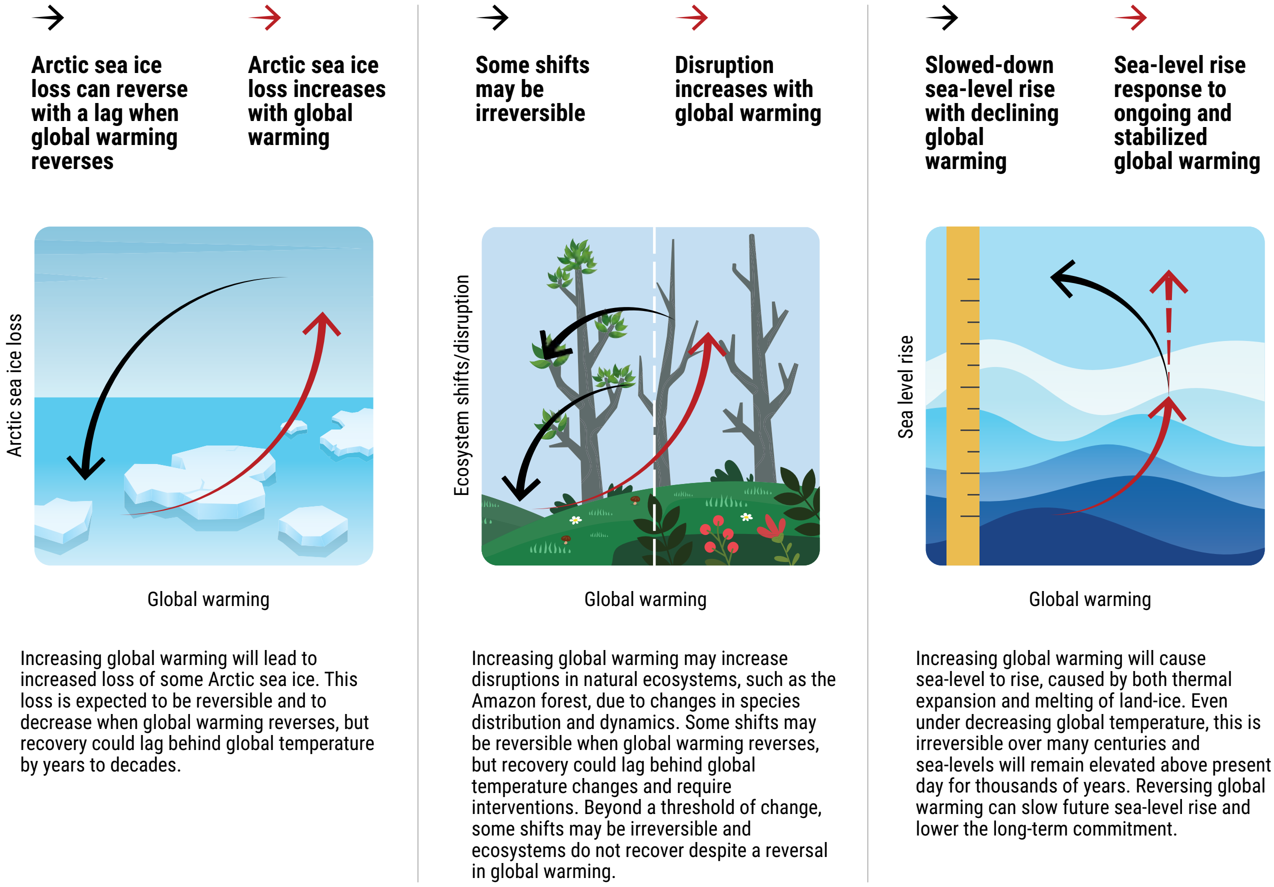
1.5 Climate impact (ir)reversibility and the benefits of long-term global warming reversal

A comprehensive view is needed. Evaluating the implications of exceeding, peaking and subsequently declining global warming requires understanding the full impact chain: from emissions to regional and local scale consequences over different timescales. In particular, the dynamics during the near-term stage until net-zero emissions, and a subsequent decline stage may differ considerably in their dynamics and are shaped by technological, societal and scientific challenges.

Decades above 1.5°C will bring major implications for adaptation. A 1.5°C overshoot, peak and decline pathways extend to the end of the century or beyond. Even under optimistic assumptions about global temperature decline, it would take multiple decades before global temperatures return to below 1.5°C — beyond the planning horizons relevant for many adaptation decisions (with the notable exception of long-lived infrastructure planning). As a result, adaptation needs and costs will largely be determined by climate risks at peak warming, while additional adaptation needs will arise under long-term reversal and stabilization (Theokritoff *et al.* 2026). This underscores the deep interdependence between near-term adaptation and mitigation action.

A decline in global mean temperature will not reverse all regional climate harms. Regional climate change can differ before and after peak warming, even at the same level of global warming, with far reaching implications for climate risk assessments and adaptation needs. Even indicators that generally closely follow global warming trajectories, such as regional temperatures, may differ before and after peak warming (Pfleiderer, Schleussner and Sillmann 2024). In many regions, regional precipitation patterns show limited reversal under global temperature decline, as do changes in extreme event indicators such as extreme day and nighttime temperatures, as well as extreme precipitation (Pfleiderer, Schleussner and Sillmann 2024). At the same time, global warming reversal will be essential to reduce long-term climate risks, subsequent adaptation investment needs, and to avoid exceeding adaptation limits.

Figure 1.4: Reversible, partially reversible and irreversible dynamics of Earth system components under global warming decline



Source: Adapted from Reisinger *et al.* 2025

Impacts will continue after stabilization. Many components of the climate system—in particular ocean and cryosphere dynamics—will respond with considerable time lags to changes in global mean surface air temperature. Adjustments in the hydrological cycle, atmospheric circulation and major ocean circulations such as the Atlantic Meridional Overturning Circulation (AMOC) are projected to continue for centuries well after emissions have ceased (Lacroix *et al.* 2024). Consequently, regional climate changes will continue even under conditions of global temperature stabilization (King *et al.* 2024).

Many impacts will be irreversible. Slow-responding components of the Earth system—such as permafrost thaw, glacier land ice sheet loss, and sea level rise—are particularly prone to impact irreversibility. Yet, it is in these components where global warming reversal can yield substantial benefits in terms of avoided long-term consequences. Under peak and decline pathways, permafrost carbon losses may be irreversible, even if permafrost areas may partially recover under global warming reversal (Cui, Ji and Chen 2025). Global glacier loss is projected to continue for centuries even if global warming were stabilized at current levels (Zekollari *et al.* 2025). Exceeding and returning to below 1.5°C will have additional, irreversible consequences for glacier mass and runoff over centuries, but reduces glacier loss compared to a stabilization at higher level (Schuster *et al.* 2025).

Sea levels will continue to rise for centuries in response to past warming. Overshoot pathways commit the world to long-term increases in coastal water levels. Achieving long-term temperature decline compared to stabilization at higher warming levels may reduce long-term sea-level rise by almost half a meter in 2300, with larger differences over longer timescales (Schleussner *et al.* 2024).

Triggering tipping elements could lead to irreversible changes. The potential to reduce long-term risks in slow-responding Earth system components through global warming reversal is especially relevant for tipping elements — large-scale systems that may undergo irreversible change once critical thresholds are crossed (Ritchie *et al.* 2026). These include the West Antarctic and the Greenland ice sheets, the AMOC and the climate-biosphere system of the Amazon rainforest (Armstrong McKay *et al.* 2022). While thresholds and response times remain uncertain, evidence increasingly indicates that sustained warming above 1.5°C raises the risk of triggering one or more tipping elements (Wunderling *et al.* 2023; Stokes *et al.* 2025). Achieving and maintaining net-zero GHGs, and thereby achieving global warming reversal, will be required to limit risks posed by climate tipping elements in the long run (Möller *et al.* 2024).

The Atlantic Meridional Overturning Circulation is projected to slow down. Limiting peak warming to less than 2°C may limit the overall weakening considerably compared to higher levels of warming (Portmann *et al.* 2026). With increasing peak warming, there is a growing risk of a long-term collapse of the circulation system (Drijfhout *et al.* 2025). Further, if such a tipping could be avoided, long-term AMOC changes in response to an overshoot, peak and decline pathway need to be expected. In model projections, the AMOC is found to recover on the timescale of centuries, and, under overshoot pathways with high peak warming, even shows periods of recovery beyond pre-industrial levels (Schwinger *et al.* 2022; Lacroix *et al.* 2024).

Many other natural systems face irreversible impacts. Ecosystems that are fundamentally disturbed in their function will not recover, species that go extinct, locally or even globally will not reappear (Meyer and Trisos 2023). Likewise, many impacts on human systems cannot be reversed. These include excess mortality and morbidity associated with climate extremes (Vicedo-Cabrera *et al.* 2018), the loss of cultural practices such as the Hajj pilgrimage under extreme heat (Saeed, Schleussner and Almazroui 2021), the inundation of UNESCO World Heritage sites (Marzeion and Levermann 2014) and lasting reductions in economic activity and productivity.

Global warming reversal will play out against these ongoing changes. The scale of climate change reversibility will also depend on the level of peak warming and duration of temperature overshoot (Schwinger *et al.* 2022; Lacroix *et al.* 2024). The higher the peak warming and the longer the overshoot period, the more persistent and durable the consequences.

The societal consequences will grow and evolve. Population composition and size, economic development and adaptive capacity, and technological progress are expected to change profoundly during this century. As a result, the consequences of the same level of global warming may differ before and after peak warming because societies themselves will have changed. Today's youth will face a triple burden over the course of their lifetime: tackling the consequences of the exceedance of 1.5°C, expediting the transition to net zero and striving for long-term warming reversal (Grant *et al.* 2025a).

Even temporary exceedance of 1.5°C will leave irreversible losses. These irreversible losses—even with a temporary exceedance of 1.5°C—underscore that a warming of 1.5°C and above cannot be considered 'safe' for most nations, communities, ecosystems and sectors and poses significant risks to natural and human systems (IPCC 2018a). The evidence of the benefits of long-term warming reversal is compelling. Permanent stabilization of global warming at levels above 1.5°C would further cement human and ecosystem losses, and commit humanity to very profound long-term risks including through potential tipping element destabilization and continued sea-level rise.

1.6 Adaptation and mitigation must move together in tackling overshoot

Responding in three phases. The prospect of crossing 1.5°C above pre-industrial levels in the next few years creates interconnected mitigation and adaptation challenges that must be addressed jointly for climate resilient development across three response phases (Figure 1.5).

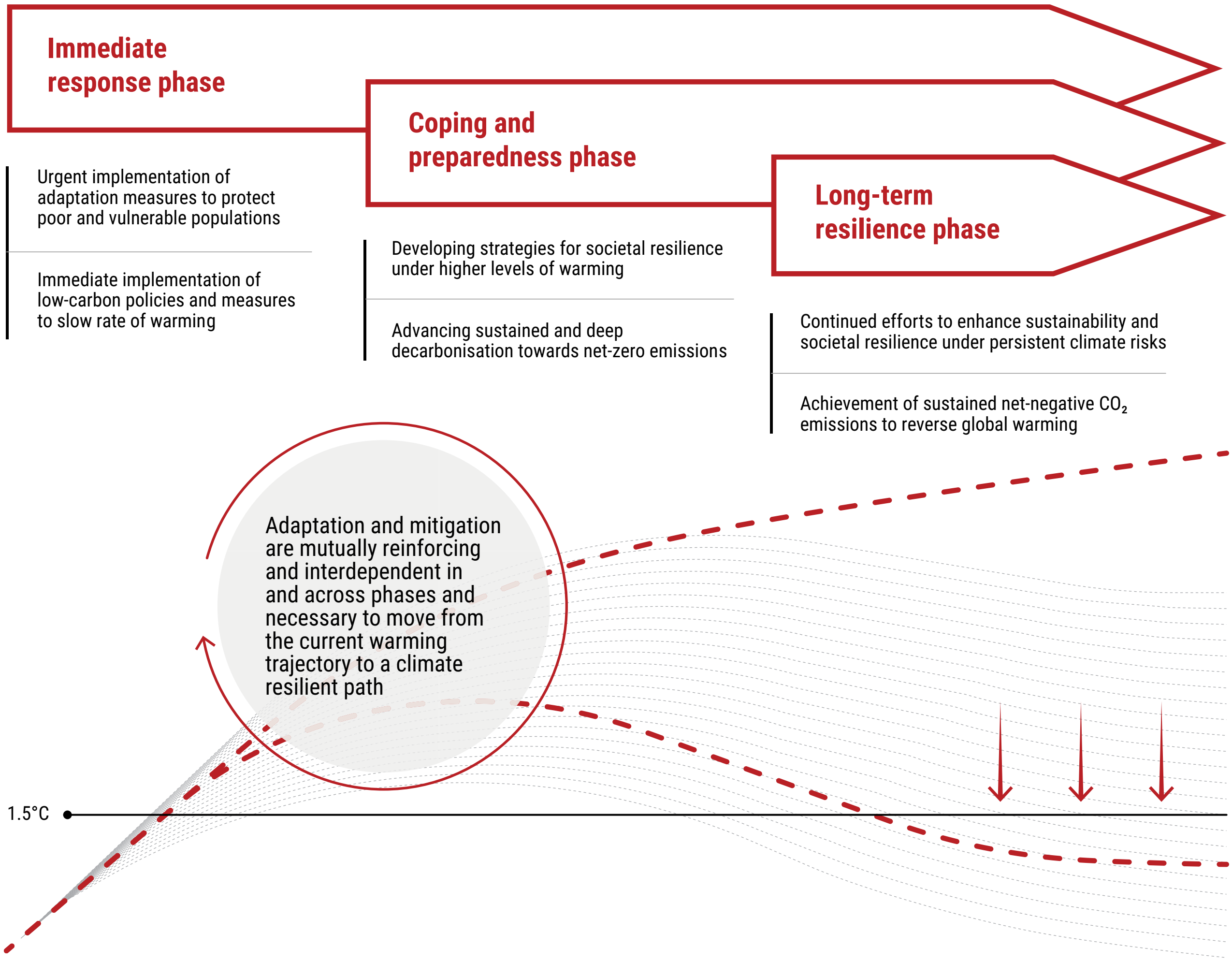
First, an immediate response phase that reflects the near-term crossing of 1.5°C. On the adaptation side, this requires the urgent implementation of measures to protect poor and vulnerable populations from foreseeable impacts. In parallel, mitigation efforts must focus on the immediate implementation of measures that reduce global GHG emissions and slow the rate of warming.

Second, a coping and containment response, starting immediately. This requires decision-makers at local and regional levels to plan for a world that has exceeded 1.5°C where warming needs to be halted while communities and societies are protected. This involves strengthening resilience under higher levels of warming, alongside sustained and deep decarbonisation towards net-zero emissions. This phase persists until global warming stabilizes.

Third, a long-term resilience response phase combining warming reversal with continued adaptation. This includes sustained net-negative CO_2 emissions to reduce climate hazards, with continued efforts to close any remaining adaptation gaps and enhance sustainability and societal resilience.

Across these phases, adaptation and mitigation are mutually reinforcing and interdependent. Mitigation strategies must be robust to climate impacts that cannot be ruled out, while adaptation planning must consider how much warming could still occur. Greater confidence in mitigation enables more targeted adaptation. Conversely, insufficient mitigation will push adaptation closer to its limits across regions and systems.

Figure 1.5: Crossing 1.5°C means adaptation and mitigation must move together as they represent mutually supporting pillars of resilient future societies



*Note: Visual features are illustrative and not an accurate representation of global warming magnitudes and rates.

Above 1.5°C, unprecedented change becomes the new normal. Even if global warming declines over the longer term, there will be no return to the previous climatic or societal conditions. The future is therefore not a stable end point, but an evolving reality shaped by intensifying extremes, adaptation limits, ecosystem loss and unfamiliar regional climate dynamics.

Resilience must encompass the capacity to cope, adapt, learn and transform. This places resilience at the centre of the response. Despite its wide use, the concept of resilience carries different meanings across research and practice. In this report, we draw on the IPCC AR6 glossary[9], which refers to resilience as the capacity of social and ecological systems—and their interactions—to cope with disturbances while retaining essential functions, and to adapt, learn or transform.

9 Working group II of the IPCC AR6 also includes a chapter on climate resilient development, which describes a process of implementing mitigation and adaptation to support sustainable development for all. Numerous other perspectives of resilience have likewise been put forward in the literature.

Resilience must be considered against a new normal of persistent change. The challenge is not only resilience to discrete shocks, but also the capacity to navigate persistent, evolving and systemic change. How societies respond will shape development pathways, capacities to cope and adapt, and the forms of resilience that emerge. These may be equitable and enabling, or may reinforce exclusion and entrench vulnerability.

02 Overshoot risks and impacts: Implications on human and environmental systems

Overshoot will create evolving and interconnected risks. This chapter examines the implications of an overshoot, peak and decline pathway for people, biodiversity, development and the planet, and assesses cascading risks across systems and regions. It examines how climate risks evolve across the different stages, with particular attention to cascading impacts across sectors and regions, the role of peak warming and duration of exceedance in determining risk, and the extent to which impacts may be reversible as global temperatures decline (Reisinger *et al.* 2025; Meyer and Trisos 2023). While some impacts may diminish during a decline stage, others are expected to persist for decades, centuries or longer. The extent to which these consequences are reversible in a decline stage is a question only partially answered by existing science literature and will vary substantially among sectors. Understanding these differences is critical for informing mitigation, adaptation and long-term risk management.

2.1 Framing risk, impacts and implications

Complex risks arise from interacting climatic, ecological and socioeconomic pressures. Complex risks emerge from multiple climate and non-climate risk drivers interacting with compound climate hazards and processes leading to cascading socio-ecological impacts and risks (Simpson *et al.* 2025). As the magnitude of exceedance increases, these interactions become more complex and increasingly difficult to manage, threatening human life, ecosystem functions and basic needs of billions of people (IPCC 2022d; Wunderling *et al.* 2023; Reisinger *et al.* 2025). If warming levels are reduced, some impacts are expected to be long-lived and only partially reversible (Reisinger *et al.* 2025), while other impacts would be reduced in the decline stage.

The decline stage will bring new and diverse risks. These impacts will differ in their timing, persistence and degree of reversibility, creating interactions that may not yet be fully anticipated (as outlined in Section 1.5). Interactions between adaptation and mitigation responses in overshoot, peak and decline pathways can be substantial, as large-scale mitigation efforts may create additional pressures on land, water and ecosystems, thereby posing new challenges for adaptation. Specific mitigation strategies may contribute to these interactions, depending on their scale and mode of deployment.

Risks and impacts are neither linear nor fully known across all stages. Overshoot, peak and decline exacerbates a number of climate risks and impacts through complex interactions of hazard, exposure and vulnerability. The subsequent autonomous responses as well as deliberate efforts to reverse warming will create additional challenges, although such challenges would be counterbalanced by the benefits of reducing warming levels (Figure 2.1). Unfortunately, there is limited scientific literature at this stage that explicitly evaluates the benefits of such reductions.


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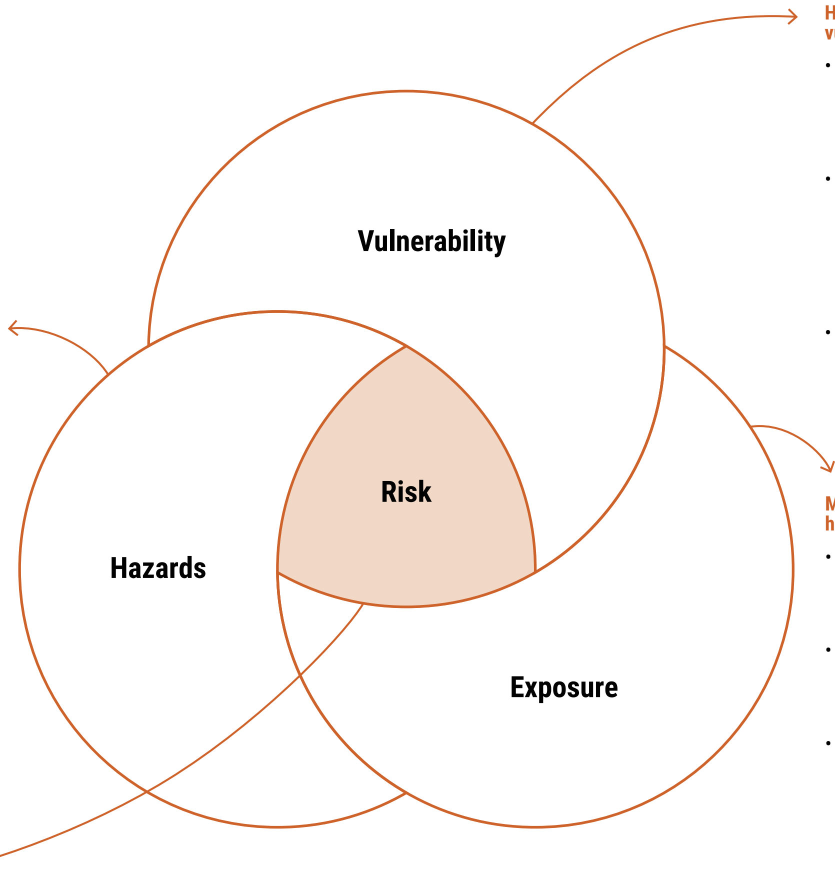
Figure 2.1: Risk propeller highlighting how risk, as determined by hazard, vulnerability and exposure, could evolve throughout an overshoot, peak and decline pathway



High and modified vulnerability

- Vulnerabilities amplified particularly in small islands, coastal areas and for undernourished rural populations
- Gender dynamics critically influence how agriculture and other human systems respond to temperature overshoot, peak and decline
- New vulnerability stressors emerging during humanitarian and emergency response

Changes in sudden- and slow onset hazards & processes

Increased frequency, intensity and duration in many world regions

Increased likelihood of tipping elements

Increased chance of earth systems tipping behaviour, some of it irreversible even during decline and stabilization (AMOC, glacial loss, sea-level rise persistence)

Compounding hazards

Peak warming increases probability of multi-hazard concurrence (heatwaves, droughts, floods)

Modified exposure of human and ecosystems

- Overshoot challenges habitability of settlements (cities, coasts)
- Long-term, irreversible impacts on ecosystems affecting also human systems
- Large gendered impacts (e.g. on women and girls in water resources systems)

Intensified risk in human and natural systems during overshoot pathways

Increased losses and damages and species extinction during peak stage

Cascading risk

Peak phase increases probability of risk cascades as earth system tipping elements may trigger systemic failures

Systemic risk

Earlier failure of ecosystems and coastal protection systems during peak phase means reduced time before soft and hard adaptation limits reached

Distributional risk

- Asymmetrical burdens across places and generations: Front-loading losses and damages, back-loading human systems' recovery
- Vulnerable groups bearing peak impacts; vulnerable groups in future generations bear remediation burdens during decline and stabilization

Epistemic risk

- Increased uncertainty in risk patterns
- Exposed and amplified deep uncertainty during decline and stabilization phases, e.g. for speed and type of local temperature and precipitation pattern reversal

Source: Building on Wunderling *et al.* 2023; Ebi *et al.* 2024; Schleussner *et al.* 2024; Alcántara-Ayala 2025; Kruczkiewicz *et al.* 2025; Reisinger *et al.* 2025

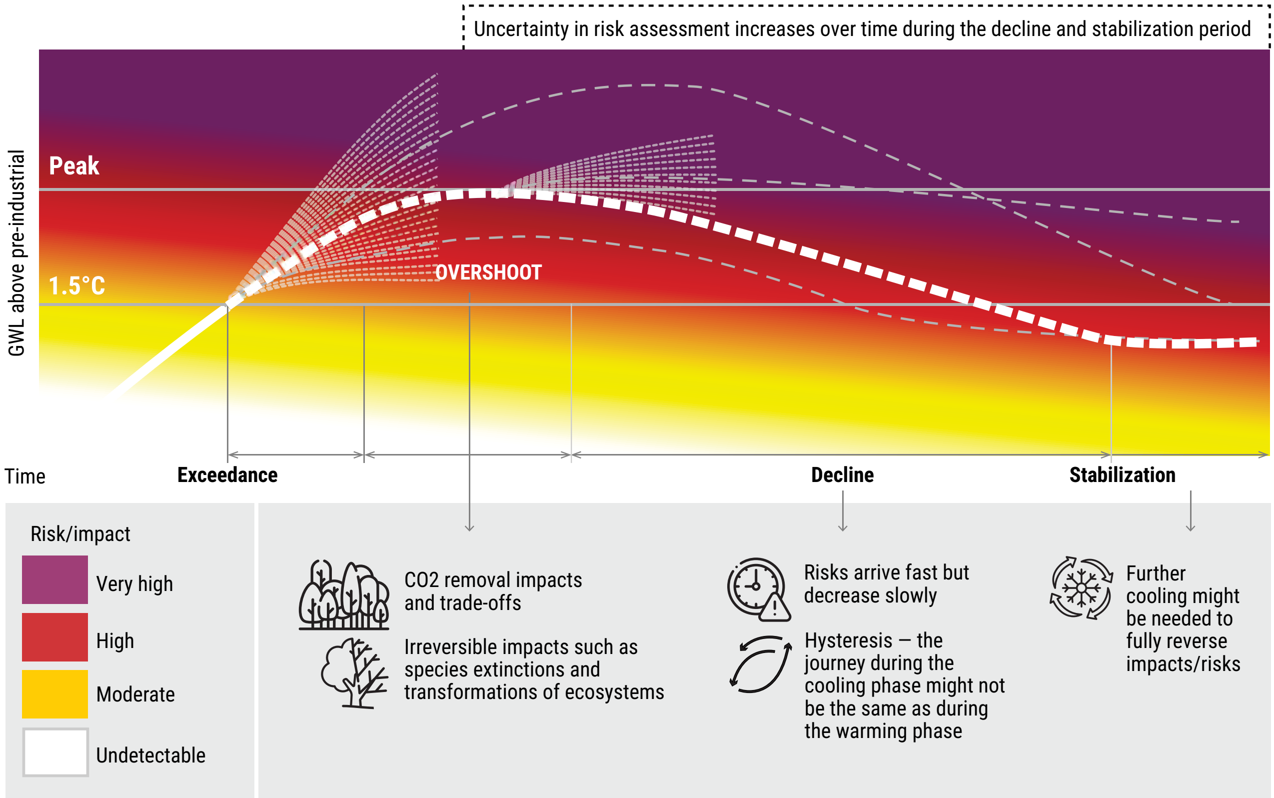
Shifting dynamics and lags between impact and response worsen uncertainty. There is solid and increasing evidence of physical tipping points and feedbacks that risk triggering self-reinforcing irreversible changes and limits to reversibility in ecological systems as well as limits for adaptation in social systems (Lenton *et al.* 2025). Avoiding high-end climate risks and tipping points may only be possible in low-temperature overshoot (Wunderling *et al.* 2023) of relatively short duration (Ritchie *et al.* 2021). Tipping points in human and environmental systems can generate irreversible effects across systems. There are lasting effects of human responses: for example, some locations might become more or less uninsurable, or even uninhabitable (Vanos *et al.* 2023; Chen and Lin 2024; Spencer *et al.* 2024). In addition, negative social tipping points—framed as limits to adaptation (Klein *et al.* 2014)—are increasingly being transgressed in an overshoot world (Theokritoff *et al.* 2026).

Interconnected risks have to be managed. When pursuing an overshoot, peak and decline pathway, the world will have to manage increasingly interconnected risks, with impacts on one sector having ripple effects across and within other sectors (Ebi *et al.* 2024). Discrepancies in timescales of reversibility require particular attention, as physical and social systems would respond to both warming and cooling trajectories at different rates, potentially creating adaptive mismatches. Reversing adaptations to habitability changes could occur on a different timescale than temperature declines (to the extent that either is possible). These dynamics intensify interactions among climate change, ecological disruption and socio-economic vulnerability.

Risks to nature cascade across food, water, health, energy and livelihoods systems. Human well-being fundamentally depends on biodiversity and ecosystem services — such as water regulation, pollination, soil fertility, coastal protection and disease control (IPBES 2024a). These risks are gender-differentiated as norms shape exposure, access to resources, decision-making power and the ability to act on early warnings. Women and girls, especially in low-income and rural contexts, are disproportionately affected by food insecurity, water scarcity and loss of livelihoods. Climate change is already contributing to biodiversity loss under current levels of warming (IPCC 2023a), and exceedance increases the likelihood of crossing ecological thresholds and tipping points, such as large-scale forest die-back, destabilization of ocean and cryosphere systems (Meyer and Trisos 2023; Dodds *et al.* 2024), and the contraction of climate refugia for species (Smith *et al.* 2018). Climate change also exposes natural and human systems to peak levels of warming and associated extremes that exceed historical experience, while creating persistent legacy impacts due to ecological lags, hysteresis and irreversible changes in ecosystems and socioeconomic structures (Meyer and Trisos 2023; Morée *et al.* 2025).

Comprehensive planning is essential. The temporal dimensions and lags between impacts rippling across sectors and environments are also important to consider when planning for both current worlds and those experiencing overshoot. Some recovery may be possible following peak warming, but it will often be protracted and incomplete, with some ecosystems unable to return to pre-overshoot conditions even after temperatures decline (Figure 2.2) (Meyer *et al.* 2022; Meyer and Trisos 2023). Long recovery times may intensify human and social risks, with consequences for food security, health, displacement and humanitarian logistics that evolve before, during and after peak warming (Kruczkiewicz *et al.* 2025). This increases the probability that limits to adaptation may also be exceeded, which weakens many nature-based solutions and exacerbates inequities where dependence on ecosystem services is high or adaptive capacity is low (IPCC 2023a; Kruczkiewicz *et al.* 2025). For example, initial assessments of risks to food systems, water security, health and migration from ecosystem decline have shown to be disproportionally greater in low-income regions under temporary temperature overshoot (Dodds *et al.* 2024).

Figure 2.2: Potential impacts during exceedance, peak, decline and ultimately a stabilization period will be path-dependent, likely with higher impacts for a given Global Mean Surface Temperature (GMST) level in the decline stage than in the exceedance stage.



Location of risk colours in this figure are conceptual and not a result of assessment.

2.2 Nature, ecosystems and biodiversity

Nature's services to humanity are at risk. Overshoot is expected to severely compromise Nature's Contributions to People (NCP), with risks increasing as warming rises and persists. NCP—in terms of material and non-material benefits, and regulating functions (Diaz *et al.* 2018)—are expected to be severely compromised depending on the magnitude and duration of the overshoot; with multi-sector risk exposure projected to double for global warming levels between 1.5°C and 2°C and to double again in the case of warming levels between 2°C and 3°C (Byers *et al.* 2018; IPCC 2022c). Irreversible consequences include spatial patterns of temperature and precipitation changes that persist even in a stabilization stage, loss of polar and alpine glaciers, persistent sea-level rise, and significant shifts in the distribution and composition of biodiversity around the world.

Regional differences will evolve and emerge. Overshoot will affect temperatures and precipitation differently across regions, shaping where its impacts are greatest. Spatial patterns of temperature and precipitation changes in overshoot relative to non-overshoot conditions are essential to understanding differences in impacts. During the peak stage, surface temperatures are particularly elevated in the northern latitudes, relative to the rest of the globe (Smith *et al.* 2025). In the decline stage and following stabilization of the Global Mean Surface Temperature (GMST), spatial patterns of differences in temperature and precipitation patterns persist. There are fairly large discrepancies among Earth System Models (ESM) about the persistence of precipitation and temperature changes in a stabilization period. However, there is agreement that average air temperatures in much of the Northern Hemisphere are substantially cooler in the decline stage of an overshoot pathway than in a monotonic warming scenario (where GMST steadily increases over time without any temporary cooling period), with warmer temperatures in the southern oceans (Douglas *et al.* 2025). Precipitation patterns are much more uncertain, with disagreement among ESMs on precipitation differences between scenarios with and without overshoot (Douglas *et al.* 2025). This spatial distribution is significant in determining which ecosystems and biophysical components of the Earth system will be most affected throughout an overshoot, peak and decline trajectory.

2.2.1 Low resilience ecosystems

There are irreversible consequences for low-resilience ecosystems. The IPCC AR6 Synthesis Report (IPCC 2023a) concluded, with high confidence, that during a temperature exceedance period, low resilience ecosystems will experience irreversible adverse impacts from excess warming: including polar, mountain and coastal ecosystems impacted by ice sheet melt, glacier melt or by accelerating higher committed sea-level rise (IPCC 2023a). Importantly, it was concluded, with high confidence, that every increment of global warming will intensify multiple and concurrent hazards.

Some ecosystems are inherently vulnerable to minor increases in warming. Low resilience can result from inherent vulnerability of the biological system. Sensitive marine ecosystems—particularly warm water corals—face irreversible shifts during temperature exceedance, even when followed by a decline, with greatest impacts in equatorial regions (Chaudhary *et al.* 2021; Bauer *et al.* 2023). Warm water coral reefs have a warming threshold of 1.2°C (range 0.7–1.5°C) (Pearce-Kelly *et al.* 2025), and coral destruction is already occurring. Although the Fourth Global Coral Bleaching Event (which ran from 2023 to mid-2025) was confirmed by the United States National Oceanic and Atmospheric Administration (NOAA) and the International Coral Reef Initiative (ICRI) (Reimer *et al.* 2024), warm water corals are now experiencing heat stress on a near-annual basis. Coral regrowth and calcification rates are potentially reduced by 20–40 per cent due to ocean acidification (Bauer *et al.* 2023). There is a low possibility of corals surviving this century under either a scenario of stabilization at 2°C or that of temperature exceedance, overshoot, decline and stabilization at 1.5°C (Hoegh-Guldberg *et al.* 2018; Tachiiri *et al.* 2019), with recovery possible if warming is kept below 2°C (Bozec *et al.* 2025).

Human activities are damaging nature's resilience. The natural resilience of ecosystems can be especially compromised by anthropogenic activities, such as by habitat fragmentation and landscape change (Costello *et al.* 2022). The Amazon forest system, considered as a potential global tipping element (Armstrong McKay *et al.* 2022), is one case where human induced fires and deforestation leading to reduced forest area and fragmentation have resulted in substantial changes to the integrity of the ecosystem, increasing its vulnerability to global warming (Reis *et al.* 2021; Lapola *et al.* 2023; Flores *et al.* 2024; Silva *et al.* 2024; Wunderling *et al.* 2026), with potentially cascading impacts to the regional moisture budget (Silveira *et al.* 2025; Huntingford 2026).

Slow onset risks to ice sheets and coastlines increase over centuries to millennia. Observations, palaeo-records and modelling of the cryosphere's response to warming levels of +1.2°C above pre-industrial, already indicate future Global Mean Sea Levels (GMSL) some metres higher than present (Höning *et al.* 2023; Chandler *et al.* 2025; Stokes *et al.* 2025; Winkelmann *et al.* 2026). Evidence suggests that critical thresholds for long-term ice loss in parts of the Western Antarctic Ice Sheet basins may have been crossed even below +1°C of warming above pre-industrial levels (Reese *et al.* 2023; van den Akker *et al.* 2025; Winkelmann *et al.* 2026), potentially committing these basins to irreversible ice loss over the next two centuries. Marine-based sectors in East Antarctica—representing ~5 m of potential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sea-level rise—may also lose stability above 2°C of global warming (Winkelmann *et al.* 2026). Even if the ice sheets do not undergo a transition to a new state, they will likely contribute to several metres of sea-level rise, resulting in inundation of global coastal ecosystems and communities, depending on the warming and cooling rate, and final temperature reached (Bochow *et al.* 2023; Coulon *et al.* 2025; Stokes *et al.* 2025) after an initial overshoot.

Due to relatively nascent scientific literature, assessment of overshoot impacts often requires the integration of the limited overshoot-specific analysis that exists with qualitative, process-based understanding.

2.2.2 Cryosphere

Ice sheets and other cryosphere ecosystems on the frontline. These ecosystems are already experiencing among the highest magnitudes and rates of climate change impacts in the world. Different components of the cryosphere (such as ice sheets (*see above*), sea ice, glaciers, permafrost and snow) respond differently to a temporary overshoot of 1.5°C, depending on climate sensitivity, response behaviour, thresholds and lag times of the cryospheric system elements, with irreversibility as a potential outcome (Constable *et al.* 2022).

Arctic sea-ice loss is transforming habitats, ecosystems and regional climate dynamics. In the Arctic Ocean, sea ice has thinned and its extent declined (Parkinson and Comiso 2013; Constable *et al.* 2022). A global temperature of 1.5°C results in an extremely warm Arctic (Stroeve *et al.* 2025) and several months of ice-free conditions can be expected every year if warming approaches +3°C by the end of the century (Heuzé and Jahn 2024; Jahn, Holland and Kay 2024; Stroeve *et al.* 2025). Contracting habitats are affecting the range, abundance and viability of polar flora and fauna, both terrestrial and marine, endangering species viability (Constable *et al.* 2022). Warming of the cryospheres, with loss of sea ice (Heuzé and Jahn 2024; Jahn, Holland and Kay 2024; Stroeve *et al.* 2025) results in:

- reduced light reflection (albedo) from the remaining sea ice — reinforcing warming (Wunderling *et al.* 2020; Marcianesi, Aulicino and Wadhams 2021);

- new Arctic shipping routes — with associated ecosystem impacts (Constable *et al.* 2022);
- altered atmospheric flows such as the North Atlantic jet stream — potentially affecting the behaviour of weather extremes (Doblas-Reyes *et al.* 2021; Cvijanovic et al 2025; Hay *et al.* 2025; Jiang, He and Fan 2025);
- altered ocean circulation (Schwinger *et al.* 2022; Zhou *et al.* 2023; An *et al.* 2024);
- cascading impacts on permafrost — potentially releasing stored carbon as CO_2 and methane, potentially exacerbating warming (IPCC 2019); and
- slow and long-term sea-level rise (Fox-Kemper *et al.* 2021; Schleussner *et al.* 2024).

Glacial retreat is one of the most visible impacts of global warming. Under a 1.5°C temperature scenario, global peak glacier extinction rates may be seen as early as 2041 (van Tricht *et al.* 2025). Temperature exceedance, even when followed by a peak and decline in global warming, can drive continued glacier decline for centuries.

Permafrost thaw can trigger persistent, cascading changes even after peak warming. In permafrost systems, feedbacks among energy, water and carbon cycles can yield multiple stable ecosystem states, allowing for persistent effects even after peak warming (de Vrese and Brovkin 2021). Complex processes in permafrost thaw and degradation, regionally and locally, affect soil water, carbon content and vegetation productivity (de Vrese and Brovkin 2021; Natali *et al.* 2021; Schuur *et al.* 2022; Schädel *et al.* 2026) among other ecosystem characteristics. These lead to cascading ecosystem impacts, such as through boreal forest dieback, intensification of wildfires and potentially modified ocean circulation (Ritchie *et al.* 2026).

Glacier loss/possible regrowth may change water availability and adaptation needs. Global temperature declines can result in glacier regrowth for many faster-responding alpine glaciers (Schuster *et al.* 2025). In basins where glaciers regrow after peak temperature, glacier runoff reduces further, leading to a peak in runoff followed by 'trough water' (Schuster *et al.* 2025). These non-linear changes in water availability for glacier dependent river basins under a temperature exceedance, peak and decline pathway can have substantial adaptation implications. Cryosphere-related impacts effect ecosystems and downstream communities dependent on seasonal meltwater for their functioning with consequences for water security and long-term adaptation planning (Afzal, Wang and Luo 2025; Cao *et al.* 2025; Hermans *et al.* 2025; Kumar *et al.* 2025; Skiles *et al.* 2018; Velasquez Casallas *et al.* 2025; Xia and Gómez-Baggethun 2026). Temperature decline pathways could be relatively beneficial for seasonal snow, which is sensitive to interannual climate variability and has limited long-term path dependence, but is influenced by broader changes in temperature, precipitation, wildfire, and land cover (Skiles et. al. 2018; Douglas *et al.* 2025; Marshall and Rittger 2025)

Temperature decline could reduce polar ice loss and long-term sea-level-rise. Rapidly declining global temperatures after peak warming could reduce the extent and rate of polar ice loss (Robinson, Calov and Ganopolski 2012; Garbe *et al.* 2020; Bochow *et al.* 2023; Höning, Willeit and Ganopolski 2024) and reduce long term risks of sea-level rise (Schleussner *et al.* 2024).

2.2.3 Biodiversity and forest ecosystems

Sudden risks to biodiversity emerge with exceedance (Meyer *et al.* 2022). Impacts arise from both long-term climate trends as well as intermittent extreme events (heatwave, wildfire, floods, etc.) (Harris *et al.* 2018). Their interaction may significantly shape outcomes, though this remains poorly quantified (Meyer *et al.* 2022; Meyer and Trisos 2023). Marine biodiversity impacts may be more persistent than terrestrial ones due to ocean temperature dynamics, while terrestrial recovery may be constrained by land use change (Meyer *et al.* 2022). Peak biodiversity impacts generally lag peak temperature.

Forest and other ecosystem changes may persist after temperatures decline. There are also risks of irreversible impacts on forest and other ecosystems, such as Amazon forest loss and high-latitude woody encroachment (Munday *et al.* 2025). Existing evidence suggests that committed ecosystem responses in constant temperature scenarios include continued Amazon forest loss (Boulton *et al.* 2017), increased shift toward woody C3 vegetation in Africa (Scheiter *et al.* 2020) and persistent increased boreal forest cover (Pugh

et al. 2018). While this work focused on ongoing forest response under constant warming levels rather than temperature overshoot, peak and decline, it nonetheless suggests the potential for long-term hysteresis in ecosystem dynamics even in a temperature decline period.

Species redistribution and mismatch will accelerate. Intensifying climate velocities under overshoot peak and plateau conditions will further accelerate species climate-driven redistribution across terrestrial and marine systems, with direct consequences for adaptation planning and for ecological functioning for example through emerging mismatches between predator and prey distribution and seasonal abundance. By mid-century, more than half of the world's terrestrial protected areas are projected to face significant climate zone shifts (Cui *et al.* 2025), while deep-ocean biodiversity, which is often highly specialized, slow-growing and evolved under millennia of environmentally stable conditions, faces unavoidable escalation in climate velocities even under ambitious mitigation pathways (Brito-Morales *et al.* 2020).

2.2.4 Ocean and coastal biodiversity and ecosystems

Threats to marine ecosystems and communities will increase. Warming oceans, declining oxygen levels and rising acidity from CO_2 absorption make it harder for marine life to survive and weaken ocean ecosystems and habitats (Bijma *et al.* 2013). These changes also threaten food supplies, jobs and the stability of coastal communities around the world.

Lasting damage can occur to marine species. Ocean warming and oxygen loss reduce habitable volume for marine species, and this loss can last for centuries and be difficult to reverse (Santana-Falcón *et al.* 2023). Even after global temperatures stabilize, the damage to ocean life continues. The combination of warmer water and less oxygen make it harder for many species—including commercially-important fish species—to survive. In fact, these impacts can be more severe and longer-lasting than during the period when temperatures were still rising, especially in scenarios where warming temporarily exceeds targets before cooling again (Santana-Falcón *et al.* 2023; Morée *et al.* 2025).

Ocean acidification reduces habitable zones, with strong regional variation (Jiang *et al.* 2023; Ma, Gregor and Gruber 2023; Müller and Gruber 2024). In some areas, the vertical habitable zone of marine calcifier species had been reduced by more than 200 m. The Arctic is observed to be acidifying at three to four times the rate of other seas (Qi *et al.* 2022). Critical levels of acidification are reached already in portions of the Arctic and Southern Oceans, impacting the growth of marine calcifiers further beyond, to the north and central Pacific Oceans, and in the Indian Ocean (Findlay *et al.* 2025).

Rising seas occur for centuries. Sea-level rise unfolds over centuries to millennia due to deep ocean warming and delayed cryosphere responses (Park *et al.* 2023). Depending on how much the planet warms, glaciers (excluding the Antarctic and Greenlandic ice sheets) could lose roughly a quarter to over 40 per cent of their mass by 2100, which would raise global sea levels by about 9 cm (+1.5°C scenario), 9.9 cm (+2°C scenario), 12.5 cm (+3°C scenario) and 15.4 cm (+4°C scenario) from glacier melt alone (Rounce *et al.* 2023). Compared to non-overshoot conditions, Schleussner *et al.* (2024) found that every 100 years of exceedance above 1.5°C could lead to an additional median sea-level rise commitment of around 40 cm by 2300. Declining warming would be able to reduce long term risks of sea-level rise.

Sea-level rise threatens ecosystems and communities. Long term sea-level rise will challenge the viability of marginal terrestrial-coastal ecosystems (e.g. mangroves, saltmarsh) with acceleration of coastal erosion, reduced space for ecosystems and alteration of physico-chemical and geomorphic properties of the ocean reclaimed lands. In the decline stage of overshoot sea-level rise would still be occurring, affecting the role of terrestrial-coastal ecosystems as natural coastal protection barriers and fisheries nursery grounds, as well as carbon sinks. Habitat loss from inundation and coastal changes will be greatest in tropical regions, where warming also drives shifts in species distributions (Santana-Falcón *et al.* 2023). Limited space for ecosystems to move inland will constrain adaptation, affecting livelihoods and coastal management.


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Different impact timeframes occur at different depths. Some surface-ocean changes may reverse as temperatures decline, while changes throughout the full ocean depth may persist for centuries. There are both encouraging and concerning signs, to be further studied and assessed. In modelled temporary temperature overshoot, peak and decline pathways—with a peak below 2°C—sea surface temperature, pH and dissolved oxygen concentrations in surface sea waters would largely be reversible, but their global averaged ocean values—over the whole water depth—would not, even after centuries (Li *et al.*2020) due to the slow vertical mixing processes. Physical and biogeochemical changes will vary widely across time and space (Tachiiri *et al.* 2019; Bertini and Tjiputra 2022; Holt *et al.* 2025). For an overshoot with higher peak warming (Shared Socioeconomic Pathway [SSP] 5-3.4-OS), many marine communities may never recover, which underscores the importance of limiting peak warming and returning to 1.5°C (Meyer *et al.* 2022) as quickly as possible.

In Focus: Sea-level rise and the small island developing states adaptation challenge

For small island developing states (SIDS) and other low-lying island territories, sea-level rise (SLR) under overshoot is not just a future submergence problem (Vousdoukas *et al.* 2023). Some islands will lose their habitability long before they become completely submerged. This collapse of habitability has already begun. Storm surges are pushing further inland, freshwater lenses and farmland on atoll islands are turning salty, coastal-buffering ecosystems such as coral reefs are being lost, and high-tide flooding now reaches further inland and happens more often than at any time in the historical record (Di Fonzo 2025; Bower *et al.* 2024; Magnan *et al.* 2022). A further five-to-ten centimetres of SLR—expected between roughly 2030 and 2050—is projected to double the frequency of flooding across much of the Indian Ocean and tropical Pacific (IPCC 2022c; IPCC 2023a).

SIDS face an order of risk no comparably exposed coastal geography shares, produced by the convergence of four factors. First, SIDS territories are small, fixed and finite: unlike delta cities or low-lying developed states, which retain higher ground to retreat to, most SIDS have nowhere else to go, which is why populations and infrastructure are concentrated—out of necessity rather than choice—in a narrow coastal fringe. In the Caribbean, an estimated 22 million people live below six metres of elevation, and most Pacific islands have over half their infrastructure within 500 metres of the coast; even higher-elevation islands such as Fiji are exposed, given how much sits near the shore (Mycoo *et al.* 2022). Second, this goes beyond a threat to infrastructure: sea-level rise puts the continuity of statehood itself in question — a question the ICJ addressed directly in its 2025 advisory opinion, affirming that a state does not necessarily lose its statehood through the loss of territory (ICJ 2025). Third, chronic, structural resource scarcity leaves no buffer: since 1970, SIDS have sustained disaster-related Gross Domestic Product (GDP) losses of USD 153 billion against an average GDP of just USD 13.7 billion (WMO 2020), and 70 percent of the 33 SIDS assessed now exceed the critical 40-percent-of-GDP debt-sustainability threshold (GCA 2025). Fourth, narrow and often single-sector economies mean each shock lands harder and recovery draws down the same limited resources needed for the next: Vanuatu was struck by two category-5 cyclones within five years, the second compounding an already-unfolding COVID-19 economic shock, leaving progressively less capacity to withstand what came next (UN DESA 2021). No delta city or low-lying developed state faces this convergence.

Overshoot sharpens each of these vulnerabilities still further, in three specific ways:

First, near-term rise is essentially locked in: how high sea level rises by 2050 is largely independent of whether 1.5°C overshoot occurs — and is locked in even more tightly at the regional level for Pacific atoll States and territories such as Tuvalu, Kiribati and others (NASA Sea Level Change Team 2023; NASA Sea Level Change Team 2024).

Second, the choice of emissions pathway only begins to affect the rate of SLR after mid-century. By that point, atoll freshwater lenses and farmland are projected to be contaminated by saltwater, and port and transport infrastructure in the Caribbean and Pacific is projected to be past key adaptation thresholds (IPCC 2022c). The longer-term benefits of returning to 1.5°C come too late to save what has already been lost (Lee *et al.* 2023b).

Third, SLR will continue for centuries to millennia even after temperatures return to 1.5°C; the depth and duration of overshoot shape by how much, with deeper or longer overshoots risking ice-sheet threshold crossings that lock in additional rise (NASA Sea Level Change Team 2023; NASA Sea Level Change Team 2024). Indian Ocean SIDS face this trajectory with the thinnest evidence base, exemplifying a broader SIDS data-scarcity problem that the ICJ (2025) and International Tribunal for the Law of the Sea (ITLOS) (2024) have held does not diminish states' due-diligence obligations.

Cascading impacts are compounding (UNEP 2024c). As coasts become progressively less inhabitable, displacement is shifting from a distant prospect to a present reality. Yet Pacific Islanders have explicitly rejected the framing of 'climate refugees', and both Pacific and Caribbean SIDS communities have consistently expressed a preference to remain in place, with relocation viewed only as a last resort (IPCC 2022c). Where movement does occur, the IPCC finds with high agreement that the degree of agency and choice individuals retain over if, where, how and when they move is a key determinant of whether mobility leads to positive adaptation outcomes or becomes an additional layer of climate-related impact.

Despite this, empirical research involving UNFCCC negotiators from Pacific and Caribbean SIDS indicates that consultation remains very limited in practice, including with populations whose movement is being planned (Thomas and Benjamin 2018; Nalau and Handmer 2018; Bhatti 2025).

The adaptation toolkit underpinning these choices is itself eroding: ecosystem-based protection, freshwater management and early warning can buy time in the near term, and international law requires their pursuit under stringent due diligence (ICJ 2025). But Ecosystem-based Adaptation (EbA) faces significant constraints above relative SLR rates of roughly 5–7 mm/year, expected within decades (IPCC 2023a; Saintilan *et al.* 2023); and seawalls are costly, maladaptive and merely shift erosion laterally (IPCC 2022c).

This unvirtuous cycle of climate-induced erosion of development and resilience, already documented by the IPCC across many SIDS, will accelerate as overshoot deepens—and by peak warming, the IPCC concludes with high confidence that vulnerability in some SIDS may exceed adaptation limits well before 2100—even under low-emission pathways, because the locked-in component of SLR is largely insensitive to near-term mitigation choices.

Strategic questions

Four of many questions demanding urgent discussion, research and strategic action stand out—questions on which the international community will be measured by whether it recognizes, finances and enables the continued sovereignty, agency and survival of States—whose habitability has been altered, detrimentally or existentially, by emissions caused by activities within the jurisdiction or control of other States

1. What adaptation options are realistically available to SIDS, and at what physical, environmental and social thresholds must protection give way to transformation or mobility?

2. If, as the evidence shows, those whose movement is being planned are rarely consulted, then whose relocation is it? What would it take to shift from mobility planned for SIDS populations to mobility determined by them — across the individual, community and state interests that do not always align?

3. What legal and institutional arrangements are needed to ensure that all States and international organizations continue to respect the sovereignty, state continuity and maritime entitlements of SIDS—and of their increasingly dispersed peoples—as their land territory becomes uninhabitable or submerged — particularly during and after the decline stage, when, despite falling temperatures, sea level will continue to rise?

4. The institutional architecture for adaptation finance and loss and damage is now taking shape — Bridgetown, the Multidimensional Vulnerability Index, the Fund for Responding to Loss and Damage. But it is being built just as the underlying adaptation toolkit erodes. The question is no longer whether these instruments exist; it is whether they can deliver at the scale and speed that locked-in climate impacts demand, or whether they will remain a paper response.

2.3 Impacts on social and human systems

Cascading and potentially irreversible impacts ripple across social and economic systems. Social systems will be affected by temperature overshoot, peak and decline with significant potential for cascading impacts and irreversible changes linked to disruptions in social systems and evolving risk interactions during the decline stage. For example, ecological changes driven by the global warming up and until the overshoot plateau are likely to propagate across sectors: degradation of watershed forests can undermine hydropower generation and drinking water security; declines in pollinator populations can impair food production; and disruption or collapse of coastal ecosystems will increase exposure of people and infrastructure to storm surges and erosion. Many of these impacts are likely to persist even in a decline stage, particularly for small islands and other low-lying coastal areas with high vulnerability (Anderson *et al.* 2020). However, there is currently a lack of detailed analysis of how this will play out, particularly in economic and social dimensions (See Box 2: Debt, insurance, and fiscal capacity; and In Focus: Economic impacts and distributional risks under overshoot). Impacts will occur in systems including agriculture and food security, water availability, human settlements and infrastructure, health and livelihoods with broad-ranging consequences for human well-being.

There is a major gap in the understanding of how cultural and social constructs/norms may evolve before and after peak warming, including human relationships and risk perception, particularly in relation to extreme hazards (which may change/increase in frequency for certain areas) and their associated impacts. However, there is limited analysis comparing the challenges associated with the return stage relative to those that would be expected with continued warming.

Reversible changes will require societies to adjust repeatedly. Reversible climate effects will have their own unique challenges for human systems as adaptation to warming will occur over decades, and any subsequent transition to cooler conditions would require a further period of adjustment and readaptation over similarly long timescales. For example, health impacts may arise from changes in the distribution and change of vector-related diseases during a cooling stage. Agricultural practices that have adapted to warmer conditions may have to change again, potentially impacting yields and food security. Such transitions may not be smooth, or easy, as some risks and impacts may decline with temperature but changes may not be immediate or linear, and there is a high level of uncertainty about climate responses to climate at regional or local scales.

Socioeconomic inequity shapes vulnerability. Socioeconomic conditions will continue to shape exposure, vulnerability and response capability, often amplifying climate-related risks. Interactions between climate and socioeconomic variability increase uncertainty, complicating projections of impacts. Without deeper assessment, policy and humanitarian responses risk overlooking the most vulnerable (Kruczkiewicz *et al.* 2025).

2.3.1 Agricultural land, crop yields and land-use implications

Agricultural productivity and food security under threat. The effects of climate change on agriculture will drive significant productivity losses and threaten the food security and livelihoods of billions of people (FAO 2023a; FAO and WMO 2026). Projections indicate potential declines of up to 14 per cent in global food production by 2050 in the absence of effective adaptation measures (Farah *et al.* 2025). Extreme heat is a serious and acute hazard for agriculture, with impacts across crops, livestock, fisheries and aquaculture, and forestry (FAO and WMO 2026). Future crop yields will be shaped both by climate change and by direct biophysical effects of rising emissions, such as CO_2 fertilization. Modelling shows that 0.5°C of warming reduces crop productivity across most regions (Schleussner *et al.* 2018). Reshaping and redesigning for a more climate-friendly global food production system could be essential to achieve sustainable food security (Li, Roy and Dong 2022; Islam and Fraser 2026).

Agricultural land systems may face heightened and persistent risks. Pathways that involve a temporary temperature exceedance while aiming to return global warming to 1.5°C are associated with heightened and potentially persistent risks for agricultural land systems. Rapid mitigation efforts required in these pathways may increase input costs such as fertilizer and energy, leading to yield reductions even without severe climate impacts


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(Liu *et al.* 2025). These effects highlight the importance of considering agriculture within the broader mitigation context.

Human health is at risk. Climate-related changes in food availability and diet quality are estimated to increase nutrition-related diseases and the number of undernourished people, affecting tens (under low vulnerability and low warming) to hundreds of millions of people (under high vulnerability and high warming), particularly among low-income households in low- and middle-income countries in sub-Saharan Africa, South Asia and Central America (IPCC 2023a).

Competition for land poses challenges. Unless adequately governed, competition between food production and land-intensive CDR could create additional food-security risks. Where land availability is constrained, competition between food production and CDR can limit the feasibility of land-intensive mitigation strategies (Chapter 3). Food security risks are closely intertwined with land-use constraints and mitigation design, requiring integrated strategies that align climate objectives with agricultural productivity and prioritize low-land-footprint mitigation and CDR options (Liu *et al.* 2025).

Different functions, different power, different vulnerabilities. Gender dynamics also critically influence how agriculture and other human systems respond to temperature overshoot, peak and decline. Women farmers, who constitute more than 40 per cent of the agricultural labour force in low- and middle-income countries (WAF 2025), face structural barriers to land, credit, technology and climate information (FAO 2023b). These constraints increase their vulnerability to climate shocks and limit their ability to benefit from mitigation or CDR-related shifts in land use (Chapter 3).

2.3.2 Water resources

Complex, regional and potentially irreversible water impacts are expected. Temperature overshoot, peak and decline will affect water supplies in complex and partially irreversible ways with hysteresis in hydrological systems arising from changes in weather patterns, water flows and how people use and manage water (Walton and Huntingford 2024; Marshall, Grubert and Warix 2025; Steinert *et al.* 2025). While precipitation hysteresis is limited, regional variability—particularly related to Inter-Tropical Convergence Zone (ITCZ)[10] shifts—could yield substantial differences in water availability (Steinert *et al.* 2025). These global-scale simulations do not likely capture the full suite of conditions that could affect

10 This is where northeast winds from the Northern Hemisphere converge with the southeast winds from the Southern Hemisphere. The ITCZ appears as a band of clouds consisting of showers and occasional thunderstorms that encircles the globe near the equator.

hydrologic outcomes throughout the overshoot, peak, decline and stabilization periods, and these discrepancies are particularly understudied in decline periods (Marshall, Grubert and Warix 2025). Long-lasting impacts to forest ecosystems as described above, or land cover and land use changes more broadly, in peak warming periods could affect water and energy balance dynamics in ways that reflect the broader impacts of forest conditions and land cover on water quantity and quality (Goeking and Tarboton 2020). For example, enhanced fire risk during a peak period could affect water quantity and quality for years (Williams *et al.* 2022) and yield earlier successional forests that further alter water availability. Conversely, to the extent that a decline period would reduce forest disturbance frequency relative to baseline policies, disturbance influences on water could theoretically be reduced. Overshoot impacts on alpine glacier change and permafrost would similarly propagate through water resources systems (de Vrese and Bovkin 2021; Schuster *et al.* 2025).


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Human interactions change the hydro-dynamics. Some of the biggest effects may come from how people interact with water systems. These impacts are not equal — women and girls often carry the responsibility for collecting and managing water and providing care. This can increase their exposure to water shortages, time poverty and health risks during overshoot conditions. Because of this, water governance should include women in planning and decision-making to ensure fair and effective solutions.

Infrastructure built during overshoot may shape risks after decline. Water infrastructure can last for decades, so systems built during a temporary warming period may continue affecting communities and ecosystems long after (Medeiros and Sivapalan 2020). Energy systems in a temporary temperature overshoot—both during warming and later cooling—can also impact water availability, since water is needed for energy production (Grubert and Marshall 2022) and for removing CO_2 (Fuhrman *et al.* 2023). For example, droughts can increase reliance on fossil fuels due to reduced hydropower generation and increased cooling demands (Kern, Su and Hill 2020); this suggests a reinforcing feedback that could make it more difficult to achieve net-negative emissions unless decarbonization pathways are carefully constructed to achieve resilience to hydroclimate variability (Marshall and Upadhyay 2024; Li *et al.* 2025a). These interconnected effects—long-term adaptation to warmer climates, water use in clean energy systems and lasting changes to the water cycle—have not been fully studied, but they are likely crucial for managing water resources under temperature overshoot, peak and decline conditions.

2.3.3 Human settlements, infrastructure and cities

There will be higher risk in cities, especially low-income and informal settlements. Climate impacts have severe consequences for urban communities, particularly in low- and middle-income countries and in low-income and informal settlements, with serious impacts on human health and livelihoods (Lee *et al.* 2023b). Urban populations are large and growing, with the latest World Urbanization Prospects indicating that 45 per cent of the world's population live in cities and a further 36 per cent in towns (UN 2025). By the end of the century, 84 per cent of the projected global population will live in urban areas, emphasizing the critical concern of impacts and risks for urban systems. Overshoot intensifies urban impacts, including longer and more frequent heat waves, skyrocketing energy demand and consumer costs, and shifting risk for insect-borne diseases, with residents of both low-income cities and lowest-income areas of wealthier cities, hardest hit, and severe consequences to cities' economies, infrastructure and public health systems (Wong and Mackres 2024). Uncertainty in risk patterns increases, requiring flexible and adaptive decision-making (Dodman *et al.* 2022).

Impacts are highly unequal. Informal settlements—home to around one billion people—face disproportionate risks due to inadequate infrastructure (Satterthwaite *et al.* 2020). Basic service deficits remain widespread, with more than 2 billion people lacking safe water and 3.5 billion without safely managed sanitation (WHO and UNICEF 2025). A temporary temperature overshoot is likely to worsen flooding risks, and make meeting safely managed targets for drinking water and sanitation even more difficult (Dodds *et al.* 2024). Climate change related threats may also overlap, be compounded or cascade through feedback between impacts on infrastructure and at-risk populations (IPCC 2012; Raymond *et al.* 2020a). Exposure to dangerous heat in urban regions and settlements is already a significant health and development problem affecting labour productivity and local economies (Burke, Hsiang and Miguel 2015; Day *et al.* 2019) as well as increasing morbidity and mortality (Matthews, Wilby and Murphy 2017; Nazarian *et al.* 2022; Matthews *et al.* 2025).

Urban development under threat. Overshoot of 1.5°C will undermine urban development gains and objectives, exacerbating risks to infrastructure especially for low-lying coastal settlements which, together with small island contexts, are projected to be home to approximately one billion people by mid-century (IPCC 2023a). For urban areas, this translates into heightened exposure to climate extremes and cascading secondary effects. For instance, relative to a 1.5°C pathway, a 3°C warming scenario could result in significantly prolonged heatwaves (with an average increase in duration of 28 per cent), a higher annual frequency of heatwave events (25 per cent increase), greater cooling energy demand and an expanded number of days conducive to arbovirus transmission (Wong and Mackres 2024). The combined result of the local-scale urban heat island effect, with increased mean and extreme temperatures from a larger-scale climate change is projected to exacerbate overheating in cities globally, with negative impacts on people's health, comfort and productivity and associated urban systems (Nazarian *et al.* 2022). Nature-based solutions such as urban forests may themselves be at risk, as by 2050 76 per cent of tree species in urban areas will be at risk from projected changes in mean annual temperature and annual precipitation with 1.8°C warming (Esperon-Rodriguez *et al.* 2022), thus hampering the potential for this type of nature-based solution at the time when it is most required.

The co-benefits of decarbonisation: cleaner air and better health. A study examining the influence of different economic growth patterns, energy transitions and non-CO_2 mitigation strategies found that most pollutant emissions show a marked reduction under all scenarios, with Sulphur Dioxide (SO_2) and Nitrogen Oxide (NOx) decreasing by approximately 60–80 per cent and stabilizing over time (Liu and Wei 2025). Addressing air pollution—both in itself and in association with mitigation—is key to protecting public health, which could be a positive outcome of a period of decline following peaking of temperature. Lower air pollution would be particularly valuable in low-income neighbourhoods, which have the poorest air quality in many cities (Dodds *et al.* 2024).

2.3.4 Public health

Overshoot will intensify existing health risks and create new ones. These include infectious diseases, malnutrition, mental stress and strain on health systems (Climate Overshoot Commission 2023). More frequent and intense heatwaves are expected to increase heat-related illness and deaths by 2050. Indirect impacts—especially food insecurity—may drive malnutrition and diet-related diseases, potentially exceeding direct heat risks.

Diseases can shift in range and become more widespread. Rising temperatures will shift vector-borne diseases into higher latitudes while reducing them in some endemic areas (Dodds *et al.* 2024). Nonlinear ecosystem changes and shifting species ranges can increase pathogen spillover and expand disease vectors, raising health risks (Pfenning-Butterworth *et al.* 2024).

Heat and humidity threaten workers. This is particularly true for informal workers in low- and middle-income countries (Dodman *et al.* 2023; Sverdlik *et al.* 2024). These risks are experienced differently across and within communities: exposure and access to protection vary according to occupation, working conditions, income, social roles and other intersecting factors, including gender. Adaptation must address occupational risks, unpaid care burdens, mental health and reproductive health needs.

Heat-related mortality can rise sharply. Events expected only once every 100 years in 2000 now occur every 10–20 years under 2020 conditions. As global warming reaches 1.5–2°C, such high-mortality summer seasons are expected to become commonplace without adaptation (Lüthi *et al.* 2023). Warmer regions, including Central and South America, Europe and especially Southeast Asia, are projected to experience substantial escalations in heat-related health burdens, with net increases by the end of the century ranging from 3 per cent in Central America to 12.7 per cent in Southeast Asia under the highest-emission trajectories. However, many of these temperature-driven health impacts could be significantly reduced under pathways that implement strong mitigation measures to limit (Gasparrini *et al.* 2017) or reverse further warming.


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Post-peak heatwave behaviour remains poorly understood. While temperature reversibility has been studied (Douglas *et al.* 2025) heatwave trends and compound risks—such as heat coinciding with floods—may persist differently across regions. Understanding these dynamics is essential for effective, timely heat-action planning.

2.3.5 Humanitarian responses

New risk hotspots and more complex humanitarian emergencies are expected. As the timing, frequency and geographic distribution of climate-related hazards are expected to shift, impacts will become increasingly compounding and cascading, creating new risk hotspots and increasing uncertainty for humanitarian planning and response. Humanitarian crises may become more complex as multiple hazards interact, existing vulnerabilities are exacerbated and the characteristics of emergencies evolve over time.

Disaster risks are unlikely to reverse as temperatures decline. Some risks will persist while others will emerge or change unevenly, requiring humanitarian systems to adapt to evolving hazard patterns and complicating preparedness, resource allocation and long-term planning in already constrained humanitarian systems (Kruczkiewicz *et al.* 2025). The impacts of overshoot—and the measures taken to limit its magnitude and duration—are also likely to be experienced unevenly. Low-income populations, countries, such as LDCs, and sectors with systemic response capacity constraints, women, and Indigenous Peoples, all communities, groups and individuals are expected to face disproportionate risks, highlighting the importance of ensuring that humanitarian responses remain equitable, inclusive and responsive to the needs of those most affected (IPCC 2022c; Kruczkiewicz *et al.* 2025).

Flexible, multi-level governance is required. To manage risks across all stages of an overshoot, peak and decline pathway rigid and static institutions and governance will no longer suffice. They will need to integrate new knowledge, addresses unequal impacts and places equity and inclusion at the centre of humanitarian and climate action.

Box 2. Debt, insurance and fiscal capacity

Economic frameworks poorly capture how actors weigh risks and preferences across the stages of an overshoot. The fiscal difficulty compounds in a loop and this is illustrated in the climate shocks (See 2.3.5) and stresses (See 2.3.3) that are anticipated. Climate vulnerability raises the cost of sovereign borrowing before any disaster occurs, so vulnerable countries pay more for capital simply for being exposed (Kling *et al.* 2025). When damage then arrives, the borrowing that meets it is contracted at that higher rate. Debt service subsequently crowds out the adaptation and development spending that would have reduced the vulnerability, and ratings can deteriorate further, raising borrowing costs again during the decline, when investment is most needed. Debt sustainability analysis that omits climate impacts understates this by construction (Zenios 2022), and adaptation financed through additional borrowing can worsen debt dynamics even where it improves output (Calcaterra *et al.* 2025).

The pattern is already visible in small island states that borrow heavily to rebuild after successive catastrophic cyclone seasons, with the resulting constraints shaping development for decades. Financial models assume warming that only rises, in project lifetimes, return calculations and risk pricing alike, so a pathway that peaks and returns needs purpose-built analysis (Bolton *et al.* 2020; Schleussner *et al.* 2024).

Similar pressures appear in the private and subnational sectors. Insurers may withdraw from high-risk regions before a peak is reached, shifting costs to governments and households and eroding the property values and tax base that local adaptation depends on (Hemmati *et al.* 2025). Firms may relocate supply chains, and many local and provincial governments continue to treat extreme events as discrete rather than as a sustained shift (Gilmore, Kousky and St. Clair 2022). Deferred decisions, such as upgrading building codes or committing to protective infrastructure, raise long-term risk where fiscal capacity has already been eroded. These pressures are documented for warming in general rather than for overshoot specifically, but they would apply across an overshoot pathway.

In Focus: Economic impacts and distributional risks under overshoot

Rising costs can be softened with adaptation. The available literature does not yet provide a comprehensive assessment of economic and distributional impacts across the full 1.5°C overshoot, peak and decline pathway. Producing comprehensive economic estimates for any temperature scenario is challenging and associated with large uncertainties, arising from, inter alia, complex interactions among physical, natural and social systems; pervasive climate, socioeconomic and system response uncertainties; and the heterogeneous nature of climate impacts that vary across space and time (O'Neill *et al.* 2022, p. 2495). However, the existing literature consistently finds that the costs of climate change increase with higher global warming and that adaptation can substantially lower projected economic impacts although it cannot eliminate all losses and becomes increasingly constrained as warming rises (IPCC 2022c). This is also reflected in the World Bank Group's Country Climate and Development Reports (CCDRs), which examine how countries can pursue development goals while adapting to and mitigating climate change.

Country outcomes can be modelled. Some country findings are summarized below, focusing on labour productivity and health, sectoral productivity, water and infrastructure, and poverty, social protection and adaptation. CCDR scenario architectures vary. The examples below include RCP8.5, SSP5-8.5, dry/hot and wet/warm futures, as well as lower-warming, no-damage and adaptation/resilience comparators. Most modelled results concern the 2040s to 2050s, but some are warming-level, stress-test or end-century estimates. Because RCPs are concentration pathways rather than complete socioeconomic scenarios (van Vuuren *et al.* 2011), the estimates below retain each CCDR's own scenario label and horizon rather than impose a uniform RCP8.5/RCP2.6 comparison. These assessments do not model the full overshoot, peak and decline pathway. They are used here to illustrate economic and distributional impact channels likely to remain relevant during exceedance, rather than to estimate the specific economic costs of overshoot.

Labour productivity and health. Across mid-century adverse-warming scenarios, CCDRs show clear links between extreme heat and reductions in workers' productivity. In Ghana, under RCP8.5, heat stress and heat-related diseases are projected to reduce agricultural labour productivity by about 8.5 per cent by 2050, compared with 2.6 per cent in manufacturing and 0.3 per cent in services (World Bank Group 2022b). A separate warming-level estimate in the same report, not tied to a specific year, suggests that at 3°C above 1990 levels labour capacity could fall by about 11 per cent for manual labourers, versus less than 1 per cent for office workers. This warming level uses the CCDR's 1990 baseline and is not directly comparable with the pre-industrial baseline used for the Paris Agreement temperature goal.

A similar pattern emerges in Sri Lanka: agricultural labour-productivity losses by 2050 are projected at around 6 per cent under a wet/warm future and almost 8 per cent under a dry/hot future, with labour heat stress accounting for roughly 60–70 per cent of modelled GDP losses by 2053 (World Bank Group 2025). In Guinea-Bissau, the dry/hot scenario leads to labour-productivity declines by 2050 of 9.5 per cent in agriculture, 5.5 per cent in industry and 3.6 per cent in services (World Bank Group 2024c). Limited access to ventilation and cooling can further widen inequalities. In Sri Lanka, heat-adaptation costs across Colombo, Jaffna, Point Pedro and Wennappuwa are estimated at USD263 million by 2050, with low-income households in unplanned settlements facing higher barriers to adaptation (World Bank Group 2025).

Sectoral productivity, water and infrastructure impacted The CCDRs stress that sectoral shocks in agriculture, water and fisheries can translate into broader economic losses. In Argentina, a no-action diagnostic that holds water infrastructure and water-use efficiency at current levels estimates that higher temperatures and evapotranspiration could compromise about 25 per cent of current irrigated area, causing roughly USD837 million in annual losses; the CCDR does not link this conditional estimate to a dated RCP/SSP (World Bank Group 2022a). In Ghana, under RCP8.5 warming of about 1.12°C by 2050, crop yields are projected to fall by 1–21 per cent by 2050, depending on the crop, with average food-price increases of about 13 per cent relative to a no-climate-change scenario (World Bank Group 2022b). In Iraq, a modelled 20 per cent reduction in water supply lowers GDP by about 3.5 per cent; adding temperature impacts on crop yields increases the loss to about 3.9 per cent, while a 10–20 per cent rise in food prices could increase poverty by 1.6–4.4 percentage points. These are water and temperature shock scenarios, not dated RCP projections (World Bank Group 2022c). In Pakistan, under a high-growth and high-warming scenario reaching 3°C by 2047, water demand is projected to increase by almost 60 per cent, with warming accounting for up to 15 per cent of the increase. The CCDR also reports crop-yield declines of 14–50 per cent under some climate-change scenarios, without assigning the full range to a single pathway (World Bank Group 2022d). Small Island Developing States (SIDS) are similarly vulnerable: under SSP5-8.5, fisheries export losses in the Maldives are estimated at about USD202.3 million per year, around 3.35 per cent of GDP by end-century (World Bank Group 2024b).

Asset and infrastructure damage cascades through the economy. Under a high-emissions climate future in Sri Lanka, a flood with a 25-year return period is projected to cause 26 per cent more damage by the 2040s than in the 1995–2020 baseline. Separately, diagnostic estimates put annual urban-flood damages above USD160 million and expected combined annual transport-network losses at USD66 million (World Bank Group 2025). In Argentina, modelled annual expected flood asset losses reach up to USD1.4 billion, with associated welfare losses up to USD4 billion; in a mid-range case in which flood frequency doubles, expected asset losses rise by 125 per cent. The CCDR does not tie these estimates to a specific RCP (World Bank Group 2022a). In Ethiopia, under a wet/warm future and the Conventional Generation (CG) scenario, additional road and bridge repair costs reach USD755 million per year in 2041–2050; under the Renewable Energy Sources (RES) scenario, about USD9 billion in proactive adaptation over the same period could avoid up to USD13 billion in road and bridge costs relative to CG (World Bank Group 2024a). The observed 2022 floods in Pakistan provide an event-based illustration rather than a scenario projection: 33 million people were affected, nearly 8 million were displaced, and combined damage and losses exceeded USD30 billion (World Bank Group 2022d).

Poverty and social inequity can worsen. These examples show that macroeconomic risks relevant to overshoot pathways arise from unequally distributed micro-level impacts. In Pakistan, preliminary post-2022-flood estimates suggest that national poverty could rise by 3.7–4.0 percentage points, equivalent to 8.4–9.1 million people, while multidimensional poverty could increase by 5.9 percentage points; these are post-disaster rather than climate-pathway estimates (World Bank Group 2022d). In Ghana, poverty in 2050 is projected to be about 0.8 percentage points higher under RCP4.5 and 1.7 percentage points higher under RCP8.5 than in a no-damages scenario, corresponding to roughly 400,000–900,000 additional people in poverty (World Bank Group 2022b). The Côte d'Ivoire CCDR illustrates how climate change alters development trajectories: without climate change, poverty is projected to fall from about 39 per cent in 2020 to 16.7 per cent by 2050; under a dry/hot scenario it would fall only to 23.4 per cent, while adaptation/resilience investments could reduce it to 20.5 per cent, leaving about 1.5 million fewer people below the poverty line than without those investments (World Bank Group 2023a). In Colombia, a severe climate-shock stress test, rather than a specific RCP and horizon, finds that around 45.5 per cent of households in the most affected departments would not be covered by existing social assistance, while around three million poor people would fall deeper into poverty (World Bank Group 2023b).

Adaptation is key to reducing economic harm. The CCDRs emphasize that adaptation is economically material. In Colombia, adaptation investment is conservatively estimated to increase GDP by up to 2 per cent relative to a scenario without adaptation. Expressed in terms of avoided climate damages, by 2050 adaptation reduces the modelled GDP loss by about 1.2 percentage points in the most benign damage scenario and about 2 percentage points in the most extreme scenario, cutting damages by up to 80 per cent but not fully offsetting them (World Bank Group 2023b). In Côte d'Ivoire, adaptation/resilience investments reduce projected poverty in 2050 from 23.4 per cent under the dry/hot scenario to 20.5 per cent (World Bank Group 2023a). Yet, adaptation costs can be high. In the Maldives, sea-level-rise impacts could reduce GDP by almost 11 percentage points by 2050 under a high-emissions scenario, while sustained reconstruction and adaptation could reduce the impact to less than 6 percentage points; financing requirements for adaptation to sea-level rise and flooding alone are estimated at USD2–4 billion (World Bank Group 2024b).

03 Limiting overshoot - mitigation pathways

Immediate cuts to greenhouse gases are needed. Rapid and sustained mitigation within this decade is both necessary and feasible across all sectors and GHGs to hold warming well below 2°C and as close to 1.5°C as possible by the end of the century. This requires reaching global net-zero CO_2 emissions in the 2050s, alongside deep reductions in other gases, especially in methane from fossil fuels, agriculture and waste. Continued efforts to tackle sources of residual emissions reduces the reliance on CDR upscaling.[11] CDR will be needed to achieve net zero and net-negative emissions, but its sustainable scale is constrained by risks to biodiversity and food security, and its effectiveness may decline with climate feedbacks that also weaken natural carbon sinks.

Sustained mitigation action is essential. Keeping the possibility of returning warming to 1.5°C by 2100 relies on achieving sustained net-negative CO_2 emissions at global scale in the second half of this century, and potentially further reductions of non-CO_2 emissions. The feasibility of this depends on early and deep mitigation that minimizes reliance on large-scale CDR to counterbalance avoidable residual emissions, while considering the environmental sustainability and social justice implications of CDR deployment. Achieving not only net-zero but sustained net-negative CO_2 emissions requires strong institutions and effective global cooperation and multilateralism that demonstrably supports equitable, regionally differentiated action with high-emitting and high-capacity countries taking the lead. Current national net-zero CO_2 and GHG targets should be understood as a milestone towards a net-negative emissions future rather than the final destination.

Decisions taken now will determine the chances of returning to 1.5°C. Planning to go beyond net-zero is a challenge for the present generation, not future ones, given the time it will take to develop and scale strategies, policies and institutions to support net-negative emissions, and to integrate these into existing policy frameworks. Decisions taken this decade will determine whether viable options remain to gradually reverse warming back to 1.5°C.

3.1 Accelerating mitigation to limit climate related risks

Every increment of warming avoided matters. Chapter 2 demonstrated that every increment of warming not only increases harm, losses and damages caused by climate change, but that warming rises above 1.5°C also constrain some mitigation options. For example, Land Use, Land-Use Change and Forestry (LULUCF) currently takes up around a quarter of mitigation in Paris-compliant scenarios, yet recent wildfires have weakened land-based carbon sinks, temporarily accelerating the growth rate of atmospheric CO_2 and underscoring the urgency of mitigation. Rapid emissions cuts, complemented by CDR, are therefore essential to limit the magnitude of overshoot and climate-related risks, and enable a return

11 In this report, CDR methods are classified following the terminology of Edwards *et al.* (2026) in The State of Carbon Dioxide Removal report. This distinguishes conventional CDR, which comprises methods already practiced that largely rely on enhancing carbon storage in the terrestrial biosphere via ecosystem restoration, afforestation and soil carbon sequestration; and, novel CDR that is typically at lower technology readiness and comprises new technologies such as bioenergy combined with carbon capture and storage (BECCS), Direct Air Carbon Capture and Storage (DACCS), biochar and enhanced weathering. Given their reliance on carbon storage in the terrestrial biosphere, conventional CDR carries higher risks of reversal but can offer co-benefits for biodiversity and livelihoods if implemented under strong sustainability criteria (Smith *et al.* 2019b). However, strong sustainability criteria also limit the scale at which conventional CDR can be deployed globally (Deprez *et al.* 2024).

of global warming back to 1.5°C. Given uncertainties in Earth system feedbacks, carbon sinks and CDR effectiveness, a precautionary approach is necessary and best estimates provided in this chapter should be seen as minimum requirements (Section 1.4; Schleussner *et al.* 2024). Developing future CDR portfolios also requires a comprehensive framing in terms of risks and opportunities to support sustainable development objectives.

Limiting the peak and length of overshoot. This chapter outlines two distinct, yet interconnected strategies to achieve a temperature pathway that peaks and returns to 1.5°C: first, limiting the magnitude of the exceedance by reaching net-zero CO_2 as soon as possible and reducing non-CO_2 emissions as much as possible (Section 3.2); and second, limiting the duration of the overshoot and bringing warming back down by achieving net-negative CO_2 emissions and further methane reductions (Section 3.3).

Climate policy must evolve to include removal strategies. While immediate and rapid emission cuts in the short-term are critical to limit the magnitude of overshoot and reduce reliance on future CDR, keeping 1.5°C within reach requires climate policy to evolve to include the removal of already emitted GHGs. This shift will require governance, fiscal and policy frameworks that enable the responsible deployment, monitoring and scaling of CDR, while embedding net-negative emissions objectives in long-term strategies from international to city scales (Fuss *et al.* 2024; Abernethy and Jackson 2024; Edenhofer *et al.* 2025; Ulpiani *et al.* 2026). Furthermore, considerations of equity and justice emphasize critical concepts such as fair technology transfer, and safeguards to prevent CDR strategies from creating disproportionate impacts on land, water security and vulnerable livelihoods, and new concepts such as carbon debt obligations (Deprez *et al.* 2024; Pelz *et al.* 2025a). Within the UNFCCC framework, navigating the shift from net-zero to net-negative emissions will be governed by the principles of common but differentiated responsibilities and respective capabilities (CBDR-RC) and equity, where the credibility of the transition rests on the commitments of front-runner nations (Mohan *et al.* 2021).


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3.2 Stringent near-term mitigation to limit peak warming

Near-term mitigation is critical to limit peak warming, reduce duration of temperature overshoot and avoid reaching adaptation limits (Chapter 4).

Avoiding carbon lock-in in infrastructure is central to this effort. Investments in long-lived, high-emission infrastructure, such as fossil-based power plants, transport systems and industrial facilities, can constrain future emissions reductions and lock countries into high-carbon trajectories (Seto *et al.* 2016; Smith *et al.* 2019a). Existing and planned fossil fuel infrastructure alone could exceed the CO_2 emissions consistent with 1.5°C in 2030 by 120 per cent, and would consume a substantial share of the remaining carbon budget for 2°C (SEI, Climate Analytics and IISD 2025). This underscores the need to avoid new high-carbon assets and accelerate retirement or retrofitting of existing high-emission infrastructure.

Urgent reductions in methane and other short-lived climate pollutants are needed. Significant low-cost abatement options are available especially in the oil and gas sector, but also through reductions of food loss and waste, waste segregation and methane capture from landfills. Methane contributes around 0.5°C of current global warming (IPCC 2021; UNEP 2025c) and early reductions can significantly lower peak warming while delivering health co-benefits (McKeough 2022; Smith and Mathison 2024; UNEP 2025c). Early mitigation requires combined supply- and demand- side action. High-leverage measures could deliver up to 41 $GtCO_2e$ annually by 2035 under USD200/tCO_2e, with about half of this potential at costs below USD20/tCO_2e (Figure 3.1). However, these estimates assume action beginning in 2020; given delayed implementation, the achievable potential is likely lower but still necessary.

Accelerating the renewable energy revolution is crucial. On the supply side, limited-overshoot scenarios suggest scaling renewables to 60–70 per cent of global electricity generation by 2030, supported by grid expansion, storage and demand flexibility (Byers *et al.* 2022). This modelled trajectory is broadly consistent with the COP 28 commitment to triple global renewable energy capacity to at least 11,000 GW by 2030 (UNFCCC 2023a; UNFCCC 2023b). Improvements in supply-chain efficiency, fuel switching in heavy industry and deployment of low-carbon heat and transport technologies can lock in long-term emission reductions while avoiding new carbon-intensive infrastructure (Pathak *et al.* 2022).

Reducing demand is an important piece of the puzzle. Significant emissions reductions in end-use sectors are possible by 2050 in some regions. However, durable demand-side change depends on enabling policy, infrastructure and shifts in social norms, rather than relying on individual choice alone (Creutzig *et al.* 2022; Albarracín, Fayaz-Farkhad and Granados 2024). High mitigation potential options available at low costs include energy efficiency improvements, electrification of heating and cooling, and more efficient appliances, as well as behavioural shifts to change urban mobility patterns, including greater use of public transport and micromobility (Jaramillo *et al.* 2022). Dietary shifts could reduce food system emissions by 0.7–8.0 $GtCO_2$-eq yr^{-1} by 2050, while also delivering health and land-use co-benefits (Mbow *et al.* 2019; Rosenzweig *et al.* 2020).

These measures can also deliver substantial co-benefits. Cleaner air, improved public health, lower energy costs, enhanced energy security and greater equity all come with mitigation (Dinh, Tran and Hensher 2024; O'Garra *et al.* 2024; UNEP 2025e). These measures also help moderate peak energy demand, ease pressure on energy systems and enhance resilience, reducing reliance on high-cost supply-side responses. Transitioning away from fossil fuels is thus a key investment in resilience and public welfare (Johnsson, Kjärstad and Rootzén 2019; Langevin *et al.* 2023).

Early emission reductions can reduce reliance on uncertain future CDR strategies. Pathways limiting warming to 1.5°C with limited exceedance[12] typically require global GHG emissions to decline by 55 per cent (from 2019 levels) by 2035, assuming action began in 2020 (UNEP 2025b). As global emissions have continued to rise, the most ambitious pathways incorporating observed emissions up to 2025 now project peak warming of 1.6–1.8°C with 50 per cent probability (UNEP 2025b; Gidden *et al.* 2026a). Pathways with higher peak warming exceedance (up to about 1.8°C) depend on substantially greater cumulative removals—often hundreds of gigatons of cumulative CO_2 removal during the second half of the century—to return to 1.5°C by 2100 (Byers *et al.* 2022; Riahi *et al.* 2022; Ganti *et al.* 2024; Gidden *et al.* 2026a). Yet most CDR strategies remain uncertain in terms of scalability, permanence, durability and social acceptability, with the main sources of uncertainty dependent on the CDR method (Brunner, Hausfather and Knutti 2024; Bindl, Edwards and Cui 2025; Mendez, Creutzig and Fuss 2025).

As the planet warms, the potential of CDR falls. In a warmer future, climate and biogeochemical feedbacks constrain nature's removal and carbon retention capacity. Heat stress, drought, wildfire risk and pest outbreaks can thus reduce carbon uptake and storage in CDR approaches, and increase reversal risks across land- and

12 Warming levels stated in this chapter are generally given with a 50 per cent probability. Limiting warming with higher probability would require more deeper reductions and/or greater removals than those indicated in the text. UNEP (2025a) provides more detailed information on emission reductions to achieve warming with 50 per cent and 66 per cent probability.

ocean-based systems (Boysen *et al.* 2017; Krause *et al.* 2025; Jeltsch-Thömmes *et al.* 2024). For example, blue carbon and marine-based sequestration potential can also be constrained as their carbon storage potential is sensitive to sea-level rise, warming and ecosystem degradation (Sandi *et al.* 2021; Song *et al.* 2025b; Grosselindemann, Burger and Frölicher 2026). These feedbacks underscore the need to protect carbon stocks in natural ecosystems and imply that removal potentials estimated under present-day climate conditions may not be fully realised under higher levels of warming, particularly during and after overshoot periods. In addition, rising temperatures are linked to increased natural methane emissions from wetlands, reinforcing the urgency of reducing human-caused emissions (Shindell *et al.* 2024; Zhang *et al.* 2026).

Higher temperatures can undermine low-carbon energy systems. Climate extremes reduce the performance and reliability of electricity generation, transmission and storage infrastructure, reducing the efficiency of thermal and renewable power systems while increasing maintenance and adaptation costs (Cronin, Anandarajah and Dessens 2018; Perera *et al.* 2020; Yalew *et al.* 2020). Specifically, renewable energy systems are increasingly exposed to climate variability and extremes and become more uncertain (Gernaat *et al.* 2021). Prolonged droughts can sharply reduce hydropower generation, heatwaves lower solar photovoltaic efficiency and altered wind regimes affecting its predictability and raising generation costs (Yalew *et al.* 2020; Cruz *et al.* 2025). These impacts may also constrain energy-intensive CDR technologies, such as direct air carbon capture and storage (DACCS), precisely when large-scale deployment is expected.

Demand for cooling is a risk. Rising cooling demand further pressures energy systems: global electricity use for cooling could increase from nearly 5,000 terawatt-hours (TWh) in 2022 to up to 18,000 TWh by 2050 under a high-emissions pathway (UNEP 2025d). Although efficient technologies and supportive policies could keep electricity demand close to current levels, climate-driven increases in cooling, water pumping and other energy services may offset efficiency gains and constrain demand-side emissions reductions (van Ruijven, De Cian and Sue Wing 2019; Bezerra *et al.* 2021).

Mitigation pathways must be designed for robustness amid climate risk and uncertainty (Lecocq *et al.* 2022). Accelerated mitigation involves trade-offs. Poorly designed policies risk lock-in, increase land-use pressures and generate social or economic disruption, especially under overshoot conditions (Chapter 4). Effective strategies must therefore integrate equity, justice and risk management while addressing persistent barriers—including vested interests, limited international cooperation, financial and infrastructure constraints, and supply chain challenges—through strong governance, strategic policy sequencing and inclusive institutions (O'Brien 2016).

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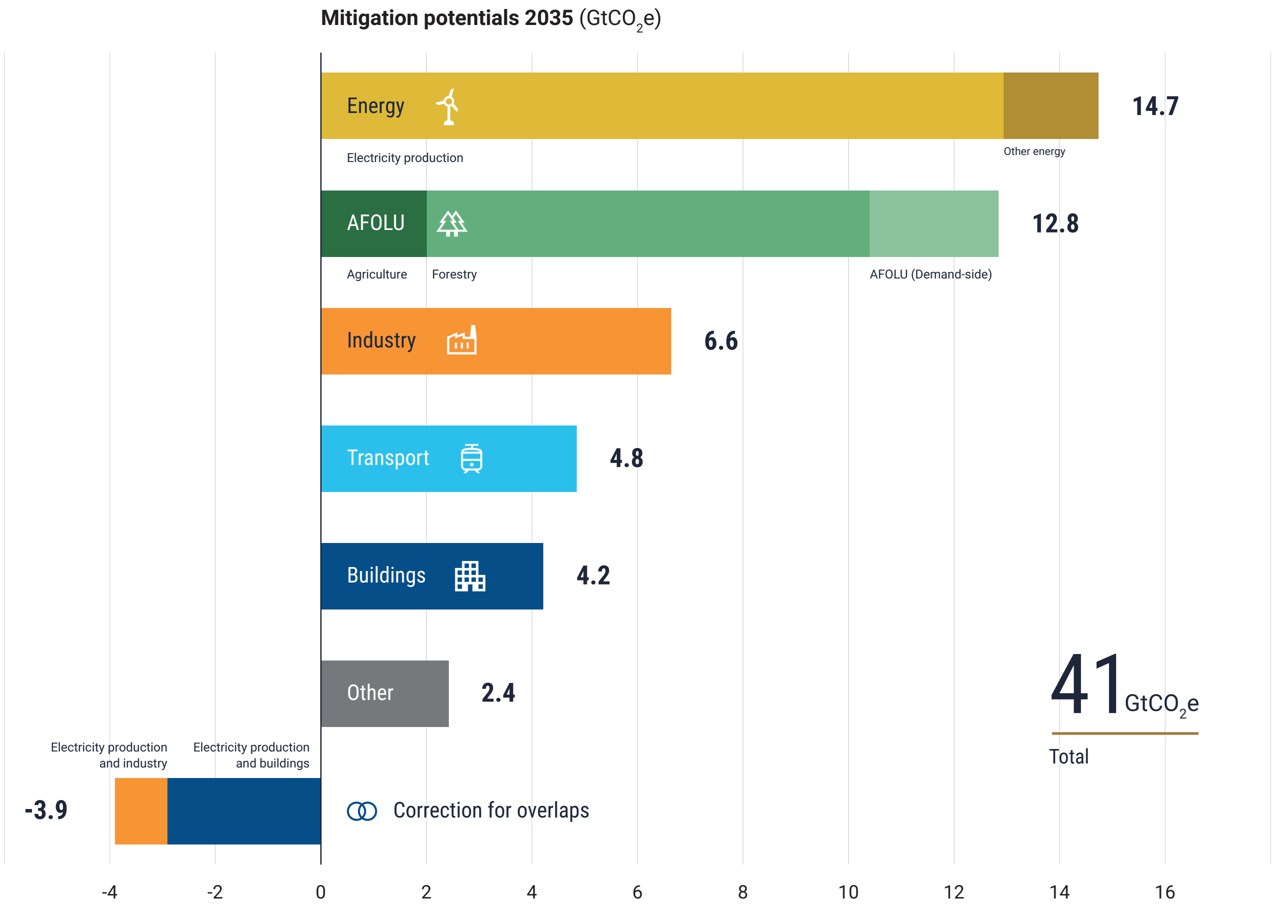
Figure 3.1: Overview of annual mitigation potentials by 2035 by sector up to USD200/tCO_2e



Source: UNEP 2024b

3.3 Strategies to bring global warming back below 1.5°C

Moving from halting to reversing global warming. Building on the mitigation pathways outlined in the previous sections, returning warming to 1.5°C after an overshoot requires going beyond what is necessary to halt global warming**.** Halting global warming at any level below 2°C already requires reaching at least net-zero CO_2 emissions globally, along with deep reductions of other GHGs, particularly methane (IPCC 2021). Reversing global temperature would rely on mitigation efforts going beyond this, to reach sustained global net-negative CO_2 emissions alongside continued further reductions in residual non-CO_2 GHGs. The higher the magnitude of exceedance, the larger the cumulative net-negative CO_2 emissions required, making early mitigation to limit peak warming a prerequisite (Section 3.2).

Nature's carbon stocks must be preserved. Minimizing losses of existing carbon stocks in a warming climate will require proactive adaptation in forest and ecosystem management (Cook-Patton *et al.* 2021; Park *et al.* 2025; Buma *et al.* 2026; Ciais *et al.* 2026; Schädel *et al.* 2026). Minimizing residual CO_2 emissions therefore limits the scale at which CDR needs to be deployed, increases flexibility and reduces trade-offs with such deployment. Accelerated near-term mitigation to minimize the magnitude of exceedance would also reduce the risk of climate change feedbacks jeopardising a return to 1.5°C through accelerated carbon losses from ecosystems. Achieving global net-zero CO_2 is a challenging but essential milestone for the world to halt global warming.

Two complementary strategies are available to achieve net-negative CO_2 emissions (See Figure 3.3). The first is to reduce residual emissions while maintaining CDR at the same rate as at the point when global net zero emissions are first reached. The second is to further scale up CDR beyond the level needed to offset remaining emissions at the point of net zero. In practice, achieving sustained net-negative emissions is likely to require both approaches, with the balance differing across sectors and regions.

Minimizing residual emissions is a key strategy. Global integrated assessment model (IAM) results suggest that 10 Gt or more of residual CO_2 emissions could remain when global net-zero CO_2 emissions are reached and thus need to be counterbalanced by the equivalent amount of CDR (Gidden *et al.* 2026a). Reducing these residual emissions further could enable net-negative emissions without proportionally increasing CDR (Reisinger *et al.* 2025; Tavoni *et al.* 2026). Scenarios assessed in the IPCC AR6 and developed subsequently differ materially in the amount of residual emissions modelled to remain at the point of global net-zero CO_2 emissions, spanning a range from about 2 to almost 15 Gt CO_2 (Lamb 2024; Gidden *et al.* 2026a), reflecting different policy choices, technology assumptions and development pathways (Figure 3.2). This wide range indicates substantial scope to reduce residual emissions further through more ambitious mitigation. Nevertheless, most scenarios that return warming to 1.5°C after a peak rely on further upscaling of CDR beyond the level achieved at net-zero CO_2, with removals reaching between about 15 and 24 Gt CO_2 per annum in 2100 to achieve deeply net-negative CO_2 emissions (Gidden *et al.* 2026a).

Balancing emissions cuts and CDR. The relative contribution of emissions reductions and CDR has important implications for the sustainability, feasibility and risk of achieving a temperature decline. Strategies that minimize residual emissions reduce dependence on large-scale carbon removal, increasing flexibility while lowering environmental and social trade-offs associated with extensive CDR deployment. However, some emissions are challenging to avoid entirely or rely on large-scale biofuel production (e.g. aviation fuels), highlighting the challenges of sustaining net-negative CO_2 emissions (see Section 3.4).


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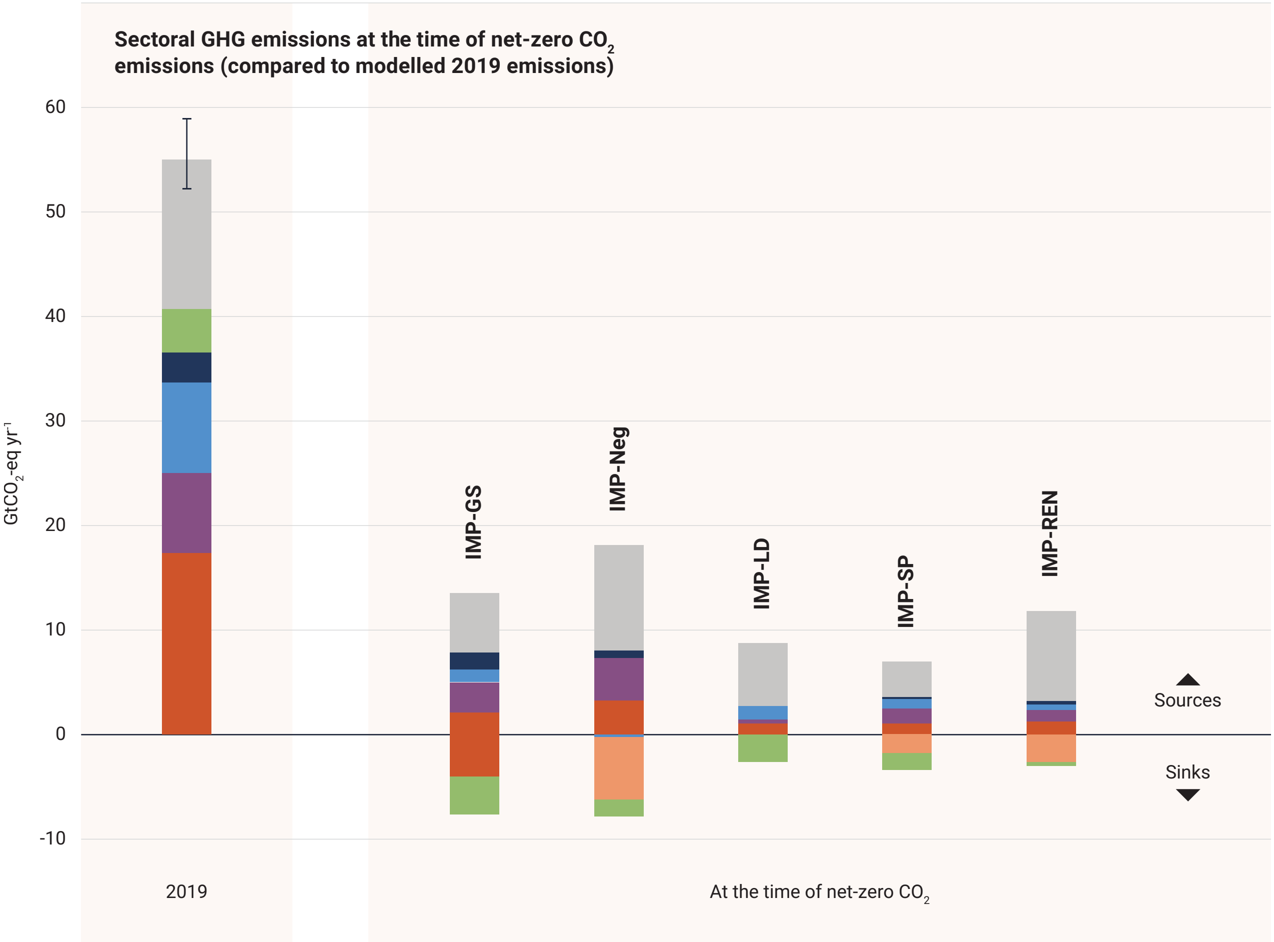
Figure 3.2: Examples of residual GHG emissions and CO_2 removals at the time of global net-zero CO_2 emissions are reached in modelled mitigation pathways assessed in the IPCC AR6 that limit global warming likely to 2°C and below



Source: IPCC 2022b

Note: Coloured bars indicate residual gross CO_2 emissions and CO_2 removals, grey bars indicate residual non-CO_2 emissions. Individual scenario names refer to Illustrative Mitigation Pathways used in the contribution of Working Group III to the IPCC AR6 (IPCC 2022b).

There are limits to conventional CDR. To give a sense of scale of the net-negative CO_2 emissions needed to achieve a decline in temperature, total global afforestation and reforestation currently achieve about 2.2 [1.8–2.6] $GtCO_2$ removals per annum (Smith *et al.* 2026). Even if global fossil CO_2 emissions reached zero and deforestation were halted entirely, it would take about 100 years of sustained afforestation and forest management activities at the current scale to reduce global temperature by 0.1°C. Upscaling carbon storage in terrestrial ecosystems (such as via afforestation, forest management, soil carbon storage) is inherently prone to reversal and constrained by land suitability and increased risk of climate-driven disturbances (Burton *et al.* 2024; Jäger *et al.* 2024; Liang *et al.* 2025; Schädel *et al.* 2026).While protecting and enhancing ecosystems and utilising natural carbon sinks can have large benefits for biodiversity and livelihoods, evidence remains insufficient that such approaches alone can deliver net- zero let alone net-negative CO_2 emissions at the global scale (Smith and Torn 2013; Dooley, Nicholls and Meinshausen 2022; Niu *et al.* 2024; Tölgyesi *et al.* 2025).

Novel CDR also faces limits. The temperature reduction achievable through further upscaling novel CDR that relies on geological carbon storage is not unlimited once geologic, environmental, human and policy risks to carbon storage in sedimentary basins are taken into account. A recent study estimated storage capacity in sedimentary basins at below 1,500 $GtCO_2$ (Gidden *et al.* 2025). If residual CO_2 emissions remain at the higher end of global scenarios, e.g. at 10 $GtCO_2$ per year from 2050 (Lamb 2024), this capacity could be exhausted by 2200 even just to maintain net-zero CO_2 emissions. However, if residual emissions were halved to 5 $GtCO_2$, then the same amount of CDR would deliver a temperature decline of about 0.1°C over 50 years.

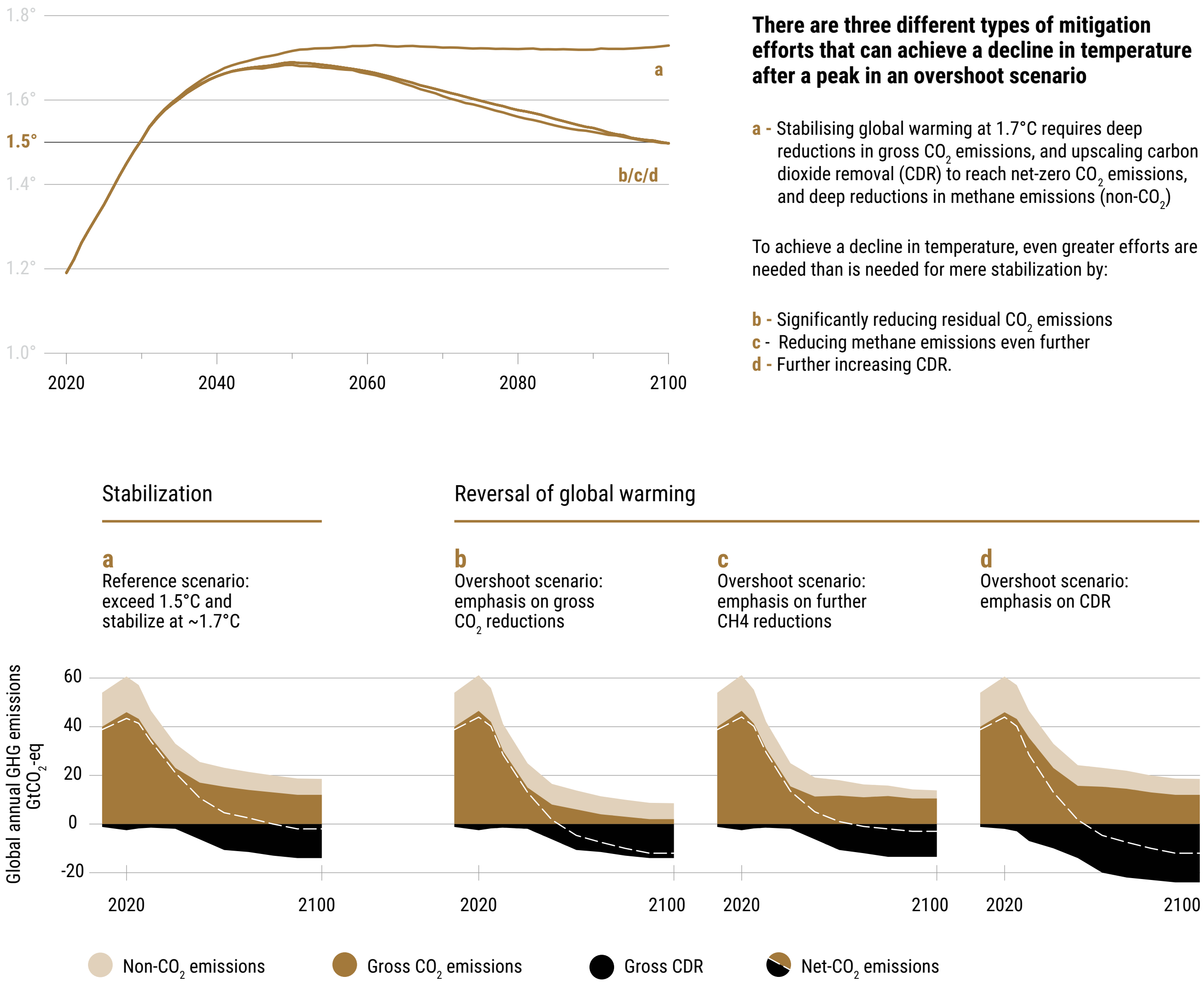
Overall, CDR cannot deliver a high temperature decline. Even optimistic CDR scaling is unlikely to deliver a temperature reversal beyond a few tenths of a degree this century, and the feasibility of this depends strongly on concurrent further reductions of residual CO_2 emissions. Even a decline of 0.2–0.3°C within a few decades would require globally coordinated policy action far beyond the net-zero emission frameworks currently dominating national and corporate climate targets (Section 3.4).

Reducing short-lived climate pollutants post-peak can be effective. Reducing emissions of short-lived climate pollutants, particularly methane, is an effective additional and complementary way to rapidly reduce global warming after its peak. Many long-term modelling studies roughly halve methane emissions by mid-century but leave on-going emissions of about 150–200 Mt methane per year unabated in 2050 (Byers *et al.* 2022; Riahi *et al.* 2022). Further reductions of those residual emissions beyond 2050 by 60–70 Mt methane could lower temperatures by about 0.1°C over the following 50–100 years (Forster *et al.* 2021; Shindell *et al.* 2024). Such reductions would be challenging as they need to tackle emissions from agriculture and waste, assuming that most methane emissions associated with fossil fuel extraction and use would have been eliminated already by 2050 given the significant low-cost abatement options (Riahi *et al.* 2022; Shindell *et al.* 2024; UNEP 2025c). Tackling unabated emissions from agriculture and waste could therefore make an important (though limited) contribution to achieve a more rapid and deeper temperature decline than is possible through net-negative CO_2 emissions alone.[13]

Figure 3.3 illustrates conceptually these three key strategies that could contribute to a decline of several tenths of a degree Celsius in temperature and a potential return to 1.5°C by the end of the 21st century: further reductions of residual CO_2 emissions, further reductions of residual emissions of non-CO_2 forcers (particularly methane but also nitrous oxide and black carbon; see also Grant *et al.* 2025b) and further upscaling of CDR. None of these strategies is likely to be sufficient alone; all must build on but go beyond reductions envisaged already in net-zero pathways and face significant feasibility constraints (Section 3.4). A combined, regionally differentiated approach is therefore essential.

13 As noted in Chapter 1, a reduction in temperature by 0.1°C requires about 220 Gt net-negative CO_2 emissions as best estimate. A sustained reduction of residual methane emissions by 60–70 Mt methane would therefore have the same effect on temperature over the following 50–100 years as an additional 220 Gt net-negative CO_2 emissions (Shindell *et al.* 2024; Collins *et al.* 2019).

Figure 3.3: Pathways returning warming to 1.5°C after overshoot, compared with stabilizing at 1.7–1.8°C. Overshoot, peak and decline pathways achieve this through deeper CO_2 cuts, enhanced methane reductions or increased CDR



Source: Reisinger *et al.* 2025

Note: This figure shows the change in global temperature (top panel) under three illustrative example pathways (bottom panel, b-d) that would bring global warming back to 1.5°C after a period of overshoot, compared to a mitigation pathway that stabilizes global warming between 1.5°C and 2°C (bottom panel, a). The stabilization pathway (a) implies mitigation efforts substantially more ambitious than current policies and NDCs (Chapter 1 and Section 3.2; UNEP 2025b): it exhibits rapid reductions in CO_2 emissions and a gradual increase in CDR to reach net-zero CO_2 emissions in about 2075; these reductions are accompanied by immediate reductions in non-CO_2 emissions, particularly methane, but limited further reductions beyond 2050. The three illustrative overshoot, peak and decline pathways (b-d) reach a similar peak warming level but then return global warming back to 1.5°C by 2100. In near-term, they follow similar emission reduction trends to the stabilization pathway (a) but differ in the additional mitigation effort beyond 2050 to reverse global warming. Pathway (b) achieves deeply net-negative CO_2 emissions by further reducing residual CO_2 emissions while maintaining CDR at the same level as the stabilization pathway; pathway (c) relies mainly on further reducing residual methane emissions while maintaining similar CO_2 emissions and removals as the stabilization pathway; pathway (d) achieves deeply net-negative CO_2 emissions by further increasing CDR while maintaining similar gross CO_2 and non-CO_2 emissions as the stabilization pathway.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3.4 Feasibility, equity and avoiding over-reliance on a future temperature decline

3.4.1 Feasibility of accelerated near-term emission reductions

The barriers are not technological or geophysical. Feasibility challenges along near-term pathways are predominantly institutional, economic and practical. The rapid pace of emissions reductions implied by 1.5°C pathways exceeds historical mitigation efforts and requires unprecedented governance capacity, policy coherence, investments in technology and innovation and scale up finance (Vinichenko *et al.* 2021; Pathak *et al.* 2022). Institutional readiness, including legal frameworks, planning authorities, permitting systems and inter-sectoral coordination, remains a key limiting factor (Bertram *et al.* 2024). For many countries and regions, development needs are a priority, therefore mitigation options that support economic development are more politically feasible.

Finance flows are not enough to support accelerated decarbonization. While mitigation options costing under USD100 per ton CO_2-eq can deliver more than half of global emissions reductions by 2030–35, global climate finance flows remain three to six times lower than what is estimated to be needed for consistent 2030 targets (IPCC 2022b). This constrains both deployment and economic feasibility. Overall, the energy system alone requires approximately USD2.4 trillion per year for deployment of renewables, grids, storage and efficiency measures (Kreibiehl *et al.* 2022).

Equity and justice are central to accelerated near-term reductions (Table 3.1). Within countries, transitions affect fossil-dependent workers and regions (Nacke *et al.* 2024), requiring just transition policies (Lecocq *et al.* 2022). Across countries, differing capacities and responsibilities shape mitigation potential, making access to finance, technology and capacity-building critical. Ignoring equity and justice risks undermining political support and increasing reliance on long-term, riskier options such as large-scale CDR. In contrast, equitable frameworks enhance legitimacy, durability and alignment with development goals (Table 3.1).

3.4.2 Further reducing residual emissions beyond mid-century

Temperature decline depends on reducing residual emissions. Given the potential limits, risks and trade-offs associated with large-scale CDR, further reductions of residual CO_2 and non-CO_2 emissions are essential to achieve a future temperature decline. Such reductions are inherently challenging as these represent emissions that will have proved harder to abate than others up to the point of reaching net-zero CO_2 emissions (Ganti *et al.* 2025). However, the concept of 'hard-to-abate' emissions potentially hides a range of factors (economic, technical, social, political) that can be addressed by different policy mechanisms (Gidden *et al.* 2026b).

Hard-to-abate emissions can be tackled. Some emission sources with high abatement costs can be reduced through sustained technology innovation and deployment. Demand reduction, material substitution, and material efficiency can lower reliance on carbon-intensive products such as steel and cement. Structural shifts are slow and institutionally and politically challenging, reinforcing the need to anticipate net-negative targets and avoid fossil fuel lock-in through near-complete phase-out.

Estimates of residual CO_2 emissions when global net-zero CO_2 is reached vary across different studies, reflecting the different assumptions of what emissions are considered hard-to-abate and the potential for progress in overcoming barriers to their abatement (Lamb 2024; Gidden *et al.* 2026b).

Agriculture and waste are the next frontier for methane emissions. Further reductions of residual methane beyond mid-century must increasingly target agriculture and waste, since fossil fuel emissions can be largely eliminated at relatively low cost by 2050 already under stringent policies (Sections 3.2 and 3.4.1; Höglund-Isaksson *et al.* 2020; Riahi *et al.* 2022). Agriculture and waste present greater technical, cultural and social challenges and have received relatively little targeted mitigation policy. Emerging livestock methane mitigation technologies show promise (FAO 2023a; FAO 2023b) but remain underrepresented in modelled mitigation pathways (Reisinger *et al.* 2021). Dietary shifts could significantly cut emissions and free land for carbon sequestration (Hayek *et al.* 2020; Humpenöder *et al.* 2024), although implementation must consider nutritional, cultural and livelihood constraints (Kaljonen *et al.* 2021; Zhao *et al.* 2024). Societal preferences can also evolve in response to changing contexts and socio-cultural narratives (Berger and Creutzig 2026). Waste-sector measures also offer mitigation with co-benefits for health and air quality (Xuan Hoy *et al.* 2023; Wang *et al.* 2024; UNEP 2025c).

Innovation can cut emissions further. Addressing residual emissions inherently requires going beyond closing efficiency gaps, using available technology or relying on co-benefits to drive adoption. Achieving emissions reductions beyond those implemented already by mid-century in ambitious mitigation pathways will increasingly depend on social and market innovation alongside further technological progress. Most of the existing literature on demand-side interventions focuses on their potential contribution to mid-century emission targets. Even deeper reductions beyond mid-century will remain challenging to just transitions within countries and to the distribution of effort among countries, but demand-side strategies can also alleviate some pressures


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associated with shifting material requirements (Gidden *et al.* 2023; Creutzig *et al.* 2024; Okedele *et al.* 2024; Pelz *et al.* 2025b; Song, Li and Lee 2025a; Table 3.1).

3.4.3 Further upscaling CDR beyond mid-century

Taking CDR beyond net-zero will be complicated. Further upscaling CDR, beyond the level required already to achieve net-zero CO_2 emissions, faces multiple, quantifiable biophysical, technological, economic and governance constraints, with the key constraints depending on the method (Tavoni *et al.* 2026). Recognizing and addressing these constraints will be critical to avoid overreliance on CDR while enabling its sustainable deployment to help achieve a long-term decline in global temperature. Conventional CDR methods that require large land resources, including afforestation, reforestation and other natural carbon sinks, are limited by competing demands for pastures, water, biodiversity protection and local livelihoods, but can also have strong synergies if implemented well (Smith *et al.* 2019b). Current model estimates suggest that sustainable afforestation and reforestation could remove about 5.6 [3.3–8.4] $GtCO_2$ per year by 2050, with limited potential for further expansion (Gidden *et al.* 2026a). Warming-induced ecosystem feedbacks, such as increased fire frequency and drought, could reduce and partly reverse carbon storage in terrestrial ecosystems (Liang *et al.* 2025; Buma *et al.* 2026; Schädel *et al.* 2026). While important for net-zero CO_2 emissions, it is unlikely to deliver net-negative CO_2 emissions at scale without deeper cuts in residual emissions.

Most return pathways rely on novel CDR technologies alongside afforestation. These include bioenergy combined with carbon capture and storage (BECCS) and DACCS, both of which ultimately store CO_2 in geological formations; biochar, a form of charcoal produced from plant biomass that is spread on or incorporated into soil and that retains carbon over centuries; enhanced rock weathering, which relies on crushing and spreading some types of rock that absorb carbon when exposed to air and durably bind it (Babiker *et al.* 2022; Edwards *et al.* 2026; Gidden *et al.* 2026a).

Current novel CDR provides little carbon storage. Although these approaches generally provide more durable carbon storage than terrestrial biomass, they currently account for less than 0.1 per cent of conventional CDR (Smith *et al.* 2026). Nonetheless, deep mitigation scenarios project rapid expansion to 0.9–6.4 $GtCO_2\ yr^{-1}$ by mid-century and 4.7–17.8 $GtCO_2$ yr-1 by 2100. Even pathways with the least overshoot require total CDR to increase from around 2.2 $GtCO_2\ yr^{-1}$ today to 2.7–4.1 $GtCO_2\ yr^{-1}$ by 2035 and 6.5–13.3 $GtCO_2\ yr^{-1}$ by 2050, illustrating the scale-up challenge. Pathways with delayed mitigation require substantially higher deployment to return to 1.5°C, reaching 8–23.6 $GtCO_2$ yr-1 by 2100 (Gidden *et al.* 2026a).

Upscaling novel CDR involves trade-offs. The feasibility of novel CDR methods depends on technology readiness, costs and resource requirements, as well as potential trade-offs with sustainable development goals (Gidden *et al.* 2026a) and climate adaptation (Chapter 4). The scale of these trade-offs varies by technology, location and governance, particularly through demands on land, water and energy. While most novel CDR methods do not inherently pose greater risks to biodiversity and food security than conventional CDR, larger deployment scales increase the likelihood of exceeding sustainability limits (Smith *et al.* 2019b; Prütz *et al.* 2026). For example, some IPCC AR6 pathways envisage an increase in land used for energy crops by several hundred million hectares by 2100. By contrast, more recent studies that explicitly incorporate sustainability constraints generally limit deployment especially of BECCS to one million hectares or less and up to a few gigatons per year (Deprez *et al.* 2024; Prütz *et al.* 2026). DACCS has fewer land constraints but is highly energy-intensive and remains costly (approximately USD100–600 tCO_2^{-1}), limiting deployment where low-carbon energy is constrained (IPCC 2022b; van der Spek *et al.* 2025).

Institutional and socio-economic barriers impose additional constraints. Modelled pathways show that effective scaling of CDR depends on governance capacity, finance and infrastructure (Smith *et al.* 2019b; Bertram *et al.* 2024), while local integration with energy and land systems, labour availability and safeguards for livelihoods are also critical (Gidden *et al.* 2026a). Differences in technical capacity and financial resources between countries, together with the uneven distribution of CDR potential, raise important equity concerns and reinforce the need for international cooperation, technology transfer and robust governance frameworks (Lee *et al.* 2021; Yang *et al.* 2023; Ganti *et al.* 2025; Pelz 2025b; Table 3.1).

CDR faces credibility risks. Measurement, reporting and verification requirements for CDR are complex and evolving, with credibility risks if standards are not met. Failure to meet these standards could undermine confidence in net-negative emissions pathways by reducing the credibility of reported removals. Public acceptance and social acceptability also influences deployment, particularly where land competition is high. These socio-institutional and economic factors underline that technical potential alone is insufficient; scaling CDR requires near-term investment in governance, capacity-building and stakeholder engagement (Edenhofer *et al.* 2025; EEA 2025).

Ocean-based CDR is uncertain and challenging. Ocean-based CDR approaches face significant uncertainties and challenges regarding their effectiveness, environmental impacts and governance, with additional limits from delayed climate responses, complex ocean–atmosphere feedbacks and challenges for monitoring, reporting and verification (Boyd *et al.* 2024; Chopin *et al.* 2024; Yamamoto, DeVries and Siegel 2024; Delval *et al.* 2025; Doney *et al.* 2025). Relevant intergovernmental instruments and decisions on this topic apply precautionary approaches to these activities, although their scopes differ. In 2010, Parties to the Convention

on Biological Diversity (CBD) adopted a decision inviting Parties to ensure no large-scale climate-related geoengineering activities that may affect biodiversity take place until there is an adequate scientific basis. Separately, in 2013, Parties to the London Protocol adopted a resolution to regulate the placement of matter for ocean fertilization and other marine geoengineering activities, although this amendment is not yet in force. Research nevertheless continues on approaches to enhance the ocean's absorption of CO_2 from the atmosphere (Babiker *et al.* 2022; Filbee-Dexter *et al.* 2024).

3.4.4 Policies and emissions targets consistent with reversing global warming

Peak warming must be minimized. The preceding sections demonstrate that the combined challenges to scaling CDR and further reducing residual emissions are likely to limit temperature decline to only a few tenths of a degree by 2100. Consistent with this, most pathways that return warming to 1.5°C by 2100 generally reach peak warming of no more than 1.8–1.9°C as best estimate (Byers *et al.* 2022; Riahi *et al.* 2022; UNEP 2025a; Gidden *et al.* 2026a). At the same time, recent analyses suggest that the minimum feasible peak warming has increased to around 1.7–1.8°C following delays in global emissions reductions (Bertram *et al.* 2024; Grant *et al.* 2025b; UNEP 2025a; Gidden *et al.* 2026a; Tavoni *et al.* 2026). Whether a return to 1.5°C remains achievable therefore depends on near-term policy choices that deliver rapid emissions reductions while creating the conditions for sustained global net-negative CO_2 and potentially even net-negative GHG emissions after mid-century.

Net-zero is a milestone towards net-negative. For many developed countries, net-zero GHG emissions should increasingly be viewed not as the endpoint of climate policy, but as a milestone towards sustained net-negative emissions. Taken together, the findings elicited above imply that mitigation policy can no longer be framed solely around achieving net-zero emissions. Instead, countries need to consider the conditions under which net-negative GHG emissions may become necessary to reverse warming. This interpretation is consistent with Article 4.1 of the Paris Agreement when viewed through the principle of common but differentiated responsibilities. Achieving global net-zero GHG emissions while allowing countries with lower historical responsibility and more limited capacity to meet basic development needs will require many advanced economies to move beyond net zero and achieve net-negative GHG emissions (Klinsky and Winkler 2018; Fyson *et al.* 2020; Li *et al.* 2025b; Robiou du Pont *et al.* 2025). The need for net-negative GHG emission targets would be sharpened further if net-negative GHG emissions are needed globally to return more rapidly from a high overshoot.[14] Keeping a return to 1.5°C within credible reach thus relies at a minimum on net-negative GHG emissions targets for most developed countries beyond 2050 (Geden and Reisinger 2025).

The next decade is crucial for effective and just CDR. Preparing for sustained net-negative emissions requires long-term structural changes in production systems, energy, land use and patterns of demand, supported by sustained investment, innovation and just transitions. Decisions made during the coming decade will shape future technology development, infrastructure and land-use choices, determining whether countries retain the capacity to move beyond net zero if required. Governments will therefore need new policy frameworks and institutions to scale CDR, manage long-term removal obligations and provide clear investment signals to the private sector (Bednar *et al.* 2021). Developing these governance arrangements well before large-scale deployment is required will be essential (EEA 2025).

Governance and international cooperation will have to evolve. A transition towards a net-negative future may amplify the potential for inequities and allocation of responsibilities internationally, which could in turn amplify barriers to collective decision-making (Andreoni, Emmerling and Tavoni 2024). The international community will need to contend with a growing demand for finance and other forms of support for adaptation and dealing with loss and damage (see Chapter 4), while at the same time upscaling financing for on-going mitigation to achieve net-negative emissions futures that ensures sustainability and climate resilience of communities and of mitigation strategies (Honegger 2023). At the same time, mitigation priorities will evolve across the different stages of overshoot: rapid emissions reductions before peak warming; achievement of at least global net-zero CO_2 emissions together with deep reductions in other GHGs at peak warming; and sustained net-negative GHG emissions during the temperature decline stage. Each stage presents distinct equity and distributional challenges that require mitigation strategies, governance arrangements and international cooperation to evolve over time rather than ending once net zero is achieved. Table 3.1 summarises these changing priorities across the stages of overshoot, peak and decline pathways.

14 Global net zero GHG emissions would result in a very gradual decline in temperature of approximately 0.3°C per century, with the rate depending on the balance between residual emissions of short-lived gases such as CH_4 and CDR (Fuglestvedt *et al.* 2018; Tarshish *et al.* 2026). If global mitigation action is limited to achieving net zero GHG emissions, a return to 1.5°C would be unlikely before the second half of the 22nd century even if peak warming is limited to about 1.8°C. Reducing the duration of overshoot therefore would require global mitigation efforts beyond net zero to reach net-negative GHG emissions globally.

Table 3.1: Feasibility of mitigation strategies across stages of overshoot, peak and decline pathways, considering intergenerational and interregional equity

Strategy: Emission reductions			
Actions	**Immediate response phase**	**Coping and containment phase**	**Long-term resilience phase**
Transition away from fossil fuels	Early action, led by countries with the greatest capacity and responsibility (CBDR-RC), preserves the remaining 1.5°C-consistent carbon budget; delay increases carbon debt and lock-in.	Net-zero CO_2 timing determines peak warming and regional carbon debt distribution; consistent with CBDR-RC, countries with greater capacity and responsibility accrue greater responsibility. Requires managing stranded assets and just transitions. Accrue greater responsibility. Requires managing stranded assets and just transitions.	Residual emissions add to carbon debt relative to 1.5°C and could exhaust feasible and sustainable levels of CDR; delays increase intergenerational burden and removal obligations.
Renewables, low-carbon energy and electrification	Rapid scale-up needed; equity requires leadership from high-capacity countries and inclusive access. Strong governance is required to avoid environmental and social trade-offs.	Institutional and capacity constraints shape deployment; equitable participation in value chains is key for inclusive transitions.	Enables sustained low-carbon systems; demand-side changes and innovation can further reduce hard-to-abate emissions but need inclusive and just transitions.
Methane reductions	Fast reductions, especially of fossil gas limit rate of warming; for agricultural and waste emissions, equity requires support for low-capacity regions and balancing agricultural livelihoods.	Deep (>80%) reductions of fossil gas emissions are feasible alongside net-zero CO_2; scale of agricultural reductions depends on support for agricultural development and innovation, inclusive just transitions and food security.	Demand-side changes and reduced livestock numbers can free land for sequestration, with outcomes depending on context and potential distribution impacts on food security and rural livelihoods. Addressing hard-to-abate emissions relies on innovation and inclusive governance.

Strategy 2: Carbon Dioxide Removal (CDR)			
Actions	**Immediate response phase**	**Coping and containment phase**	**Long-term resilience phase**
CDR (general)	Overreliance risks moral hazard and increases burden on future generations; not a substitute for rapid emission reduction	Ability to achieve net-zero or net-negative emissions depends on level of residual emissions as much as the ability to scale up CDR. A focus on global least-cost deployment of CDR would not result in equitable sharing of costs and would increase risks to sustainable development.	
Conventional CDR (afforestation, ecosystem restoration)	Can provide strong co-benefits but durability of storage depends on governance of reversals; risks to food security and biodiversity if misapplied.	Limited by durability, especially at higher warming, and land constraints, requires strong safeguards for vulnerable groups.	Climate impacts increase reversibility risks; careful governance needed to avoid inequitable outcomes.
Novel CDR (BECCS)	Costs and land demands can shift burdens to land-constrained or lower-capacity regions and increase potential for trade-offs with food security and biodiversity.	Deployment is constrained by land, biodiversity and cost; Costs and land-use competition may create distributional impacts, particularly for food systems and rural livelihoods.	High land demand and sustainability risks; burden falls disproportionately on certain regions if deployment is based on least cost and land availability rather than sustainability and equity.
Novel CDR (DACCS)	Speculative and costly at scale; high costs may concentrate development and deployment in high-income regions	Limited scalability by net-zero; obligations tied to carbon debt and responsibility; costs may reinforce global inequalities depending on access and burden-sharing.	Long-term governance and storage risks; requires equitable burden-sharing and oversight.

Note: CDR is needed in addition to rapid emission reductions, not as a substitute for a failure to reduce emissions. Finance underpins all stages but is not detailed here. This table focuses only on the CDR methods that are most prevalent in IAMs (conventional CDR, BECCS and DACCS). The literature on other CDR methods in relation to equity and feasibility is still limited, and many equity issues are common across CDR methods.

04 Adapting to overshoot realities in the context of development

Adaptation under overshoot is no longer optional — it is urgent, and it must be proactive. The challenges go beyond those addressed in conventional adaptation planning**.** Physical, ecological and social systems respond differently to peak warming and subsequent temperature decline, while risks, vulnerabilities and adaptive capacity vary across regions and over time. Because evidence specific to adaptation under overshoot remains limited, this chapter draws on the emerging scientific literature together with expert judgement to assess how adaptation can anticipate changing risks across the stages of overshoot. It considers how adaptation can reduce irreversible losses where possible, avoid maladaptation and support resilient development, recognizing that adaptation interventions and implementation happen primarily at local and regional scales, not at the global scale at which mitigation and physical trends are often summarised. Regions also warm and cool at different rates, face different hazards and hold different capacities to respond.

Adaptation is not only a complement to mitigation, but also a precondition for it. Critically, preventive adaptation investment can itself help preserve the institutional and financial capacity needed to also sustain mitigation ambition through temperature overshoot, peak and decline — making adaptation not only a complement to mitigation but a precondition for it. Addressing these challenges will, however, require urgent coordinated multilateral political will, appropriate governance responses and planning foresight, visions and imaginations across all scales.

Adaptation is context-specific and heterogeneous. It cannot be reduced to a single curve, technical aggregate and scientific figure, as this would misrepresent how adaptation is actually understood, experienced, planned, financed and lived. Accordingly, this chapter has two aims: to open the conversation about what adaptation in an overshoot world could entail, and to speak directly to those who face on-the-ground realities — practitioners, planners, communities and the most vulnerable, in local cases and across regions.

Transformational adaptation is an overarching requirement. Responding to overshoot requires a futures-oriented, systems-based approach grounded in multilateral political will and the integration of local and regional perspectives instead of global frameworks alone. Rather than relying on incremental adjustments, adaptation must address the underlying drivers of vulnerability and support transformational change across practical, institutional and political spheres (Figure 4.2). All actions must be anchored and undertaken in ethical and just ways (Feola 2015; Göpel 2016; Blythe *et al.* 2018; O'Brien 2018; Fazey *et al.* 2020; IPBES 2024a).

This chapter understands transformational adaptation as:

Adaptation that changes the fundamental attributes of a socio-ecological system in anticipation of climate change and its impacts (Möller et al. 2022) — a fundamental, system-wide reorganization that reaches beyond technology and economic structures to paradigms, goals and values (IPBES 2024b), and that addresses the underlying drivers of climate risk in inclusive ways, enhances the capacity to cope with and recover from future impacts, and guards against maladaptive outcomes now and in the future (Biesbroek et al. 2026).

Meeting this challenge means addressing the root causes of vulnerability through change that is continuous rather than one-off — evolving as overshoot itself unfolds.

4.1 Adaptation in an overshoot context

Under overshoot, adaptation is as essential as mitigation. Both are now preconditions for sustainable development, not trade-offs against it. Adaptation refers to the process of adjustment to actual or expected climate and its effects, and under overshoot it must evolve across the exceedance, peak, decline and stabilization stages. Understanding how those effects unfold across each stage is central to effective adaptation planning and implementation — because the 'thresholds' and 'tipping points' crossed under overshoot rarely arrive as discrete events. They unfold instead as complex processes and pathways — 'non-linear processes'. Crossing the 1.5°C is expected to amplify these non-linear increases in impacts, compounding their complexity and disproportionately affecting the poor and vulnerable (Chapter 2), especially in LDCs where multiple forms of capacity are already constrained.

Business-as-usual responses are inadequate. They do not correspond to the speed and scale of climate, economic and livelihood change (Schlitz, Vieten and Miller 2010; Pereira *et al.* 2020; Salomaa and Juhola 2020). As outlined in Chapter 3, strengthening adaptation and mitigation requires coordinated multilateral political will, governance, finance, equity and justice considerations, attention to loss and damage, and broader enabling conditions. Temperatures returning to 1.5°C will not automatically undo the impacts sustained at prior stages, many of which are irreversible and fall hardest on those least responsible and least resourced (Schleussner *et al.* 2024). Continuous recovery and the revision of planning baselines are therefore already needed and will become more so as temperatures shift (Kropf, Leung and Caughey 2024; Marshall, Grubert and Warix 2025).

These evolving conditions have fiscal and institutional implications (UNEP 2025a). Preventive adaptation investments are more cost-effective than reactive crisis response and help maintain fiscal and institutional capacity as climate impacts intensify. Without such investment, governments risk shifting from long-term planning to reactive crisis management and short-term recovery. Finance ministries and central economic planners therefore play a critical role in managing these trade-offs under overshoot conditions.

Building on this background, the chapter develops the following themes:

1. **Current implementation will not deliver transformational adaptation, and it must be integrated with sustainable development.** Delivering transformational adaptation requires a rethink of today's adaptation and mitigation conditions. International, regional and local agendas need to be integrated, with development and adaptation planned jointly to protect vulnerable people and the ecosystems they depend on. Many of these systems are already degraded, and basic resources—water, food, energy, healthcare—are under growing stress. Left unaddressed, these pressures compound across sectors, ecosystems, finance and governance, demanding urgent, anticipatory attention.
2. **Overshoot will generate persistent, uneven and cascading risks.** Risks will evolve differently across regions and sectors, with irreversible impacts and compounding pressures that may divert resources from wider development priorities, with the deepest displacement in regions where development needs are already most acute.
3. **Adaptation must become systems-based and forward-looking.** Where vulnerability and exposure remain high, risks can stay elevated or increase further under overshoot, following less predictable, short-term trajectories. Persistent and evolving risks require anticipatory planning across ecosystems and societies while addressing long-term impacts on biodiversity, food security, health and human development (Chapter 1; Chapter 2; Meyer *et al.* 2022). Repeated droughts during exceedance, for example, can drive lasting food insecurity, undernutrition, child stunting, impaired human development and increased child mortality (Chapter 2). These dynamics are already emerging under current levels of warming.
4. **Adaptation must remain flexible as conditions change.** Uncertainty during the exceedance, peak, decline and stabilization stages of overshoot requires adaptive infrastructure, iterative planning and flexible decision-making. Adaptation responses—such as the infrastructure cases shown in Table 4.1 below and in the National Adaptation Plans (NAPs)—must therefore be much more adaptive and flexible (Siehr, Sun and Aranda Nucamendi 2022; Haasnoot *et al.* 2024; UNEP 2025a; Theokritoff *et al.* 2026).
5. **Effective adaptation depends on inclusive and just decision-making.** Responses to overshoot must connect international and local action, draw on diverse knowledge systems and place equity, justice and local contexts at the centre of decision-making (Waddock *et al.* 2020; Living in the overshoot age 2026).
6. **Cross-level cooperation must replace siloed responses**. Existing plans can be recalibrated to navigate the stages of overshoot rather than be overtaken by them. Strengthening governance and integrating climate and development agendas will be essential to scale coordinated systems-based, transformational action across all levels.

4.2 Contexts matter: The difficulty in aligning adaptation to lived realities, both now and in the future

Adaptation on the ground still falls far short in scale, in depth and in reach. This is especially true for those most vulnerable and who have contributed least to the warming they must live with. Current adaptation approaches, most acutely in resource-constrained regions but increasingly also in wealthier contexts, do not undertake the deeper, transformational work that overshoot requires. Despite growing attention, adaptation also remains only weakly linked to policy, practice and everyday realities, even as the discourse on overshoot emerges (Reckien *et al.* 2023; Chapter 3).

Planning and implementation also remain poorly aligned. Planned adaptation does not reliably translate into action, and much of the adaptation actually undertaken—by individuals, households and civil society—goes undocumented, making the true extent of progress hard to assess (Berrang-Ford *et al.* 2021). These gaps are most acute where the most severe climate impacts are also emerging, most notably in vulnerable contexts, regions and places — such as in small island nations, parts of Latin America, Africa and Asia (Olazabal *et al.* 2019; Berrang-Ford *et al.* 2021; Magnan *et al.* 2023). Many plans also overlook gender and age dimensions, and fail to address the needs of groups with higher sensitivities and lower capacities to adapt. The health sector, for example, illustrates these challenges: adaptation efforts lag behind current needs (Cissé *et al.* 2022). Overshoot will likely widen these implementation gaps, and prolong them, affecting health systems and the upstream drivers of health such as food and water security.

Poorly designed adaptation efforts can have negative consequences. Adaptation efforts may also feed back into the system, reinforcing existing social, economic, infrastructural, technological and ecological risks and vulnerabilities across sectors, regions and timeframes (Figure 4.1) (Reisinger *et al.* 2025; Simpson *et al.* 2025). This occurs when adaptation responses are designed within existing institutional frameworks and power structures that fail to address—and may even entrench—the root causes of vulnerability. Hard coastal defences such as sea walls, for example, can protect high-value assets while shifting risks to lower-income communities and foreclosing longer-term adaptation options such as managed retreat — deepening the underlying drivers of exposure rather than easing them (Hino, Field and Mach 2017; Simpson *et al.* 2021).

Because adaptation plans are not yet fully locked in, a window of opportunity remains. Current adaptation plans can be recalibrated before, rather than after, implementation sets them in place (Table 4.1).

Implementation gaps are chronic and widening. They are especially significant across different development contexts. Adaptation must therefore be integrated further with development to protect communities and ecosystems from climatic changes that are now unavoidable — particularly in the Global South, where resources are limited and development needs remain largely unmet (Berrang-Ford *et al.* 2021; Haasnoot *et al.* 2024; Amorim-Maia and Olazabal 2025).

Given these challenges, systems-based planning for overshoot must begin now. Its horizons must extend across all stages of overshoot (Table 4.1), and its scope must recognize that sectors and systems are interconnected rather than siloed. Planning should be proactive, flexible and just — addressing complexity and focusing on the most vulnerable individuals, communities and ecosystems. This includes addressing gender disparities and intra-household inequalities, and ensuring meaningful participation of women, girls and minorities (UNEP 2023; UNEP 2024a; UN Women and UN DESA 2025).

Adaptation planners also face two interrelated challenges. There is deep uncertainty about the timing and level of peak warming, given warming now exceeding 0.25°C per decade; and multiple adaptation limits are likely to be breached. Planning must therefore account for this uncertainty while preparing for threshold crossings and monitoring potential tipping dynamics.

The impacts are intergenerational. Impacts across multiple sectors—including infrastructural challenges (Table 4.1), health, ecosystem services, livelihoods and education—are expected to leave lasting and intergenerational effects on well-being (Cissé *et al.* 2022; Mohamed *et al.* 2025) and on long-term economic performance (Stern 2007; Burke, Hsiang and Miguel 2015) particularly in least developed countries.

Current adaptation is not fit for purpose. Where adaptation efforts are emerging—across planning, decision-making, political and development arenas worldwide—they often remain limited and require rethinking and repurposing (UNEP 2025a; Chan *et al.* 2026). Even where adaptation has been implemented, it rarely results in transformation (Engbersen, Biesbroek and Termeer 2024; Juhola *et al.* 2024; UNEP 2024a; Wannewitz, Ajibade and Mach 2024; Di Giulio *et al.* 2025): adaptation is instead interpreted and applied in short-term, sector-specific and incremental ways. Such opaque transformational ambitions, unclear timelines and weak, inflexible sequencing logic all risk deepening lock-in and maladaptation rather than addressing overshoot-relevant vulnerabilities (O'Brien 2018; Pelling *et al.* 2018; Simpson *et al.* 2021). Transformational adaptation must integrate development and mitigation, addressing opportunities, constraints and limits, and their implications for equity and justice across all stages of the overshoot pathway.

Transformational adaptation, not incremental adjustment, is urgently needed. Limited coping responses that pass for adaptation, while useful, are insufficient given the scale and depth of change required — particularly for people in poor and marginal contexts and in smaller cities and communities (Milkoreit 2017;

Elmqvist *et al.* 2018; O'Brien 2021b; Petzold *et al.* 2023; Amorim-Maia and Olazabal 2025). The scale of change required leaves little room for delay.

4.3 Implementation of mitigation and adaptation pathways: Interdependencies and trade-offs

Adaptation actions to reduce and manage the risks of climate change will need to be radically rethought, reimagined and recalibrated under overshoot.

Even the most successful mitigation will not eliminate the need for adaptation. A key point often underemphasized in mitigation-focused discourse is that the 1.5°C level of warming (IPCC 2018a) is not considered safe for most nations, communities, ecosystems and sectors, and continues to pose significant risks to natural and human systems (see Chapter 1, Chapter 2). Large adaptation needs will therefore remain even if mitigation efforts eventually return global warming to 1.5°C. At current warming levels of approximately 1.4°C, adaptation demands are already considerable owing to historical emissions and demands continue to grow as States (including governments, organized business and human lifestyles) persistently fail to meet mitigation targets.

Adaptation and mitigation must be considered together. Overshoot conditions require integrated strategies that manage the synergies and trade-offs between mitigation and adaptation. Current adaptation options too often overlook mitigation linkages (Ürge-Vorsatz *et al.* 2018; Grafakos *et al.* 2020; Sharifi 2020; Sharifi 2021), neglect intersectional inequalities and justice considerations (Anguelovski *et al.* 2016; Olazabal and Ruiz De Gopegui 2021; Amorim-Maia *et al.* 2022; Garcia and Tschakert 2022; Cannon *et al.* 2023), and insufficiently address loss and damage and adaptation limits, at times mislabelling irreversible loss as transformation (Mechler *et al.* 2020). Yet many interventions can achieve simultaneous adaptation and mitigation goals — increasing appropriate urban tree canopy coverage, for example, reduces the urban heat island effect, lowering heat-related morbidity and mortality while also storing carbon (Iungman *et al.* 2023). Overshoot impacts and responses may also deepen vulnerability, especially across regions with high adaptation deficits. Weaker near-term mitigation will intensify severe, inequitably distributed and irreversible impacts across natural and human systems, reaching even the most basic of needs such as water, food and health (Riahi *et al.* 2022; IPCC 2022a; Schleussner *et al.* 2024). Delayed mitigation will also directly escalate adaptation costs and losses, particularly for more vulnerable populations, deepening existing global, inter-regional and intra-regional inequities (IPCC 2022b; Chapter 3).

Crisis response diverts valuable resources. Where proactive adaptation is inadequate, scarce resources are often diverted away from forward-looking adaptation, mitigation and development towards more reactive crisis response to escalating climate impacts (Aligishiev, Bellon and Massetti 2022; Raikes *et al.* 2019). Effective transformational adaptation should instead provide tangible, actionable solutions that increase the safety, sustainability and well-being of human and natural systems in the near term, even as mitigation benefits slowly unfold.

Insufficient adaptation may constrain mitigation ambition. Transformational adaptation is a precondition for the ambitious mitigation that overshoot demands. While it is commonly asserted that mitigation supports successful adaptation, in the sense that greater mitigation can reduce future adaptation needs, the reverse is equally true: insufficient adaptation can itself constrain mitigation ambition, particularly where reactive disaster response absorbs the fiscal and institutional capacity that both ambitious mitigation and forward-looking adaptation require (Aligishiev, Bellon and Massetti 2022; Bellon and Massetti 2022; Panwar, Wilkinson and Nur 2023).

Preventive transformational adaptation investment is highly cost-effective. In low- and middle-income countries, each dollar invested in climate-resilient infrastructure yields about four dollars in avoided losses (Hallegatte, Rentschler and Rozenberg 2019). IMF analysis confirms that ex-ante adaptation investment significantly reduces ex-post remedial costs and improves long-term macro-fiscal outcomes (Aligishiev, Bellon and Massetti 2022; Bellon and Massetti 2022). Countries with stronger adaptive capacity can therefore arguably spend less on reactive emergency response, freeing fiscal and political space for sustained investment in mitigation and longer-term adaptation — although this margin may narrow as cascading and compounding climate risks intensify. Without such investment, intensifying impacts may compel governments to prioritize disaster response over forward-looking action, creating a self-reinforcing feedback loop in which insufficient adaptation erodes the capacity for mitigation and adaptation across subsequent overshoot stages — potentially prolonging the exceedance stage (Reisinger *et al.* 2025). This dynamic is already evident in small island developing states, where the constant diversion of scarce resources toward repeated disaster recovery limits investment in long-term adaptation and development, despite these States' minimal contribution to global emissions (OECD and World Bank 2016; Panwar, Wilkinson and Nur 2023).

Limited or misguided adaptation during the exceedance stage has repercussions — across multiple sectors and for the most vulnerable countries, communities and people (Simpson *et al.* 2021; IPCC 2022b Figure 16.1; Figure 2.1). Conversely, effective and proactive adaptation and mitigation before and during the overshoot period could reduce vulnerability and so lower overall risk.

Transformational adaptation must recognize that successful outcomes will evolve as temperatures rise then fall — and that for many communities, the reversal of global mean temperature will not automatically reverse the harms sustained during the overshoot period.

Stage-specific adaptation under overshoot

Abrupt regime shifts and possible irreversible change can outpace or undermine current adaptation approaches. Most existing adaptation frameworks—whether sectoral, ecosystem-based or infrastructure-focused—were designed around assumptions of gradual, continuous and one-directional climate change. However, the consequences remain uncertain for climate, ecosystems and infrastructure and are further compounded because future populations will differ in their governance, socioeconomic conditions and demographic composition, with direct implications for human systems' exposure and vulnerability to impacts (Chapters 2 and 3). The need for cross-sectoral, systemic and flexible approaches to adaptation is well established (IPCC 2022b; SR1.5). Exceedance of 1.5°C does not create this need, but it fundamentally complicates it. As outlined in section 4.1, warming that rises, plateaus and eventually falls rather than continuing in one direction fundamentally reshapes adaptation requirements. Strategies must function under worsening conditions, withstand a potentially prolonged peak and remain relevant as conditions eventually change in multiple directions alongside broader development dynamics.

Adaptation must be flexible and evolve. Adaptation investments rigidly calibrated to any single stage of the overshoot exceedance, peak and decline pathway risk being poorly matched to the conditions that follow (Pfleiderer, Schleussner and Sillmann 2024; Reisinger *et al.* 2025). Agricultural systems reconfigured for higher temperatures may prove misaligned if conditions shift. Infrastructure designed for specific hydrological regimes, for example, may face markedly different water availability as glaciers undergo irreversible loss (Schuster *et al.* 2025). Coastal defences, while unlikely to become redundant given continued sea-level rise, may, for example, entrench rigid protection strategies that foreclose more flexible or transformational responses, such as managed retreat or planned relocation of communities and infrastructure away from increasingly vulnerable coastlines. The challenge is therefore not simply adapting to a changing climate, but navigating a trajectory characterized by uncertainty, uneven legacies, evolving risks and hence evolving adaptation needs over time (Figure 4.1) (Haasnoot *et al.* 2020).

For example:

- *High-latitude and polar regions* warm at two to four times the global mean rate and may cool more slowly as ice-albedo and permafrost feedbacks continue to operate (Lee *et al.* 2021; Rantanen *et al.* 2022; Pfleiderer, Schleussner and Sillmann 2024);
- *Small island nations and territories* face disproportionate and ongoing exposure to sea-level rise already locked in by historical emissions and ocean thermal inertia, which will continue well beyond the temperature peak (In Focus: Sea-level rise and the SIDS adaptation challenge) (Fox-Kemper *et al.* 2021; Nauels *et al.* 2025); and
- *Arid and semi-arid regions* may experience prolonged hydrological disruption that persists after the thermal peak (Douville *et al.* 2021; Seneviratne *et al.* 2021).

Across the water sector more broadly, adaptation effectiveness decreases past 1.5°C (Caretta *et al.* 2022; Lissner *et al.* 2024; IPCC 2022c).

The current piecemeal, silo-based approach is insufficient for the coming challenges. In practice, multiple phases will coexist across and within regions, and impacts are expected to accumulate dynamically across the overshoot, peak and decline pathway, with each stage inheriting the legacies of those that preceded it.

Establishing the adaptation foundations under current conditions

Adaptation under current conditions forms the foundation for all later stages. The window to establish adaptive governance, robust monitoring processes, modular infrastructure and flexible investment frameworks is now. The unpredictable character of overshoot, peak and decline pathways changes the investment logic: systems must be designed not for a single projected future, but for conditions that will first worsen, potentially stabilize and then change in uncertain ways. Because any reversal of warming may occur only decades later, it has limited relevance for near-term adaptation planning and immediate transformational adaptation needs: decisions taken now must respond to the stage at hand rather than to an eventual and distant return to lower temperatures (Schleussner *et al.* 2024). This requires long-term planning horizons embedded in infrastructure decision-making (Bonjean Stanton and Roelich 2021) and in governance frameworks that outlast political cycles and integrate decision-trigger mechanisms such as adaptation pathway approaches (Haasnoot *et al.* 2013).

Making the right infrastructure decisions is crucial. Infrastructure decisions made during this stage (Table 4.1) have operational lifetimes of decades to centuries and will lock in either vulnerability or resilience through the entire overshoot trajectory and beyond. This applies to coastal protection, water systems, energy networks, urban form and transport. Across small island nations and territories, for example, this window is particularly narrow: freshwater lenses are highly sensitive to sea-level rise and drought, and once salinized may not be able to recover (Terry and Chui 2012; Storlazzi *et al.* 2018). This creates an urgent need for early, modular investment in water security.

The duration and severity of each stage will depend on how quickly emissions are reduced, how the climate system itself responds and on development choices.

During exceedance: managing progressive intensification

The exceedance stage is expected to bring intensification of climate stress, although not uniformly. In some regions, tipping point dynamics may introduce abrupt shifts alongside gradual change (Lenton *et al. 2025*). Anticipatory humanitarian action, pre-positioned emergency supply chains, heat action plans, early warning systems, scalable social protection and other adaptation strategies must already be operational during this stage, not established in response to it (Coughlan de Perez *et al.* 2015). Without these measures, vulnerabilities already emerging under current warming conditions are likely to intensify further.

Climate risks will compound across sectors. Cascading and compounding events are also expected to become more frequent, straining systems across sectors simultaneously (Simpson *et al.* 2021; O'Neill *et al.* 2022). The exceedance stage is also the first serious test of the adaptive capacity built under current conditions, and when monitoring systems must actively track the approach of critical thresholds that may be crossed at or near peak warming (Reisinger *et al.* 2025).

At peak warming: managing limits, cascading events and systems survival

At peak warming, the dynamics building during exceedance converge and intensify. This means adaptation limits being reached, cascading and compounding events, and the depletion of institutional capacity (Armstrong McKay *et al.* 2022; O'Neill *et al.* 2022). Governance frameworks and financing mechanisms must be operational for the managed relocation of populations from areas crossing habitability thresholds, whether due to lethal humid-heat conditions, coastal inundation or the collapse of subsistence systems (Hino, Field and Mach 2017; NASA Sea Level Change Team 2023; NASA Sea Level Change Team 2024).

Monitoring systems during this stage must function as active decision-triggers. This systems should be supported by pre-agreed response protocols activated when indicators—such as ice sheet mass balance, ecosystem regime shifts, freshwater lens salinity or humid-heat conditions approaching physiological survival limits—signal that critical boundaries are being approached or crossed (Raymond, Matthews and Horton 2020b; Lenton *et al.* 2025).

The peak stage also carries acute fiscal and political risks. Governments, humanitarian agencies, non-governmental organizations and local community 'first responders' will face the highest simultaneous demand for disaster response, social protection, emergency health services and infrastructure repair — while budgets will likely become severely constrained by accumulating climate costs (Catalano, Forni and Pezzolla 2020) and political attention is divided across competing demands (OECD 2024). Without robust adaptive governance and pre-committed financing mechanisms, both mitigation and long-term adaptation investment risk being deprioritized in favour of immediate crisis response (Bellon and Massetti 2022), reinforcing the same feedback loop set out above, in which insufficient forward-looking adaptation prolongs overshoot (In Focus: Governance, legitimacy and equity).

Temperature reversal, stabilization and navigating permanent change

Declining temperatures will create new adaptation challenges and opportunities. By the time temperatures return to 1.5°C or below, human systems will already have been reshaped, while natural systems may have reorganized or remain in transition. Transformational adaptation under overshoot exceedance, peak and decline pathways must therefore embed flexibility, learning and continual revision of planning baselines across all stages. Temperature decline will not simply reverse the warming trajectory. Regional climate responses will remain uneven and non-linear (Pfleiderer, Schleussner and Sillmann 2024; Schleussner *et al.* 2024). Some areas will experience prolonged thermal inertia while others face continued sea-level rise and ocean acidification well after the global mean temperature peak (Fox-Kemper *et al.* 2021). Ecosystems may have reorganized irreversibly, infrastructure may be over-specified or poorly suited to a changing return path and many communities may have already relocated or transformed their livelihoods in response to peak-stage conditions.

The reversal and stabilization stages may themselves become a second source of stress. This stress would be layered onto the accumulated impacts of the exceedance and the peak warming stages. Legacy impacts that do not reverse with temperature—continued sea-level rise, species extinctions, ecosystem regime shifts, permafrost carbon feedbacks and the displacement of communities—mean the post-peak stage inherits the full burden of what preceded it (Turetsky *et al.* 2020; Schleussner *et al.* 2024).

Societies will face the challenge of readjustment. Agricultural systems reconfigured for higher temperatures may need to be readapted, infrastructure designed for hydrological regimes at a peak stage may become mismatched, and communities weakened by decades of escalating crises will face a second transition with diminished institutional and fiscal capacity. These pressures will unfold alongside broader demographic and socioeconomic shifts, including changing population size, age structures and human capital (In Focus: Governance, legitimacy and equity; Lutz 2024).

Re-baselining must be understood as a continuous process, not a discrete event. Central to this are governance questions, spanning formal and informal levels, that current adaptation frameworks and actions do not adequately address: Who decides what gets rebuilt and what gets abandoned? What mechanisms exist for managed retreat from permanently changed landscapes, and who bears the costs? How are livelihoods reconfigured for communities whose economic base has been permanently altered? How are loss and damage addressed for irreversible impacts—including species extinction, cultural losses and permanent displacement—that occurred during the overshoot period? These are questions of justice, power and political legitimacy that require inclusive governance arrangements far beyond what most current adaptation plans envision — including where adaptation ends and Loss and Damage begins. Further, regional heterogeneity in the pace and character of post-peak change reinforces the need for context-specific, locally governed planning rather than any uniform post-peak prescription.

Figure 4.1: Conceptual trajectories of the four key drivers of climate-related risk—hazards, exposure, vulnerability and risks from mitigation responses—along an overshoot, peak and decline pathway

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 to 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 centre 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).

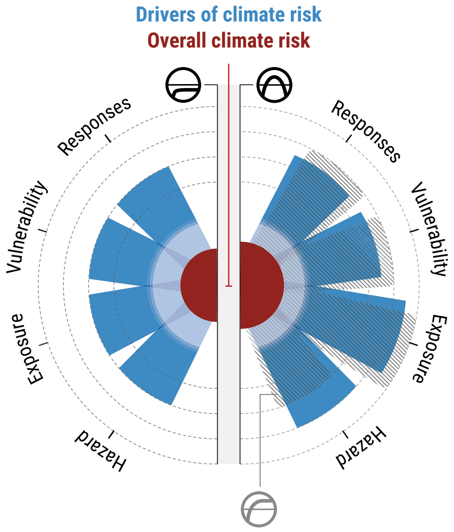
Overshoot world

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

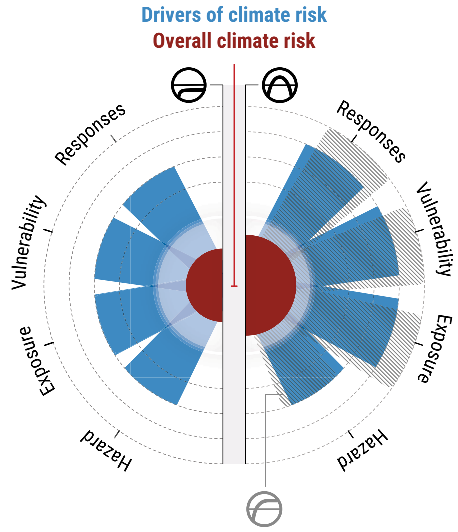
Exceedance world

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

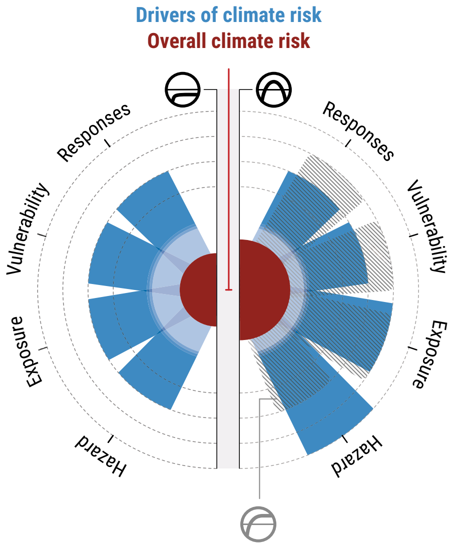
Example a: Malnutrition and rural poverty from extreme drought (increased climate risk in overshoot with partial reversal of hazard and elevated vulnerability)



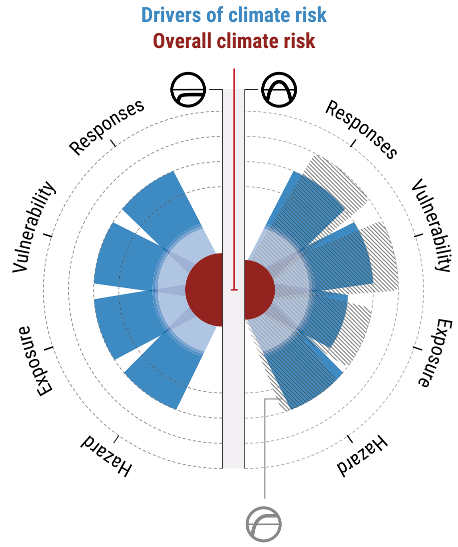
Example b: Coastal erosion and inundation from sea level rise (escalating climate risk in overshoot due to increasingly severe hazard, exposure and vulnerability)



Example c: Ecosystem disturbances intensified by land demand for mitigation (increased climate risk in overshoot due to mitigation compounding vulnerability)



Example d: Mortality from heat waves with effective adaptation measures (reduced climate risk in overshoot due to reversed hazard alongisde effective adaptation)



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.

(Source: Reisinger *et al.* 2025)

Ecosystem-based adaptation under overshoot, peak and decline

The stage logic above plays out differently across sectors. Two examples—ecosystem-based adaptation and infrastructure—show how stage-specific risks translate into concrete planning and design challenges.

Ecosystem-based adaptation is particularly vulnerable to overshoot dynamics. Above 1.5°C some of these measures will reach limits (Chapter 2; IPCC 2022b). For example, the exceedance, peak and decline stages are expected to intensify extreme wildfire activity, drought stress and biome-level vegetation changes, outpacing many existing ecological protections and rendering current approaches insufficient—or even ineffective—without substantial redesign (IPCC 2018a; Anderson *et al.* 2020; Hayman *et al.* 2024). Several ecosystem and biodiversity impacts are already emerging (IPBES 2019; Chapter 2).

Protected areas become critical climate infrastructure. Managing these dynamics requires strengthening and extending the protected area networks that underpin many current ecosystem-based adaptation approaches, and recognizing that these networks serve as critical climate infrastructure (In Focus: Species redistribution and the unmaking of protection). This includes integrating anticipatory, proactive conservation approaches that respond to species redistribution as temperatures rise, peak and eventually decline (D'Aloia *et al.* 2019), and enhancing ecological connectivity across land and sea.

Adaptation will also require smart spatial planning. This planning should anticipate shifting climatic envelopes—and the associated species redistribution, novel community formation and likely biodiversity loss that follow—rather than assuming stationarity or reacting to losses after they occur (Brito-Morales *et al.* 2022; Buenafe *et al.* 2025). Such approaches depend on governance frameworks that explicitly recognize interdependencies among biodiversity, climate and human systems (IPBES 2024a).

Some current adaptation solutions risk becoming maladaptive if not carefully designed. CDR is a case in point: afforestation, BECCS and similar approaches, when implemented in water-limited or naturally open ecosystems, can intensify water stress, displace native biodiversity and alter surface albedo. Large-scale CDR, central to many pathways (Chapter 3), carries trade-offs that remain underexplored and may compete with adaptation needs (Buck *et al.* 2020). For example, afforestation will strain water and land resources (Ricciardi *et al.* 2022; Rosa *et al.* 2021; Deprez *et al.* 2024) and although it could reduce local temperatures (Smith *et al.* 2019b), at the scale required for net-negative emissions, it is likely to compete with agricultural land and threaten food security (Deprez *et al.* 2024). Large-scale BECCS raises parallel concerns, intensifying land-use competition, straining post-peak ecosystem recovery, undermining food security and limiting adaptive capacity (Meyer *et al.* 2022; Meyer and Trisos 2023; Dodds, Vaughan and Hayman 2024). Poorly designed nature-based solutions may likewise harm biodiversity and ecosystem functioning, undermining ecosystem-based adaptation and risking the transgression of adaptation limits (Prütz *et al.* 2026). These risks will likely become more pronounced under high temperature overshoot due to scaling pressures.

Evidence of these risks is already emerging. An analysis of global forest restoration commitments found that, of the 292 million hectares pledged by 43 tropical and sub-tropical countries under the Bonn Challenge and national schemes, 45 per cent are destined for monoculture plantations of fast-growing commercial species such as acacia and eucalyptus, while only 34 per cent are committed to natural forest restoration (Lewis *et al.* 2019). The implications for adaptation and mitigation are substantial: natural forest restoration across the entire pledged area could sequester an estimated 42 billion tons of carbon by 2100, but under these current commitments—where monoculture plantations dominate—this falls to just 16 billion tons, and to a mere 1 billion if planted entirely as commercial monocultures (Lewis *et al.* 2019). Natural forests also store roughly 40 times more carbon than plantations harvested on short rotations, yet in some countries monocultures account for over 80 per cent—and in one case 99 per cent—of promised restoration. Beyond the carbon deficit, such plantations can intensify water stress in already water-limited tropical regions (Rosa *et al.* 2021); displace native grasslands, savannahs and forests that support biodiversity and ecosystem function (Veldman *et al.* 2015); and ultimately undermine the very ecosystems on which ecosystem-based adaptation depends — compounding, rather than alleviating, the adaptation challenges intensified by temperature overshoot, peak and decline.

Even well-designed ecosystem-based adaptation faces timing constraints. Many measures require long lead times to mature, while exposure rises rapidly as warming crosses 1.5°C and persists well beyond the peak (Meyer *et al.* 2022). Delayed implementation therefore reduces effectiveness and feasibility, making early action essential to preserve the natural buffers that underpin multi-sector resilience.

Infrastructural dimensions

Infrastructure (formal and informal) faces additional adaptation issues. Infrastructure and buildings have long lifespans, locking-in emissions and resilience outcomes for decades or centuries to come (Frantzeskaki and Loorbach 2010). This means that even decisions taken today will likely be tested across all stages of overshoot. It is therefore vital to recognize that infrastructure decisions could lock in long-term maladaptation or carry high opportunity costs for many years after temperature stabilization. As such, adaptation strategies for infrastructure will need to evolve over time — from anticipatory planning now and during exceedance, to containment and crisis management during peak warming, and eventually toward long-term stewardship under permanently altered climatic and environmental conditions.


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Table 4.1: Summary of the risks, overarching adaptation philosophy and key adaptation principles for infrastructure and the built environment for stages of overshoot of 1.5°C

Overarching adaptation goal at Exceedance stage:Buy time by absorbing shocks and constraining risks without foreclosing future infrastructure adaptation pathways	
Changing risks to infrastructure and the built environment	**Adaptation principles for infrastructure operators**
Conditions exceed historical norms with increased frequency and with slower recovery increasing damage and disruption to settlements and key infrastructure services such as energy, transport, water, waste management, communications and healthcare. Infrastructure design standards increasingly exceeded.	*Anticipatory adaptation over reactive response* • Shift from historical risk planning to forward-looking stress testing. Adapt before failures become too frequent. *Design margin extension, not optimisation* • Prioritise robustness, safety buffers and tolerance. Accept inefficiency in exchange for reliability and survivability. *No-regret and reversible measures first* • Prioritise actions that reduce exposure and vulnerability, and preserve future flexibility. Avoid capital-intensive fixes that assume a stable climate. *Early identification of irreversible thresholds* • Explicitly map exposure and identify weather (flood, temperature etc.) threshold that provide triggers for adaptation investment. *Keep options open for retreat and reconfiguration* • Begin discussions about potential abandonment *before* crisis forces it.
Overarching adaptation goal at Peak and plateau stage: Normalise infrastructure operation beyond continued exceedance of design limits to prevent cascading failures, sustain existing assets and avoid locking in irreversible future losses	
Changing risks to infrastructure and the built environment	**Adaptation principles for infrastructure operators**
Extreme conditions are persistent and/or overlapping reducing the window for repair; leading to partial, fragile or absent recovery. Design standards are systematically invalid, with infrastructure frequently operating beyond design envelope. High likelihood of rapid crosssector cascading failures (energy–water–Information and Communication Technology [ICT]–health) from compound extreme weather events.	*Safety over performance* Prevent cascading failure even if service quality declines. Prioritise protection of life, health and environmental integrity. *Active triage of infrastructure assets* Avoid implicit abandonment via neglect and explicitly decide what must be protected, what can degrade and what must be lost. *Operate for endurance, not recovery* Design operations to function under chronic loading and stress. Constraining services if necessary, but ensuring a minimum viable service for all. *Minimise additional irreversible damage* Avoid actions that increase contamination; degrade ecosystem function; lock-in maladaptive changes such as stranded assets, sunk costs, and longterm liabilities that constrain future investment. *Reduce system coupling* Decouple energy, water, ICT and transport systems where possible. Contain failures locally instead of allowing cascades. *Legitimate emergency governance with safeguards* Unequal impacts can erode public trust. Transparency and documentation provide accountability to communities for difficult prioritisation decisions to be taken rapidly.

Overarching adaptation goal at Decline stage (postpeak): Transition from reactive endurance operations to long-term stewardship of infrastructure systems that function safely within the permanently altered climate envelope	
Changing risks to infrastructure and the built environment	**Adaptation principles for infrastructure operators**
Impacts remain elevated, but stabilising. Infrastructure systems operating on a new baseline. Some risks are irreversible, including: • Reduced availability of key resources, such as water, food and energy, that are mediated and enabled by infrastructure services. This could have severe consequences for health. • Loss of land—and associated infrastructure and settlements—due to erosion, inundation, exposure or becoming uninhabitable. • Infrastructure assets degraded beyond repair by repeated exceedance of design standards and extreme weather. Ecosystems that support infrastructure through cooling (e.g. data centres and power stations), buffering (e.g. retaining flood water), filtration (e.g. trapping sediments or breaking down pollutants) or protection (e.g. dissipating wave energy or stabilising slopes), cross tipping points.	*Rebaseline, do not restore* Pre-overshoot conditions are no longer valid references, so design standards, safety margins and landuse must all be updated. *Govern irreversible loss explicitly* Manage retreat, abandonment, and compensation deliberately, accepting that some assets, ecosystems and service levels are gone. *Replace emergency fixes with durable solutions* Rapid rebuilds or temporary fixes that become de-facto permanent lock vulnerabilities into the next generation of assets. Avoid accidental and maladaptive permanence by auditing all plateau decisions and stopgaps. Emergency fixes must be reversed, made permanent, relocated, replaced or upgraded. *Adjust service provision to reflect environmental limits* Protect remaining buffering, cooling and filtration capacity of ecosystems. Update infrastructure design standards to reflect new ecological limits. *Institutionalise adaptation and learning* Shift from reactive responses during exceedance and plateau stages, to a culture of long-term stewardship whilst preserving institutional memory of overshoot consequences. *Equitable governance of irreversible post-overshoot losses* Longterm inequities and abandoned areas challenge legitimacy if not explicitly addressed. Distribute burdens and benefits of post-overshoot infrastructure recovery fairly across society and generations.

The following examples show how infrastructure challenges can also present development opportunities at the local and possibly regional scales:

Lock-in climate-positive infrastructure decisions

Infrastructure and buildings have long lifespans, locking-in emissions and resilience outcomes for decades or centuries to come (Frantzeskaki and Loorbach 2010). Under an overshoot pathway, adaptation choices should maximise synergies and minimize negative trade-offs between mitigation and adaptation (Ürge-Vorsatz *et al.* 2018). Early investments can reduce current service disruptions and may also reduce higher maintenance costs in the longer term. Improvements made to address peak conditions may therefore reduce risks associated with the exceedance stage while also enhancing pressing current infrastructural and sustainable structural development. However, even if temperatures return to 1.5°C, some sunk costs may be unrecoverable from investments to make infrastructure sufficiently robust to remain resilient against the highest impacts (Meyer and Schwarze 2019).

Irreversible or hard-to-reverse impacts

Exceedance may push long-lived assets such as transport networks, coastal defences and energy systems beyond local adaptation limits (Theokritoff *et al.* 2026). Planners must therefore design now for long-term irreversible changes, even if global warming levels later decline. A flexible pathway approach can help manage uncertainty in the timing and magnitude of exceedance (Haasnoot *et al.* 2021).

Greater strain on water, hydrological and energy systems

Hydrological systems are especially vulnerable because the impacts of overshoot, peak and decline can persist for decades (Marshall, Grubert and Warix 2025). Risks to glacial melt contributions, groundwater dynamics, vegetation-driven hydrological change and water-intensive energy systems may create major supply-demand mismatches (Clason *et al.* 2022; Drenkhan *et al.* 2023). Reduced water availability would also affect the reliability of hydropower, irrigation and other water-dependent services. Even a return below 1.5°C would not reverse centuries-long impacts on glacier mass and runoff (Schuster *et al.* 2025).

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Accelerated ecosystem degradation

Natural ecosystems that historically protected or supported infrastructure will degrade under overshoot. Marine heatwaves, ecosystem decline and weakening carbon sinks—all accelerated under warming—undermine coastal protection, drainage systems and flood buffers (Seddon *et al.* 2021). The loss of ecological stability increases the burden on engineered solutions, often at higher costs (Neumann *et al.* 2021). The exposure duration on natural ecosystems may outlast overshoot itself, with some ecological communities never returning to pre-overshoot exposure levels. Large-scale land-based CO_2 removal may further threaten biodiversity (Meyer *et al.* 2022).

Financial and insurance system stress

Exceedance of 1.5°C increases fiscal risks and destabilizes financial mechanisms that underpin infrastructure (Box 2: Debt, insurance and fiscal capacity) As climate risks intensify, the insurability of infrastructure assets could decline. Combined with rising sovereign debt, this limits investments in resilience upgrades or repurposing of infrastructure across all overshoot stages (including the decline stage), thereby threatening the economic viability of infrastructure corridors, housing and utilities (Zenios 2022).

Supply chain and material disruptions

Climate impacts and geopolitical instability are likely to disrupt supply chains for construction materials and energy (Ghadge, Wurtmann and Seuring 2020). Increasing supplier redundancy across regions and climate zones can provide greater resilience to disruptive events (OECD 2024). Some resources used for infrastructure construction to ensure service resilience during overshoot may also prove difficult or impossible to recover afterwards.

Legal, governance and social challenges

Infrastructure is typically a regulated sector. Overshoot exceedance, peak and decline pathways therefore raise legal questions, loss-and-damage responsibilities and equity challenges (Gunda *et al.* 2025). Rapid adaptation demands may exceed institutional capacity, necessitating new mechanisms for infrastructure governance that consider legal dimensions, long-term planning and repurposing of systems during the decline stage (Chester, Miller and Muñoz-Erickson 2020).

Measuring change

Key questions must be continuously reassessed to detect maladaptation risks early: who is involved, what is prioritized, and where and how actions occur (Eriksen *et al.* 2021; Olazabal and Castán Broto 2022; Reckien *et al.* 2023). In practice, current Monitoring, Evaluation and Learning frameworks struggle to capture maladaptation or support adaptive learning (Goodwin and Olazabal 2025) — limitations that will become more consequential and serious under temperature overshoot conditions. Such frameworks must be redesigned to detect maladaptation and respond to these risks, supported by appropriate institutions, finance and expertise (Goodwin and Olazabal 2025; Higuera Roa, Walz and Nehren 2025).

Monitoring gaps also extend upstream of adaptation itself. Effective adaptation depends on future climate projections, yet these remain unavailable or unreliable for many of the most vulnerable and least-resourced nations. A central cause is the sparseness of the historical precipitation and temperature observations that modelling communities require to generate them: across all of Africa, for example, there are only around 200 long-term temperature and 800 monthly rainfall stations, against roughly 5,000 rainfall stations in the United States alone (Williams *et al.* 2024). For small island developing states, the same scarcity constrains projection at the resolution their microclimates and high internal diversity demand (Mycoo *et al.* 2022). In many countries the constraint is not that these records do not exist, but that national data-sharing policies, access costs and limited dissemination keep them from the modelling communities that could use them (Dinku 2019; Lamptey *et al.* 2024). Where observations are genuinely absent, the urgent establishment of systematic data collection is a precondition for the baselines from which any future projections, and therefore any credible adaptation plan, can be built (Lamptey *et al.* 2024).

4.4 Systemic and transformational adaptation: What considerations are needed for overshoot risk reduction

Incorporating more radical ways of engaging with structures, views and practices, will help to foster and create the forward-looking flexibility needed to manage changing climatic and socioeconomic conditions.

Despite the high stakes and the implications for near-term planning (Fletcher *et al.* 2024; Jones *et al.* 2024; Schleussner *et al.* 2024), there remains a paucity of literature examining how transformational approaches can be considered and implemented, most notably in changed ways of engaging with structures, views and practices (Figure 4.2) (Chapters 2 and 3) (O'Brien 2018; O'Brien 2021b; Vogel and O'Brien 2021; IPBES 2024b).

Urgent action is required, as impacts are already here. At just 1.4°C, warm-water coral reefs are crossing their thermal tipping point, and parts of the polar ice sheets may already have been destabilized (Lenton *et al.* 2025). These findings align with earlier assessments showing that current warming already falls within the lower range of uncertainty for several tipping elements (Armstrong McKay *et al.* 2022). Risks are expected to increase further as warming continues toward an uncertain peak. As shown in other chapters of this report (Chapters 2 and 3) and above, many of the non-linear dynamics, irreversible impacts and planning uncertainties associated with temperature overshoot peak and decline are already emerging under current warming and will accelerate as the world enters the exceedance stage. These dynamics are illustrated for ecosystems and infrastructure in Table 4.1.

Equity considerations are a core element of urgent paradigm shift (Figure 4.2)**.** This shift should begin immediately and unfold through sustained, iterative and participatory processes rather than only rapid, top-down imposition. Attention to distributional dimensions must be central to adaptation and mitigation planning for overshoot pathways, and not treated as equity considerations to be addressed after the primary technical response (Raymond *et al.* 2020a; Birkmann *et al.* 2022; Mycoo *et al.* 2022; O'Neill *et al.* 2022).

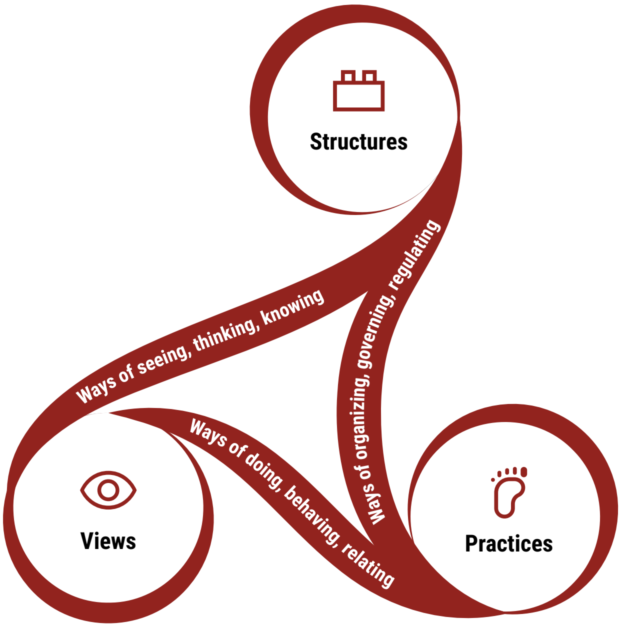
Adaptation is complicated by regional differences in warming and cooling rates — including during the decline stage (Chapters 2 and 3). Navigating these pathways, as shown in Table 4.1 and Figure 4.2, requires a continuing and deepening shift away from current, sector specific interventions toward cross-sectoral, more systemic approaches and integrated governance arrangements (In Focus: Governance, legitimacy and equity). Systems-based approaches, linking climate, nature, infrastructure and human well-being, are also critical to more transformational approaches to adaptation (Dawson *et al.* 2018; Dodds, Vaughan and Hayman 2024). 'Nexus governance' or explicitly recognizing the interdependencies across sectors and systems, can also support flexible and integrated decision-making that maximises synergies while minimizing trade-offs (IPBES 2024a).

Many planned and established adaptation measures are likely to become infeasible and ineffective as warming intensifies, increasing risks of adaptation limits, tipping dynamics and maladaptation — reinforcing existing, or introduction of new, vulnerabilities and inequities.

One possible way forward is activating a transformational adaptation approach that extends beyond formal governance. Such an approach will require a broader "whole-of-society" perspective (UN 2023; UNDP, Kjellén and Wong 2023; Ruggiero, Piotrowicz and John 2024). O'Brien and Sygna (2013) and O'Brien (2016, 2018, 2021a, 2021b) provide the 'three spheres of transformation'. More recently examples of what transformational ways may include are — the structures (ways of organizing, governing and regulating); views (ways of seeing, thinking and knowing); and practices (ways of doing, behaving and relating) (IPBES 2024b, IPBES 2024c) (Figure 4.2).

These interacting areas of action influence possible adaptation pathways; and should be accounted for in planning and policy processes.

Figure 4.2: Transformational ways of entangled organizing, seeing and doing (all requiring appropriate actions)



Source: IPBES 2024b; IPBES 2024c

Adaptation must span all of society. Adaptation efforts focused only on one area of action —for example, building more resilient infrastructure, deploying better early warning systems, establishing emergency supply chains— will be insufficient if other areas (e.g. ways of governing, regulating and organizing and ways of doing, behaving and relating) remain unchanged. The governance failures, exclusionary decision-making and short-term political horizons that characterize much current adaptation practice will reproduce themselves across each stage of overshoot, peak and decline pathways unless they are explicitly restructured around shared values, perceptions of risk and obligations to future generations (Eriksen, Nightingale and Eakin 2015; Mikulewicz 2020; IPBES 2024a; IPBES 2024b; UNEP 2024a).

New financial and governance frameworks are also likely needed to enable transformation. These may include blended finance and greater private sector engagement alongside public funding, while avoiding cost burdens on developing countries and vulnerable households (UNCTAD 2025; UNEP 2025e; Table 4.1). Finance and governance are, however, not enough. Visionary planning grounded in shared goals for a just and safe future is essential (Figure 4.2) (Colloff *et al.* 2021; Hölscher *et al.* 2022; IPBES 2024b), supported by proactive adaptation and mitigation frameworks that embed ambitious action and iteration as standard practice (Sparkes *et al.* 2023).

Neither frameworks nor vision will move without political will. Political will is a critical determinant of how feasible adaptation, across all levels, can become under overshoot, peak and decline pathways, and is discussed in depth in In Focus: Governance, legitimacy and equity. The persistent gap between adaptation commitments and implementation (UNEP 2024a), and the systematic underestimation of political barriers to adaptation in both research and practice (Javeline 2014; Eriksen, Nightingale and Eakin 2015; Eriksen *et al.* 2021), will be amplified under temperature overshoot, peak and decline conditions. The demands on political commitment will also likely intensify across every stage while the conditions for sustaining it deteriorate — with the greatest consequences for those most exposed to impacts. Increasing pressure on environmental resources and shifting lived experiences may also heighten geopolitical tensions, increase conflict risks and undermine peacebuilding efforts.

A move beyond traditional modelling and scenario thinking can open up new possibilities. Knowledge systems have to evolve to encompass ethical and just negotiations, and the inclusion of thinking drawn from creatives, artists, social media and other communicators (Wyborn *et al.* 2020; Olazabal *et al.* 2024; Brajdić Vuković and Puđak 2026). This can help to answer the question of what an overshoot world could look like.

Inclusive imagining—drawing on cognitive, social processes across disciplines, including the humanities—is an emerging adaptation frontier. It will require new research and action, including 'inclusive' public information and decision-making processes, policy and advocacy alongside careful attention to the agency required at the personal and individual, and practical and wider regional and global political levels (Braun 2015; O'Brien 2018; Moore and Milkoreit 2020; O'Brien 2021a; O'Brien 2021b; Kythreotis *et al.* 2024).

Many approaches are being designed and tested for current adaptation practices (Marín-Puig, Ariza and Casellas 2022). However, few explicitly address practical guidance for transformational adaptation for the future. Decision trees and adaptive pathways approaches (Haasnoot *et al.* 2013; Denton *et al.* 2014 [AR5 WG2 Chapter 20]; Roy *et al.* 2018 [SR1.5 Chapter 5]) offer one operational framework for structuring choices across the overshoot trajectory, linking specific decision points to monitored indicators and pre-specified trigger conditions. Other work has also begun to measure the contribution of nature-based solutions beyond climate adaptation in cities (Goodwin *et al.* 2024). But far more is needed to support transformational adaptation under overshoot as discussed below.

Such sequencing is less tractable, however, in sectors where development pathways themselves shape which adaptation options remain available, and on what timescale — foreclosing some choices that may be needed later. Complementary approaches drawn from decision-making under deep uncertainty emphasize stress-testing decisions for robustness under multiple climatic and socio-economic futures (Marchau *et al.* 2019), offering a way to navigate trajectories that cannot be fully sequenced in advance.

Even transformational adaptation is bounded. Beyond certain thresholds, reshaping socio-ecological systems would itself impose intolerable and irreversible losses — of sovereignty, ancestral land, culture or self-determination, particularly for small island, coastal and Indigenous communities. Such outcomes are not adaptation but Loss and Damage, a distinct domain tied to compensation, liability and justice (Mechler *et al.* 2020).

Building transformational capacity and planning under deep uncertainty

Act early, evolve and invest. Under deep uncertainty, transformational capacity must begin well before peak warming, evolve across all stages, and be treated as a core adaptation investment rather than an aspirational add-on. This capacity requires institutional learning and rapid unlearning, distributed agency and reflexive governance (Fazey *et al.* 2018; Feindt and Weiland 2018), together with institutions that can uphold long-term goals—including intergenerational justice and ecological integrity—while remaining responsive to rapidly changing conditions. Transformational adaptation will also need to include enabling continuous social learning, empowering actors at multiple scales to exercise adaptive agency and building institutions that can 'hold' long-term goals—including intergenerational justice and ecological integrity—while remaining responsive to the rapidly shifting conditions of each stage. Under deep uncertainty, adaptation planning must try and remain flexible, enabling learning from emerging practices while avoiding lock-in to maladaptive pathways if temperature overshoot, peak and decline proves greater or longer than expected, or overinvestment if it proves smaller or shorter.

Flexible adaptation pathways, if planned for now, can enable sequencing of low-regret, reversible and modular adaptation options rather than committing to a single endpoint (Haasnoot *et al.* 2024). However, this approach is less directly applicable in sectors such as health, where adaptation needs are shaped as much by development trajectories as by physical climate hazards. Closing these gaps will require further intensive research. Priorities include understanding how the solution space for adaptation (Haasnoot *et al.* 2020; Schleussner *et al.* 2024; Reisinger *et al.* 2025) varies across different exceedance levels, peaks and overshoot durations, and how socioeconomic development pathways interact with adaptation across overshoot stages to shape adaptive capacity (Andrijevic *et al.* 2023).

4.5 Synthesis and key take aways for adaptation

This chapter has shown the urgency of effective, efficient, equitable and forward-looking adaptation, including transformational adaptation, to manage overshoot, peak and decline pathways while advancing sustainable development.

Adaptation is not optional: it is essential. Forward-thinking, transformational adaptation, is not merely a response to the interactions of climate risks with development pathways, but also a prerequisite for the sustained mitigation that overshoot demands. Without robust adaptive governance and pre-committed financing mechanisms, investments in mitigation and adaptation—across near-term and post-peak horizons—risk being deprioritized in favour of immediate crisis response, a feedback dynamic in which the absence of adaptation extends the duration and magnitude of overshoot itself. Building both adaptation and mitigation capacity depends on enabling conditions that the preceding sections have set out — from political will and finance to equity, justice and attention to loss and damage. These demands only intensify above 1.5°C, amplifying non-linear increases in impacts, compounding their complexity and disproportionately affecting the poor and vulnerable (Chapter 2).

Acting on these messages will be extremely challenging, particularly given the current lack of actionable research on adaptation under overshoot and conditions of deep uncertainty.

Nevertheless, several priorities are clear:

- **Current adaptation implementation efforts remain insufficient in scale, depth and reach, particularly (but not only) for the most vulnerable.** Adaptation approaches are poorly aligned with the realities of an overshoot, peak and decline pathway, and require an urgent paradigm shift to effectively address exceedance — one that begins immediately but unfolds through sustained, iterative and participatory processes rather than rapid imposition. Planning and decision-making must assume that complex and deeply uncertain conditions will continue and may accelerate, emphasizing the need for constant flexibility and continuous learning in design and implementation.
- **Many planned and established measures are likely to become infeasible and ineffective** as temperatures continue to increase and impacts intensify, pushing systems toward soft and hard adaptation limits and increasing the likelihood of crossing critical tipping dynamics associated with exceedance and response actions. Without redesign, current adaptation pathways risk widespread maladaptation and the reinforcement of existing, or introduction of new, vulnerabilities and inequities.
- **Transformational adaptation can no longer be treated in isolation from current development deficits or from singular mitigation efforts.** Transformational adaptation planning and implementation must recognize: opportunities; the constraints and limits to adaptation; and the implications of these for equity and justice along the full overshoot, peak and decline pathway.
- **Political commitment is the critical enabling condition.** Political will—including multilateral political will—is the binding constraint on adaptation under overshoot pathways. The demands on political commitment will intensify across every stage as the conditions for sustaining it deteriorate, with international cooperation least reliable when most needed. The mechanisms that could close this gap—pre-committed finance, durable solidarity arrangements and inclusive governance—must be built well before peak warming, not improvised under crisis conditions.

In Focus: Legal implications of 1.5°C overshoot pathways

The international legal framework for climate mitigation and adaptation is oriented around limiting global warming to 1.5°C, and that benchmark will continue to guide States' obligations if warming exceeds it. The core framework is provided by the UNFCCC and the Paris Agreement, complemented by other treaties including the United Nations Convention on the Law of the Sea (UNCLOS), as well as customary obligations to prevent significant environmental harm. These obligations are continuing and in important respects are governed by stringent due diligence – a standard which evolves with scientific knowledge and the probability and gravity of foreseeable harm.

An overshoot pathway would not displace this legal framework; it would change only the circumstances in which States must perform their obligations.

Mitigation

In its 2025 advisory opinion on climate change, the International Court of Justice (ICJ) determined that 1.5°C is the "agreed primary temperature goal" of the Paris Agreement parties, citing their decisions reaffirming efforts to limit warming to 1.5°C. The ICJ concluded that parties' NDCs, taken together, must be capable of achieving that goal, and that parties must exercise stringent due diligence in preparing NDCs reflecting their highest possible ambition and in pursuing domestic mitigation measures to achieve them (ICJ 2025). The International Tribunal for the Law of the Sea (ITLOS) similarly tied States' mitigation obligations under UNCLOS to the 1.5°C threshold and the best available science (ITLOS 2024).

Neither advisory opinion expressly addressed the legal implications of overshoot pathways, but their reasoning indicates that overshoot would not alter the legal framework for mitigation. Due diligence evolves with scientific knowledge and the probability and gravity of harm (ITLOS 2024; ICJ 2025). The greater risks of higher and longer overshoot are thus relevant to whether State action is adequate (Rogelj and Rajamani 2025; Rajamani *et al.* 2026). As exceedance increases the probability and gravity of climate harm, due diligence becomes more demanding–especially as temperatures rise above 1.5°C–reinforcing the need for deep, rapid and sustained reductions to limit peak warming and overshoot duration, and continued efforts to return warming below 1.5°C.

All States must exercise stringent due diligence to regulate GHG emissions, including by private actors. The ICJ identified fossil fuel production and consumption, exploration licensing and subsidies as areas in which failure to take appropriate action may constitute an internationally wrongful act. After exceedance, such actions matter most where they lock in emissions or increase reliance on future removals. Differences in responsibility and capability affect the effort required, but they do not excuse feasible action not taken (ITLOS 2024; Mayer 2024; ICJ 2025; Schönfeld and Rogelj 2025; Voigt *et al.* 2025).

The ICJ also found that States must preserve and improve the absorption capacity of carbon reservoirs and sinks. The Court's emphasis on deep emissions reductions, prevention and precaution supports treating CDR as complementary to, not a substitute for, near-term mitigation. CDR also remains subject to legal safeguards concerning biodiversity, the marine environment, human rights and the interests of other States (ICJ 2025; Rajamani *et al.* 2026).

Adaptation

Adaptation obligations gain importance under overshoot pathways. The ICJ concluded that States must undertake adaptation planning and action with due diligence and in light of the best available science (ICJ 2025). This finding supports planning for foreseeable risks at plausible peak warming and for harms that persist after temperatures decline.

States must also cooperate through finance, technology transfer, capacity-building and scientific information. The ICJ recognized that disparities in access to scientific and technical information, particularly for vulnerable developing States, can constrain their ability to assess risks and implement climate obligations (ICJ 2025). UNFCCC, Paris Agreement and UNCLOS obligations on observation, data sharing and capacity-building are especially important in an overshoot context.

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In Focus: Governance, legitimacy and equity

The feasibility of mitigation, adaptation and post-peak re-baselining under overshoot pathways depends critically on governance arrangements that are configured for the shape of the overshoot trajectory: front-loading of adaptive investment under current conditions, managing cascading crises at exceedance and peak warming, and contending during the decline period with difficult choices about what gets rebuilt, what is abandoned, and who gains and who bears the costs of permanent change. Governance and institutional arrangements will also need to grapple with the distribution of resources during overshoot, with contexts as diverse as small island states and coastal megacities simultaneously facing the effects of sea-level rise. With limited finances, challenging decisions will need to be made in balancing territorial, financial and moral values for investment and protection. Peak warming will place substantial stress on political and institutional systems, and institutions that fail during this peak period may not fully recover even if climatic conditions later improve (Reisinger *et al.* 2025; Theokritoff *et al.* 2025). The political dynamics through which climate action needs are met have historically been underrepresented in climate assessments as have the ways in which climate impacts interact with distributional tensions, inequality and the risks of armed conflict (Eriksen *et al.* 2021; Leininger *et al.* 2026).

The governance pressures characteristic of overshoot will evolve across its trajectory and the governance task is to maintain capacity that meets the needs of each stage. Under current conditions, the main risk is delayed action and continued distributional inequities. During the exceedance and peak stages, reactive crisis management may crowd out strategic planning and implementation. This may also produce institutional and fiscal constraints under which allocative decisions and absent safeguards tend to reproduce and intensify existing inequalities in wealth and political access. During the decline period, falling global temperatures may weaken political urgency even while harder hit and less well-resourced regions continue to experience both novel and long-duration impacts (Reisinger *et al.* 2025; Theokritoff *et al.* 2025). Institutions capable of maintaining political commitment, fiscal capacity and social legitimacy across these stages are critical; lapses in capability in any one stage may propagate through the others. Adaptive pathways approaches that map the solution space across time and revisit decisions as conditions evolve offer a structured way to address these needs under the deep uncertainty that characterizes overshoot pathways (Haasnoot *et al.* 2024).

Overshoot governance also has a distinctive feature, its self-prolonging dynamic, that sets it apart from general climate governance challenges. During the period of overshoot, there will be an increased need for emergency responses and reconstruction. If meeting these needs diverts fiscal and institutional resources from the sustained mitigation and adaptation on which a Paris-compliant return depends, there is a risk of prolonging the overshoot's severity and duration. Adaptation and mitigation are mutually reinforcing under overshoot: adaptation that reduces vulnerability also reduces future demands placed on reactive and emergency spending; it also preserves the fiscal capacity needed to sustain the steep emissions reductions through net zero and into net negative that bring temperatures back down. Without governance arrangements that protect long-term climate investment during crises, the political conditions that have already produced a period of overshoot may reproduce themselves. Sovereign fiscal space is already constrained by climate-related shocks (Calcaterra *et al.* 2025), adaptation implementation lags commitments under current conditions (UNEP 2024b), and recent stocktakes find adaptation to be largely fragmented, local and incremental rather than transformational (Berrang-Ford *et al.* 2021). These constraints are compounded by the entrenched imbalance between mitigation and adaptation finance, which leaves adaptation chronically under-resourced even in the absence of crisis (Khan *et al.* 2020). Thus, the challenge under overshoot is to insulate mitigation and adaptation from being crowded out by the very dynamics and impacts that characterize the overshoot period.

Loss and damage is the clearest case of a governance architecture that must be capitalised —well before peak warming rather than negotiated under the crisis conditions that may occur at the peak. Strengthening diplomatic mechanisms, climate finance and solidarity arrangements before the onset of overshoot is critical for avoiding fragmentation when those instruments are most needed. Current commitments remain far below projected needs. The Fund for Responding to Loss and Damage, established at COP 27, faces a structural gap between pledged resources (of the order of USD800 million as of late 2025) and current estimates of developing-country needs, which Tavoni *et al.* (2024) place at around USD395 billion for 2025, with an indicative range of USD128 to 937 billion. National engagement with the concept itself is uneven, with different countries advancing distinct framings of what loss and damage covers and what responses it requires (Calliari and Ryder 2023; UNFCCC 2025). Under overshoot, cumulative and irreversible losses will far exceed the capacity of the present architecture.

Overshoot governance challenges unfold across deep prior inequalities and inequities. Distributional and political asymmetries determine how hazards translate into impacts (Eriksen *et al.* 2021; IPCC 2022d). Women, Indigenous Peoples and other historically marginalised groups are often disproportionately exposed because of unequal access to land, resources and political representation. Without action to address differential adaptive capacity and strengthen inclusive institutional capacity, these unequal exposures will persist and even worsen through and after peak warming. Effective national and subnational institutions can substantially reduce mortality from extreme events independent of income, while weak or less inclusive governance compounds inequality (e.g. Tennant and Gilmore 2020). These institutional asymmetries also operate across scales: in Caribbean cities, for example, climate adaptation increasingly devolves to local governments that lack the fiscal authority to act on the scale that sea-level rise demands (Mycoo 2024). In conflict-affected contexts, there is already a pronounced adaptation gap (Sitati *et al.* 2021). Where institutions are already weakened and trust low, even well-designed adaptation interventions can reinforce, redistribute or generate new vulnerabilities (Eriksen *et al.* 2021; Schipper *et al.* 2022).

Cooperation among states under overshoot is similarly conditional. Countries will experience impacts unevenly, with some continuing to face severe, novel or irreversible impacts even after global temperatures begin to decline, reflecting deep differences in geography, natural resource endowments and adaptive capacity. Beyond uneven exposure, the political and economic strains produced by overshoot, including pressure on security expenditure, anti-immigration politics, resource nationalism and elevated instability risks in contexts of pre-existing vulnerability, may further erode the conditions for cooperative response (Mach *et al.* 2019; Buhaug *et al.* 2023). The COVID-19 pandemic provides a cautionary precedent: initial international cooperation gave way to vaccine nationalism, uneven recovery trajectories and a rapid erosion of multilateral commitment once the immediate threat receded in wealthier nations, even as poorer countries continued to bear the burden (Sachs *et al.* 2022; Brown and Rosier 2023). These types of exposure asymmetries and the cooperative stresses they produce could manifest during the decline stage of overshoot: solidarity may erode precisely as the most exposed countries enter their longest exposures.

Under overshoot, mobility and displacement decisions may not reverse with the temperature trajectory: mobility and immobility decisions taken before and during exceedance and peak stages will endure even as temperatures decline. Internal displacement and planned relocation, including managed retreat in highly exposed regions, are already underway, particularly in small island developing states and other low-lying coastal areas, and will intensify as slow-onset processes such as sea-level rise progress (Mach and Siders 2021). The effects of these relocations will persist through and beyond peak warming. At the international level, climate-induced movement is shaped less by hazard exposure than by the broader political, economic and legal conditions that govern migration (Black *et al.* 2011; Cundill *et al.* 2021; Boas *et al.* 2022). Whether migration systems can support mobility as adaptation, whether slow-onset displacement is recognized within existing legal categories, and whether host communities have the capacity to support arrivals are central to addressing these challenges (Cissé *et al.* 2022). Putting the legal, administrative and financial conditions for adaptive mobility in place well before peak warming is therefore central, since the political space to negotiate them narrows during peak. Often overlooked is the further dimension that climate change can reduce mobility for the poorest by destroying the resources that movement requires, leaving populations involuntarily immobile in increasingly hazardous places (Benveniste, Oppenheimer and Fleurbaey 2022).

Ecological recovery operates on timescales that are typically longer than those of temperature decline, and frequently longer than governance, finance and political commitment cycles. Even pathways that return temperature to pre-overshoot levels may durably alter biodiversity, ecosystem function and the services on which mitigation and adaptation depend, with the highest risks in tropical regions including the Amazon, the tropical African coast, and parts of the Indian and Pacific oceans (Meyer *et al.* 2022; Meyer and Trisos 2023). Hysteresis in Atlantic cod stocks illustrates this point: marine species populations can fail to recover even as exploitation pressure declines, with prolonged consequences for the economies that depend on them (Sguotti *et al.* 2019). For fisheries-dependent small island developing states, where local food and economic systems are tightly coupled to marine ecosystem function, this mismatch between recovery timescales can pose substantial health and livelihood issues (Gordon-Strachan *et al.* 2025). Time lags between environmental response and institutional response compound the challenge, often leaving governance arrangements calibrated to conditions that have already passed (Hocherman, Trop and Ghermandi 2025).

The trajectory through and beyond an overshoot, peak and decline pathway is not only a matter of physical temperature pathways: it depends on political choices made before and during the period itself. Investments in preparedness, social protection and institutional resilience prior to peak warming shape whether societies absorb shocks without lasting damage; failure to meet adaptation needs in advance can lock in vulnerability and limit the benefits of subsequent temperature reductions. The capacities that allow the trajectory to bend back, including pre-positioned finance, legitimate and inclusive decision-making, sustained mitigation through net negative, and international cooperation that survives into the decline stage, need to be constructed well before peak; once peak conditions arrive, the political space to construct them narrows. Governance under overshoot is therefore as critical as technical pathways: it is a structural condition for those pathways to remain viable.

05 Conclusion: Through overshoot and beyond - Risks, choices and frontiers

Overshoot alters the pathway, but not the importance of limiting warming. The evidence assessed in this report indicates that exceedance of 1.5°C is now expected across central estimates, while the precise timing, magnitude and duration remain contingent on future emissions and the response of the climate system (UNEP 2025b; Forster *et al.* 2026; Tavoni *et al.* 2026). Exceedance should not be interpreted as abandonment of the 1.5°C goal, as acceptance of higher warming, or as evidence that action no longer matters. It changes the pathway: from avoiding exceedance altogether to limiting how high and how long temperatures rise above 1.5°C while preserving the possibility of returning below it.

There is no benign overshoot pathway, but its magnitude, duration and consequences are not predetermined. Every fraction of a degree and every year above 1.5°C increases exposure to climate hazards and the likelihood of irreversible loss (IPCC 2022a; Schleussner *et al.* 2024; Reisinger *et al.* 2025). Yet the range of possible outcomes remains wide. Near-term emissions reductions influence peak warming; the level of peak warming influences the scale and feasibility of the net-negative emissions that would be required for temperature decline; and adaptation influences how climate hazards translate into impacts on people, ecosystems and development (IPCC 2021; IPCC 2022b). Choices made before the peak therefore continue to shape conditions long after it.

The central finding is not one of resignation, but of constrained agency. Overshoot narrows options and increases risks, costs and trade-offs. It does not eliminate the ability to limit additional harm. Existing mitigation and adaptation options can slow warming, protect lives and livelihoods, preserve natural carbon stocks and strengthen the institutional capacity needed to sustain action through a prolonged period of exceedance. The challenge is to act while recognizing uncertainty, rather than waiting for uncertainty to disappear.

5.1 Reading of overshoot pathways

Figure 5.1 brings together the report's core insight: mitigation and adaptation must advance throughout the overshoot pathway, even as their contexts and priorities evolve.

Figure 5.1: Temperature overshoot: actions and challenges (*see next page*)

This is an illustrative depiction of temperature overshoot and the actions and challenges associated with limiting its magnitude, duration and consequences.

TEMPERATURE OVERSHOOT: EXCEED AND RETURN TO 1.5°C

Decades of **insufficient** action have locked us into **three compounding challenges** to limiting **temperature overshoot**, with an **urgent** need for **action** now

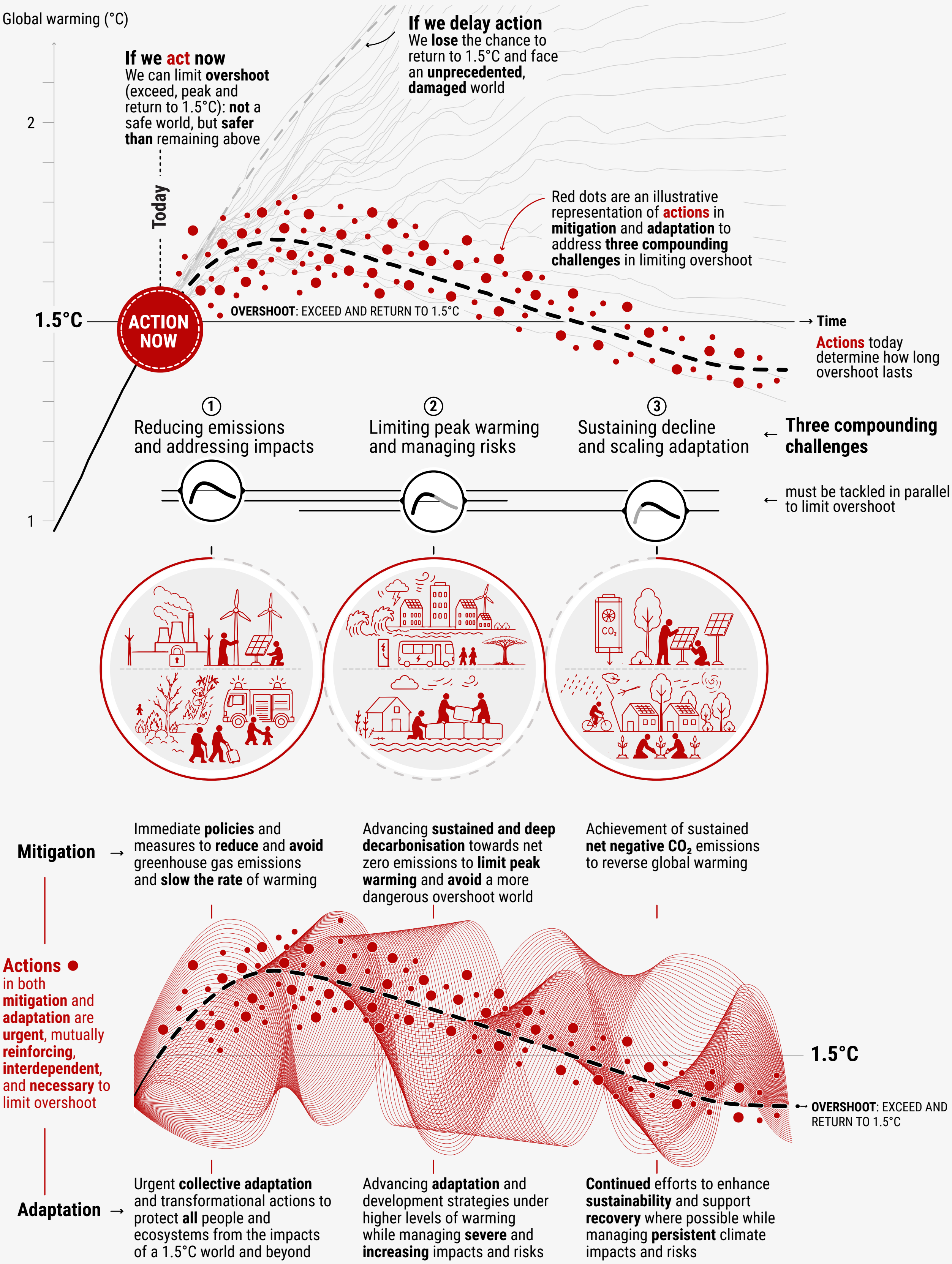

Figure 5.1: Temperature overshoot: actions and challenges (*see previous page*)

In Figure 5.1, the visual features in the **top panel** are indicative and do not represent precise warming magnitudes, rates or probabilities. The black dashed line represents an overshoot pathway adapted from an SSP2-4.5 pathway based on IPCC (2021), while the light grey dashed line represents a high-overshoot pathway adapted from Reisinger *et al.* (2025). The horizontal line marks the 1.5°C global warming level, relative to 1850–1900. The light grey trajectories in the background are illustrative and are informed by visual interpolation across an ensemble of SSP scenarios and tipping-point peaks, depicting a world that may become increasingly challenging depending on the actions we take. The red dots are an illustrative representation of actions in mitigation and adaptation to limit overshoot.

The **middle panel of Figure 5.1**, with its three circular illustrations, conveys three compounding challenges to limiting temperature overshoot: reducing emissions (top half) while addressing current impacts (bottom half); limiting peak warming (top half) while managing escalating risks (bottom half); and sustaining temperature decline (top half) while continuing to adapt to persistent impacts (bottom half). These are not discrete or sequential policy stages. Mitigation and adaptation are required throughout the entire overshoot pathway, although their emphasis and context evolve over time.

In the **lower panel of Figure 5.1**, two interwoven red flows illustrate the interdependence of actions in mitigation and adaptation: rapid emissions reductions limit future warming and reduce dependence on carbon dioxide removal, while adaptation protects people, ecosystems and development as risks intensify and persist.

The central message is that there is no benign overshoot, but neither its magnitude, duration nor consequences are predetermined. Decisions taken today influence how high warming rises above 1.5°C, how long the exceedance lasts, the risks and impacts experienced along the way, and the prospects for a sustained decline in temperature. Limiting overshoot therefore requires mitigation and adaptation to advance together throughout exceedance, peak and decline.

Before and during exceedance, rapid and sustained reductions to GHGs is the most effective way to limit peak warming. Reducing carbon dioxide emissions determines the long-term warming outcome, while deep reductions in methane and other short-lived climate pollutants can slow near-term warming and help limit the peak (IPCC 2021; UNEP 2025c). Avoiding additional emissions also reduces future dependence on carbon dioxide removal and the environmental, social and governance pressures associated with deploying it at large scale (IPCC 2022b; Deprez *et al.* 2024).

At and around peak warming, the task is to halt further warming and sustain societies and ecosystems under the highest level of climate risk. Adaptation limits may be approached or exceeded, fiscal and institutional capacity may be strained by repeated crises, and losses may compound across food, water, health, infrastructure and ecosystems (IPCC 2022b; Reisinger *et al.* 2025). Preventive adaptation and preparedness can reduce these pressures and help preserve the capacity required to maintain mitigation ambition (Aligishiev, Bellon and Massetti 2022; Bellon and Massetti 2022). This mutual dependence is one reason mitigation and adaptation cannot be planned as separate or sequential agendas.

After the peak, temperature decline would require sustained net-negative CO_2 emissions, potentially complemented by further reductions in residual non-CO_2 emissions. Carbon dioxide removal will be needed to counterbalance residual emissions and, at a larger scale, to support temperature decline (IPCC 2021; IPCC 2022b). It is not a substitute for stringent emissions reductions. Its feasible and sustainable contribution depends on the level of residual emissions, the durability of storage, climate feedbacks, resource constraints, governance and public legitimacy (Smith *et al.* 2024; Deprez *et al.* 2024; Gidden *et al.* 2026a). Protecting and restoring ecosystems can deliver important benefits, but natural sinks alone are not assessed as sufficient to achieve sustained net-negative emissions at the global scale (Dooley, Nicholls and Meinshausen 2022; Smith *et al.* 2026).

Temperature decline will not reverse all impacts, so adaptation is necessary throughout the pathway. Sea-level rise will continue for centuries; some glacier, ecosystem and biodiversity losses will persist; and societies will have changed through adaptation, displacement, investment and development (Fox-Kemper *et al.* 2021; Meyer and Trisos 2023; Schleussner *et al.* 2024; Schuster *et al.* 2025). The return towards a lower global temperature is therefore not a return to previous climatic, ecological or social conditions. It is a transition into a future shaped by both avoided harm and the legacies of overshoot.

5.2 Decisions under constraint and uncertainty

Irreversible impacts do not make the future inevitable. The extent of additional irreversible loss will depend partly on peak warming and the duration of exceedance, as well as on exposure, vulnerability and adaptive capacity (Meyer and Trisos 2023; Schleussner *et al.* 2024). Action cannot prevent every loss, but it can reduce additional risks and expand the capacity of people and ecosystems to cope, adapt and transform (IPCC 2022b). This distinction is central: acknowledging irreversibility should strengthen risk reduction, not encourage fatalism.

Decision-making must act on what is already well established and anticipate for what remains uncertain. The evidence base is strong on the need for rapid emissions reductions, protection of natural carbon stocks, reductions in methane and other short-lived climate pollutants, and stronger adaptation. Greater uncertainty surrounds the precise peak, the scale and durability of future removals, regional climate conditions during decline, and the responses of ecosystems, economies and societies after the peak. These gaps do not justify delay. They favour decisions that perform across a range of futures, preserve options and can be revised as evidence evolves.

Equity is not an additional consideration applied after the pathway is chosen; it shapes whether the pathway is feasible and legitimate. Countries and communities differ in their historical responsibility, exposure, development needs, fiscal capacity and access to technology and information. The burdens and benefits of emissions reductions, carbon dioxide removal, land-use change, infrastructure protection and adaptation finance will also be unevenly distributed (IPCC 2022b; Deprez *et al.* 2024). Under the UNFCCC principle of common but differentiated responsibilities and respective capabilities, these differences remain central to the distribution of effort and support (Klinsky and Winkler 2018; Fyson *et al.* 2020). Overshoot heightens rather than diminishes their relevance.

Finance must be aligned with the sequence and physical realities of overshoot. It must accelerate near-term emissions reductions—including the deployment of renewable energy, grids and storage—while financing anticipatory and flexible adaptation before worsening impacts lock in vulnerability or divert public resources into repeated crisis response. At the same time, financing for carbon dioxide removal must build a responsible portfolio of approaches without rewarding delayed mitigation or assuming that uncertain future removals will materialize at the required scale, durability and social acceptability. These priorities cannot be pursued sequentially: underinvestment in adaptation can erode the fiscal and political capacity needed to sustain mitigation, while inadequate investment in clean energy increases both peak warming and future dependence on removals. Financing institutions will therefore need to act faster and accept that not every uncertainty can be resolved before investment begins, using staged, modular and revisable approaches that allow learning and adjustment. Speed, however, should not come at the expense of environmental integrity, human rights, equity or community safeguards. Pre-committed financing mechanisms will be needed to protect mitigation and adaptation investment from displacement by escalating crises and sustain action through peak warming and decline.

Governance will have to remain capable of learning while sustaining long-term direction. The pathway from exceedance through peak warming and possible decline extends beyond ordinary political, investment and planning cycles. Institutions will need to interpret evolving evidence, monitor thresholds and implementation, revise baselines and retain legitimacy as priorities change. Agile planning does not mean abandoning long-term goals; it means linking them to observation, review and decision points that allow action to adjust without losing direction (Haasnoot *et al.* 2024; Reisinger *et al.* 2025).

5.3 Frontiers opened by overshoot

The journey to peak warming is better understood than the descent that must follow. Climate science has made substantial advances in understanding warming under rising emissions and the consequences of different global warming levels. Considerably less is known about ecological recovery, regional climate behaviour, social adaptation, economic adjustment and governance during stabilization and decline (Schleussner *et al.* 2024; Reisinger *et al.* 2025). Overshoot therefore opens a frontier that is simultaneously scientific, institutional, political and ethical.

How will regional climates and risks evolve during decline?

A fall in global mean surface temperature may coexist with continued sea-level rise, ocean warming, cryosphere loss and regional changes that differ from those experienced during the warming stage (Fox-Kemper *et al.* 2021; Schleussner *et al.* 2024). Rainfall, drought, extremes and compound hazards may not reverse uniformly or on decision-relevant timescales (Pfleiderer, Schleussner and Sillmann 2024; Douglas *et al.* 2025). Further assessment is needed to understand where declining global temperatures reduce risk, where risks persist and where unfamiliar combinations may emerge. This includes the cumulative exposure created by the magnitude and duration of overshoot—not only the temperature eventually reached.

What can recover, what will reorganize and what will be permanently lost?

The distinction between reversible, partially reversible and irreversible change remains incomplete across Earth system components, ecosystems and human systems. Recovery may be delayed, contingent or impossible; restored temperature conditions may not recreate lost species, cultural practices, livelihoods or ecological relationships. Understanding these differences is necessary both for adaptation and for identifying where impacts move beyond adaptation into loss and damage.

In Focus: Species redistribution and the unmaking of protection

Impacts

Another face of overshoot is the spatial unmaking of nature-conservation institutions. As warming continues, many species tracking their climate envelopes are migrating polewards and upslope. Protected Areas (PAs) cannot follow. Under 2°C, 24 per cent of climates currently within PAs globally are projected to disappear from the existing PA network, 36 per cent of PAs will develop novel climates not previously protected anywhere, and in Africa more than half of PA climate analogues cross national borders (Parks *et al.* 2022).

Impacts are heterogeneous but converging in direction. Half of African mountain plant species are projected to face range contractions under sustainability pathways, rising to three quarters under high-emissions pathways (Vidal Junior *et al.* 2025); upslope climate shifts may reach up to three times the global average — beyond the dispersal capacity of many species. Southern African savannahs and grasslands are undergoing woody plant expansion with cascading effects on rural ecosystem services (Kapuka, Dobor and Hlásny 2022; Trisos *et al.* 2022). In tropical oceans, equatorial species richness has been declining since at least the 1970s while subtropical richness rises (Chaudhary *et al.* 2021), and tropical marine biomass is projected to decline broadly (Lotze *et al.* 2019). These impacts persist well into the decline stage: moved species may not easily return, equatorial losses are irreversible on policy-relevant timescales, and PA designations grow steadily misaligned with their original ecological premise.

Yet PAs are associated with critical ecosystem services, refugia value and biodiversity benefits inside and beyond their boundaries, even as species composition shifts (e.g. Brodie *et al.* 2023). What sustains these services through turnover is, in part, functional redundancy: where multiple species perform similar ecological roles, the loss of any one is partially compensated by others (Oliver *et al.* 2015; IPBES 2019; Biggs *et al.* 2020). Climate-driven compositional change therefore does not, in itself, justify withdrawing area-based protection measures. Where resilience is already eroding, the case is the opposite: for targeted, reinforced protection of those specific functions, not relaxing or removing it. PAs also buffer microclimates relative to surrounding land (Xu *et al.* 2022), making them disproportionately important as refugia. To sustain this function under overshoot will require strengthening area-based conservation, including, where appropriate, through protected areas, other effective area-based conservation measures, Indigenous and traditional territories, buffer zones and greater ecological connectivity (Hannah 2008; Beaumont and Duursma 2012; Laurance *et al.* 2012; Anderson *et al.* 2023).The ICJ's 2025 reaffirmation of UNFCCC and customary obligations to preserve greenhouse gas sinks and reservoirs reinforces this: PAs are climate infrastructure, not only biodiversity infrastructure (ICJ 2025). The ICJ's findings reinforce the need for States to exercise due diligence in conserving and enhancing greenhouse gas sinks and reservoirs, in accordance with applicable international obligations and national circumstances. The question is not whether to sustain the PA network but how to evolve the assumptions on which sustained protection rests — and how to defend it from the new pressures overshoot creates.

Strategic questions

1. Given that the rationale for sustained protection has shifted from static species inventory to ecological function, refugia value and climate infrastructure, how can this re-anchoring be operationalised — in PA design, in implementation across the scope of the Kunming-Montreal Global Biodiversity Framework's Target 3 and in the alignment of PA networks with identified climate refugia?

2. Overshoot, peak and decline pathways depend on large-scale carbon dioxide removal. How can national and international safeguards ensure that large-scale land-based CDR, including BECCS and afforestation, does not increase pressure on protected and conserved areas or transfer disproportionate land-use burdens to developing regions?

3. Industrial-scale extraction and development is already the leading cause of protected area downgrading, downsizing and degazettement (PADDD), driving most documented events globally and at least 1.2 million km² of marine PADDD alone (Mascia *et al.* 2014; Golden Kroner *et al.* 2019; Albrecht *et al.* 2021). Climate-driven species decline within PAs now creates a new pretext for the same outcome: that since the original species are gone, protection can be relaxed for mining, oil and gas, or other development. The science does not support this — functional redundancy, refugia value, microclimatic buffering and carbon storage all argue for tighter, not looser, protection as overshoot bites. How can safeguards against inappropriate PADDD be strengthened through transparent and participatory reporting and review consistent with the Global Biodiversity Framework and national circumstances, so that climate-driven species loss is not used to justify weakening effective area-based conservation? How can buffer zones and ecological connectivity help sustain the function of national and transboundary conservation networks?

4. What forms of transboundary cooperation will be needed when climate-driven species redistribution moves species into jurisdictions where they were not previously protected?

5. Indigenous Peoples manage or have tenure rights […] over about 40% of all terrestrial protected areas and ecologically intact landscapes" (Garnett *et al.* 2018), often achieving conservation outcomes that match or exceed those under external management (Garnett *et al.* 2018; Dawson *et al.* 2021). As overshoot displaces species and reshapes ecosystems, how can implementation of GBF Target 22 strengthen their rights, authority and resources to adapt their stewardship?

How should adaptation operate in a non-monotonic climate?

Overshoot challenges the adaptation assumption that climate conditions will change progressively in one direction. Infrastructure, agriculture, health systems and ecosystem management may need to function through worsening conditions, an uncertain peak and later regional readjustment (Reisinger *et al.* 2025). Research and practice will need to examine how flexible pathways, modular investment, monitoring and decision triggers can reduce lock-in and maladaptation without postponing action that is already urgent (Haasnoot *et al.* 2024).

How can net-negative emissions be governed without weakening near-term mitigation?

The prospect of temperature decline creates new questions about the scale, timing and allocation of removals; the treatment of residual emissions; the durability and verification of storage; and responsibility for long-term stewardship (Stuart-Smith *et al.* 2023; Edenhofer *et al.* 2025). It also creates a continuing risk of mitigation deterrence if future removals are treated as an alternative to avoiding emissions today. Stronger evidence is needed on sustainable portfolios of carbon dioxide removal, their interaction with adaptation and development, and governance arrangements capable of managing environmental and social trade-offs over long timescales (Deprez *et al.* 2024; Gidden *et al.* 2026a).

What institutions can remain effective and legitimate across generations?

Overshoot, peak and decline could span much of a human lifetime. Responsibilities, capacities, technologies and social priorities will evolve, while the consequences of earlier decisions will persist. This raises unresolved questions about intergenerational responsibility, international cooperation, finance, participation and the governance of permanent change. The challenge is not simply to design institutions for an anticipated future, but to build institutions capable of learning, retaining memory and adapting without shifting burdens onto those least responsible or least able to respond.

What knowledge infrastructure is required to navigate the pathway?

Observation and monitoring are foundational. Detecting changing hazards, approaching thresholds, the performance of adaptation and mitigation measures, and the durability of removals requires sustained and accessible data. Yet major observational and analytical gaps remain, particularly in vulnerable and under-resourced regions. A stronger science–policy interface will depend not only on improved models, but also on the capacity to translate global evidence into locally relevant information and to integrate scientific, Indigenous and local knowledge into decisions.

These uncharted territories should not be mistaken for an absence of direction. The report identifies a substantial body of action that is already supported by evidence. The frontier lies in understanding how to sustain, adjust and govern that action as climate and social conditions evolve. Building this knowledge base is therefore not separate from implementation: monitoring, experimentation, learning and revision are part of navigating overshoot responsibly.

The science–policy interface will also need to become more continuous, two-way and agile. Decision-makers must be able to identify emerging knowledge needs, while researchers, practitioners, practitioners and traditional knowledge holders need channels through which observations and experience can rapidly inform assessment and action. This requires moving beyond periodic transfers of knowledge towards sustained exchange, in which policy questions help shape research and monitoring, and decisions are revisited as evidence and conditions evolve. Greater agility should accelerate learning and adjustment without lowering standards of scientific integrity, transparency or participation.

5.4 Navigating the return to a safer future

Overshoot narrows the space for action, but does not eliminate agency. Rapid and sustained emissions reductions remain the most effective means of limiting peak warming, shortening exceedance and reducing additional climate-related harm (UNEP 2025b; IPCC 2022b). Deep reductions in methane and other short-lived climate pollutants can help slow near-term warming (UNEP 2025c; Shindell *et al.* 2024). Adaptation can protect people, ecosystems and development while preserving the institutional and fiscal capacity needed to sustain mitigation. Carbon dioxide removal will be necessary, but its contribution depends on how far residual emissions are reduced and how responsibly removals can be governed and maintained (Gidden *et al.* 2026a; Tavoni *et al.* 2026).

The path beyond peak warming will not simply retrace the path by which the world arrived there. Regional climates may respond differently; sea levels will continue to rise; some ecosystems will not recover; and societies will have been reshaped by decades of impacts and responses (Meyer and Trisos 2023; Schleussner *et al.* 2024). Navigating that future will require observation, learning and institutions capable of acting under uncertainty while remaining anchored in equity, sustainable development and the long-term temperature goal.

The destination remains a safer climate, but the conditions of the journey are still being shaped. Every fraction of a degree and every year above 1.5°C matters. Decisions taken now will influence how high warming rises, how long exceedance lasts, which losses can still be avoided and the capacities available to future generations beyond the peak. Overshoot is not a reason to lower ambition. It is a reason to act earlier, learn faster and sustain cooperation for longer.

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