Overshoot pathways of 1.5°C: reversible biophysical change, irreversible socioeconomic impacts

Submitted to *Environmental Research Letters*, April 2026, Special Issues: Focus on Pathways and Consequences of Climate Overshoot

Authors:

Alaa Al Khourdajie 1,2*; Marina Andrijevic 2; Edward Byers 2; Minal Pathak 3; Anna Pirani 4; Carl-Friedrich Schleussner 2,5; Rupert Stuart-Smith 6

1 Department of Chemical Engineering, Imperial College London, UK
2 International Institute for Applied system Analysis (IIASA), Austria
3 Ahmedabad University, India
4 CMCC Foundation - Euro-Mediterranean Center on Climate Change, Italy
5 IRIThesys, Humboldt-Universität zu Berlin, Berlin, Germany
6 Oxford Sustainable Law Programme, Smith School of Enterprise and the Environment, University of Oxford, UK

Emails:

* a.alkhourdajie@imperial.ac.uk (corresponding author)
andrijevic@iiasa.ac.at
byers@iiasa.ac.at
minal.pathak@ahduni.edu.in
anna.pirani@cmcc.it
schleussner@iiasa.ac.at
rupert.stuart-smith@ouce.ox.ac.uk

ORCIDs:

Alaa: 0000-0003-1376-7529
Marina: 0000-0003-0199-1988
Edward: 0000-0003-0349-5742

Minal: 0000-0002-9474-0485
Anna: 0000-0001-7287-8347
Carl: 0000-0001-8471-848X
Rupert: 0000-0002-1854-0641

Abstract

Exceedance of 1.5°C in the near term is now unavoidable. Among pathways consistent with the remaining carbon budget, an overshoot pathway, in which exceedance is followed by decline to or below 1.5°C through net-negative emissions, is the best case of what remains achievable. Permanent exceedance produces strictly worse outcomes, yet even an overshoot pathway leaves lasting legacies. We propose a three-layer analytical framework distinguishing the hazard (the four overshoot dimensions: magnitude, duration, rate of exceedance, and rate of decline), the biophysical response (reversible vs. persistent change), and the socioeconomic outcome (reversible vs. irreversible impact). We introduce the socioeconomic commitment threshold, an adaptation limit that is endogenous to the overshoot trajectory, beyond which cumulative overshoot effects commit socioeconomic losses that persist after temperatures decline, governed by three mechanisms: non-substitutability, threshold-crossing, and lock-in. A typology linking biophysical persistence with socioeconomic irreversibility illustrates that reversible biophysical change can produce irreversible socioeconomic loss, while persistent biophysical change need not produce irreversible outcomes where adaptive capacity is sufficient. Whether temporary exceedance produces permanent harm is determined primarily by socioeconomic factors, not biophysical ones. For systems and communities with low adaptive capacity, overshoot concentrates irreversible legacies even where temperatures subsequently decline, placing justice at the center of overshoot assessment.

Keywords

Climate overshoot; socioeconomic commitment threshold; committed socioeconomic impacts; losses and damages; adaptation limits; carbon dioxide removal.

1. Introduction

Exceedance of the 1.5°C threshold is no longer a distant prospect: the first year above 1.5°C has been recorded (Bevacqua et al., 2025; WMO, 2025). The remaining carbon budget for a 50% probability of limiting warming to 1.5°C stands at roughly 130 $GtCO_2$ from the start of 2025, equivalent to three years of current emissions (Forster et al., 2025). Warming has accelerated more over the past decade than in any previous one (Foster and Rahmstorf, 2026), and nationally determined contributions remain collectively insufficient (UNEP, 2025). Throughout this paper, ‘overshoot’ denotes exceedance of a temperature threshold and ‘overshoot pathway’ a trajectory in which exceedance is followed by decline to or below that threshold (Reisinger et al., 2025); unless otherwise stated, the threshold is 1.5°C. Such a pathway, delivered through sustained emission reductions and carbon dioxide removal (CDR) to net-negative CO_2, represents the best case scenario of what remains achievable. Without sustained reductions and removals, exceedance becomes permanent and every consequence of warming irreversible. The central question is therefore how severe the consequences of temporary exceedance will be, which will prove permanent, and what is gained by ensuring exceedance is temporary rather than indefinite.

An overshoot pathway may carry an implicit symmetry assumption: that when temperatures fall, impacts reverse. This is misleading. The climate system itself shows asymmetries: regional temperature and precipitation signals only partially reversing in the decades after peak warming (Roldán-Gómez et al., 2025; Pfleiderer et al., 2024; Schleussner et al., 2024), some regions continuing to warm as global temperature declines (Yang et al., 2026), and asymmetries in carbon cycle feedbacks and transient climate response (Chimuka and Zickfeld, 2026; Zickfeld et al., 2021). The further asymmetry this paper addresses lies in socioeconomic impacts: communities displaced, livelihoods destroyed, and cultural heritage lost during exceedance do not recover simply because temperatures fall. An overshoot pathway is better understood not as a temporary detour but as a period of elevated risk that may leave a permanent residue of socioeconomic harm.

Two policy imperatives follow. First, minimising peak warming is paramount: the magnitude and duration of overshoot together determine the probability of crossing irreversibility thresholds in both biophysical and socioeconomic systems. This was recognised in the Belém Global Mutirão (COP30 decision; UNFCCC, 2025), which reiterates the resolve to limit warming to 1.5°C and to limit both the magnitude and duration of temperature overshoot. This framing is contingent on the feasibility of the decline phase: without sustained CDR at scale, an ambitious overshoot pathway collapses into permanent exceedance (see Section 5).

Second, post-peak temperature decline yields benefits even where some losses are already locked in: declining temperatures slow committed processes such as sea-level rise, allow some biophysical and socioeconomic systems to recover before crossing their irreversibility thresholds, and slow the accumulation of further irreversible losses (Schleussner et al., 2024). The case for the decline phase is not that it reverses all harm, but that it limits further harm relative to permanent exceedance and preserves recovery potential for systems not yet past the point of no return.

The socioeconomic dimension of overshoot pathways remains underexplored. Recent work develops conceptual frameworks for how the determinants of risk, including hazard, exposure, vulnerability, and (in more recent framings) responses, evolve during the overshoot period (Reisinger et al., 2025). These do not formalise the threshold conditions under which temporary exceedance produces permanent socioeconomic loss, nor the mechanisms through which reversible biophysical change translates into irreversible socioeconomic outcomes. Irreversibility in this context is itself underspecified: what counts as irreversible depends on the timescale of assessment and on who bears the impact. This paper adopts a policy-relevant timescale of decades to a century, not a geological one.

We propose a three-layer analytical framework distinguishing the hazard (temperature trajectory and overshoot dimensions), the biophysical response (reversible vs. persistent change), and the socioeconomic outcome (reversible vs. irreversible impacts). We introduce a *socioeconomic commitment threshold*: the point beyond which the cumulative effects of overshoot commit socioeconomic impacts that persist after temperatures decline below the threshold, governed by three mechanisms: *non-substitutability*, *threshold-crossing*, and *lock-in*. The threshold is dynamic, modulated by vulnerability, adaptive capacity, and the characteristics of the pathway itself. The framework identifies the conditions under which biophysical persistence and socioeconomic irreversibility decouple, and provides a typology for assessing where and for whom overshoot creates permanent legacies.

2. Conceptual framework

Figure 1 illustrates the cascading relationship between the three layers through a stylised overshoot pathway. Panel a) builds on Reisinger et al. (2025) and characterises the hazard through four dimensions: magnitude (peak exceedance above the threshold), duration (time spent above it), rate of exceedance (speed of warming during ascent), and rate of decline (speed of temperature decline during descent). A permanent exceedance counterfactual, in which temperature stabilises at the peak, is shown alongside the overshoot pathway; the shaded area between the two represents the cumulative forcing avoided by sustained net-negative emissions. An alternative rate profile shares the same peak magnitude and peak year, illustrating that the rate dimensions vary independently of peak exceedance and propagate distinct stresses through the cascade. These four dimensions interact to shape the severity, frequency, and reversibility of outcomes across the biophysical and socioeconomic layers (Sections 3 & 4).

Panel b) shows that biophysical responses to the same temperature trajectory diverge by system properties. Whether a system recovers depends on whether it remains within its recovery capacity: the range of conditions from which return is possible. This framing does not integrate feedbacks that may attenuate or amplify system behaviour. Systems pushed beyond this range, through physical inertia or threshold-crossing, may not recover on policy-relevant timescales. Four post-peak archetypes are illustrated. The fastest tracks temperature decline, representing processes such as heat extremes that reverse in approximate proportion to temperature. Two intermediate pathways recover with increasing lag, representing systems such as hydrological regimes and ecological communities whose recovery lags temperature by years to decades (Marshall et al., 2025; Meyer et al., 2022). Arctic summer sea ice may recover fully as it tracks surface energy fluxes (Fox-Kemper et al., 2021), whereas regional temperature extremes show persistent asymmetries from ocean heat redistribution and interhemispheric thermal contrasts (Roldán-Gómez et al., 2025), placing them closer to the intermediate pathways. The anchor biophysical pathway (in green) is carried into Panel c) as the biophysical forcing shared by all four socioeconomic archetypes. The persistent upper pathway continues to intensify as temperature declines, representing processes governed by physical inertia or threshold behaviour: sea-level rise and glacier mass loss (Mengel et al., 2018; Schuster et al., 2025). The shaded envelope captures the residual biophysical change after partial recovery.

The mapping between biophysical and socioeconomic archetypes is not one-to-one: the same biophysical change can produce different socioeconomic outcomes depending on adaptive capacity. This decoupling is the focus of Section 4. Panel c) illustrates divergent socioeconomic responses to the anchor biophysical change in Panel b). High-adaptive-capacity systems and communities (lightest green) experience the least cumulative impact and recover fastest as conditions improve (e.g. heat mortality reductions following institutional adaptation in European cities; Fouillet et al., 2008); two intermediate pathways accumulate greater impact with increasing recovery lag (e.g. persistent economic losses from growth-rate effects of warming; Schoengart et al., 2025). Whether recovery occurs depends on whether systems and communities remain below their adaptive capacity threshold (dash-dot), above which cumulative impacts block recovery through threshold-crossing, lock-in, or non-substitutability. A vulnerable system or community (darkest green) is driven above the threshold and, once crossed, cannot recover even as conditions improve: the permanent overshoot legacy (e.g. climate-related excess mortality and permanent livelihood collapse under repeated drought; Schleussner et al., 2024). The adaptive capacity threshold is itself dynamic: where cumulative climate impacts outpace development gains, financial and institutional resources are depleted and the threshold erodes during the overshoot period (O’Neill et al., 2022; Schleussner et al., 2021).

Throughout this paper, biophysical *changes* are classified as *reversible* (tracking temperature decline, whether fully or partially) or *persistent* (not reversing on policy-relevant timescales). Socioeconomic *impacts* are classified as *reversible* (full or partial recovery is possible given improved conditions and resources) or *irreversible* (no recovery). Full or no recovery are endpoints of a continuum: the four archetypes in Figure 1 illustrate that partial recovery and delayed recovery occupy intermediate positions in both layers, and that the timescale of any recovery determines for whom it is meaningful.

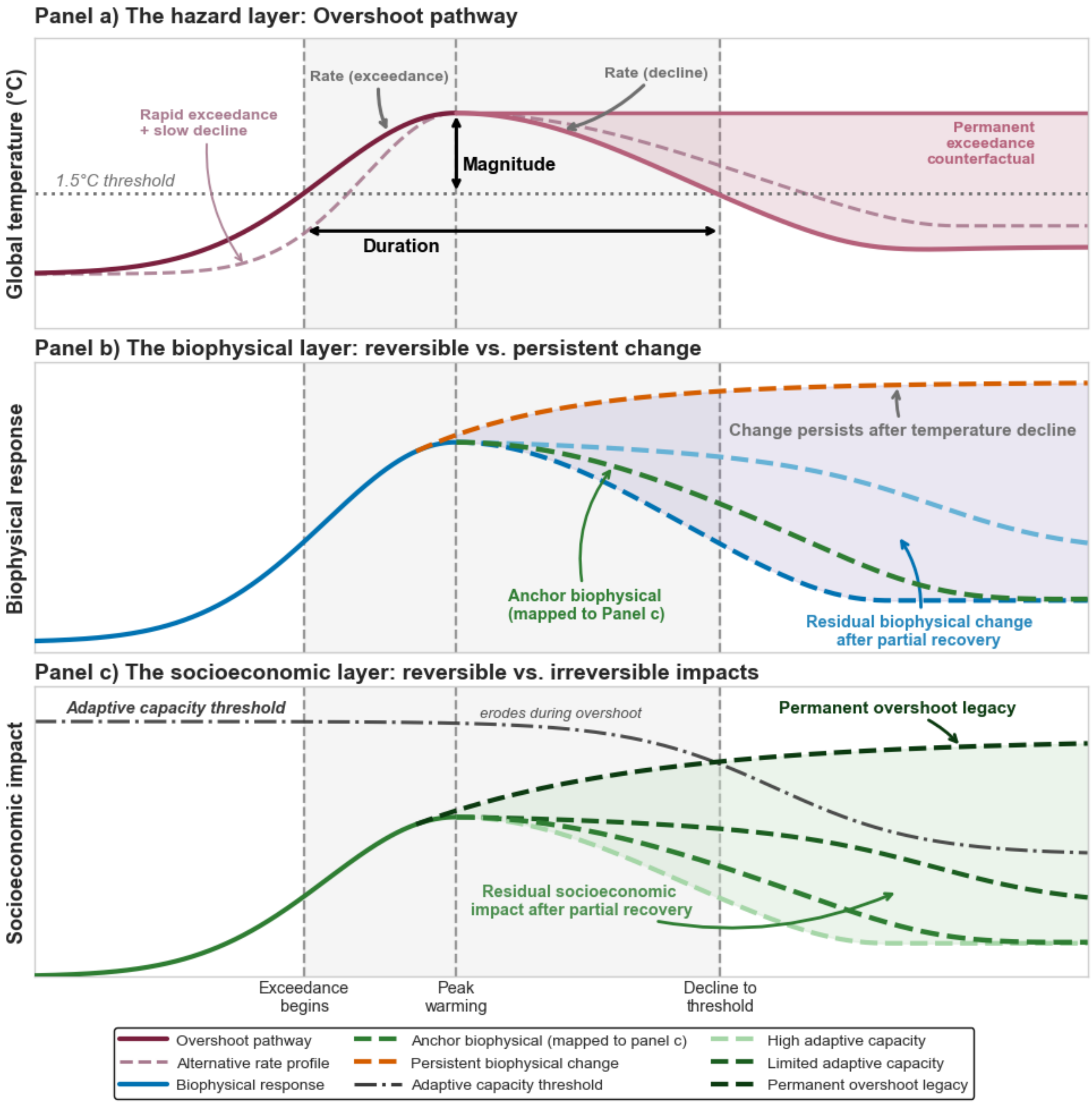

Figure 1. *Stylised three-layer framework for assessing overshoot consequences. All curves are illustrative and not derived from empirical data or model output. Panel (a) the hazard layer: the overshoot pathway characterised by magnitude, duration, rate of exceedance, and rate of decline. A permanent-exceedance counterfactual (horizontal stabilisation at peak) is shown; the fill between trajectories represents the cumulative forcing avoided. An alternative rate profile (dashed) shares the same peak magnitude and peak year, illustrating that rate dimensions vary independently of peak exceedance. Panel (b) the biophysical layer: four post-peak response archetypes. A fast-recovering response tracks temperature decline; two intermediate pathways recover (partially or fully) with progressively greater lag (the anchor biophysical, in green, is carried into Panel (c) as the biophysical forcing shared by all four socioeconomic archetypes); a persistent change*

continues intensifying. The shaded envelope captures the residual biophysical change. Panel (c) the socioeconomic layer: four divergent responses to the same anchor biophysical change under differing adaptive capacities (high, mid, limited), and permanent overshoot legacy. The adaptive capacity threshold (dash-dot) erodes monotonically during the overshoot period as cumulative impacts deplete coping resources. Vertical dashed lines align exceedance onset, peak warming, and return-to-threshold milestones in the overshoot pathway and extend across the three panels, linking the cascade.

3. From hazard to biophysical response

3.1 Characterising the overshoot hazard

The four overshoot dimensions shape biophysical and socioeconomic outcomes through distinct impact signatures. Magnitude determines whether critical thresholds are crossed in biophysical systems (e.g. coral bleaching above ~1.5°C) and socioeconomic ones (e.g. infrastructure failure beyond design tolerances). Duration governs cumulative exposure and determines whether systems and communities are pushed beyond their recovery capacity or commitment threshold. Rate of exceedance compresses the time available for ecological range shifts and institutional adaptation; rapid warming can push systems across thresholds they might otherwise avoid under gradual change. Rate of decline shapes post-peak divergence from peak-phase conditions: for most systems, decline first manifests as reduced frequency of record-breaking extremes (Schleussner et al., 2024), though non-linear responses such as reduced meltwater runoff during glacier regrowth (Schuster et al., 2025) can introduce hazards absent from the warming phase.

The *overshoot pathway integral*, the time-integrated temperature exceedance in degree-years, aggregates magnitude and duration into a single measure of cumulative exposure. It is informative for systems whose long-term state depends on cumulative thermal exposure: permafrost extent and deep ocean heat content scale approximately linearly with degree-years (Ritchie et al., 2026). For threshold-dependent systems, peak magnitude matters more: coral reef collapse is driven primarily by whether peak warming exceeds ~1.5°C (Schleussner et al., 2024; Armstrong McKay et al., 2022). Two trajectories with identical degree-years but different temporal profiles will produce different impacts on rate-sensitive systems. A complete hazard characterisation therefore requires the overshoot integral supplemented by the individual dimensions.

3.2. The biophysical response: reversible and persistent change

Climate system changes affect human systems through climatic impact-drivers (CIDs): physical conditions such as extreme heat, altered precipitation, or sea-level rise that interface Earth system processes with human systems (Ranasinghe et al., 2021; Appendix I lists the full CID set). Under an overshoot pathway, the critical question is which CIDs reverse when temperature declines and which persist. Some CIDs such as mean precipitation largely track temperature and may recover fully, while others such as regional temperature extremes and heatwave intensity recover only partially (Pfleiderer et al., 2024; Roldán-Gómez et al., 2025).

Persistent biophysical responses, those that do not reverse on policy-relevant timescales, arise through two broad mechanisms. The first is *threshold behaviour and hysteresis*: the system crosses a critical boundary into a self-sustaining alternative state, from which reversal is not possible on policy-relevant timescales even if pre-crossing greenhouse gas concentrations are restored. This mechanism can underlie tipping element behaviour, which additionally requires self-reinforcing change, abruptness, and large-scale consequences (Hegerl et al., in preparation): threshold behaviour is necessary but not sufficient. Warm-water coral reefs face functional collapse above approximately 1.5°C, with the rate of warming influencing bleaching severity and recovery between events (Schleussner et al., 2024). Ice sheets exhibit hysteresis: the Greenland ice sheet may not regrow even if temperatures decline below the threshold at which loss was initiated (Bochow et al., 2023). The probability of tipping cascades increases with both magnitude and duration of overshoot (Wunderling et al., 2024).

The second mechanism is *physical inertia and commitment*: slow processes set in motion cannot be halted by temperature decline alone. Sea-level rise continues for centuries after peak warming as thermal expansion and committed ice sheet loss proceed; declining temperature slows the rate but does not reverse it (Mengel et al., 2018). Permafrost thaw releases carbon stocks on centennial timescales and is effectively irreversible under any plausible scenario (de Vrese and Brovkin, 2021). Table 1 summarises these mechanisms.

Table 1. Persistent biophysical responses: mechanisms and overshoot dimensions.

Mechanism	**Primary overshoot dimensions**	**Metric**	**Examples**
Threshold behaviour and hysteresis	Magnitude	Peak exceedance	Coral reef collapse; ice sheet loss; tipping cascades[1]
Physical inertia and commitment	Cumulative exposure	Degree-years	Sea-level rise; glacier mass loss; permafrost thaw

The boundary between reversible and persistent is not fixed: what begins as a partially reversible response may become persistent if the overshoot dimensions are more severe. A brief exceedance may allow glacier recovery, but sustained warming converts partial mass loss into irreversible collapse (Schuster et al., 2025). Rapid exceedance can push systems and communities across thresholds they might otherwise avoid under gradual warming, while rapid decline creates distinct stresses on systems and communities that have adjusted to warmer conditions. Under the permanent exceedance counterfactual, more of these boundaries would

---

[1] Also, sensitive to cumulative exposure (degree-years); see Wunderling et al. (2024).

be crossed and a larger share would become effectively irreversible; the decline phase preserves recovery potential for systems and communities not yet past their thresholds and slows the accumulation of irreversible change in those that are.

4. From biophysical response to committed socioeconomic impacts

4.1 Mechanisms of socioeconomic irreversibility

The same climatic impact-driver, whether reversible or persistent, can produce reversible or irreversible socioeconomic impacts depending on the interplay of the determinants of risk: hazard, exposure, and vulnerability (Simpson et al., 2021). More recent approaches, particularly in the overshoot context, add responses (adaptation and mitigation actions) as a fourth determinant (Reisinger et al., 2025). Under an overshoot pathway, these determinants shift with the trajectory itself, as compounding constraints can convert soft adaptation limits into hard ones (Theokritoff et al., 2023). Climate impacts during the exceedance phase erode the financial and institutional resources that would otherwise enable adaptation, particularly in low- and middle-income countries (O’Neill et al., 2022), converting risks that might have been manageable into irreversible outcomes. The speed of conversion varies: systems and communities with deeper financial reserves or stronger institutional buffers face more delayed erosion of adaptive capacity than those already near their coping limits. What constitutes irreversibility is also not uniform across populations: a socioeconomic impact that reverses over decades is effectively irreversible for the generation that experiences it (Thiery et al., 2021).

The likelihood that a given socioeconomic impact crosses into irreversibility increases with overshoot severity and decreases with adaptive capacity. The same overshoot pathway therefore produces different outcomes across systems and communities of differing adaptive capacity. We formalise this irreversibility boundary as the *socioeconomic commitment threshold*: the point beyond which the cumulative effects of overshoot commit socioeconomic impacts that persist after temperatures decline. The threshold is an adaptation limit that is endogenous to the overshoot trajectory: as adaptation effectiveness decreases with warming (O'Neill et al., 2022), the exceedance phase simultaneously increases the hazard and narrows the range of effective responses, shifting the threshold under the cumulative stress it is meant to resist.

Under permanent exceedance, every system with finite adaptive capacity eventually crosses this threshold; the decline phase matters not because it reverses losses already committed but because it halts the stressor before further thresholds are crossed. The result is *committed socioeconomic impacts*, analogous to committed warming or committed sea-level rise in the physical climate system, but governed by three distinct socioeconomic mechanisms described below. Committed socioeconomic impacts constitute the irreversible component of losses and damages (Mechler et al., 2019) arising under overshoot pathways.[2]

Figure 2 represents this threshold as a function of overshoot intensity, a stylised composite of the dimensions in Section 3.1. The likelihood of crossing the socioeconomic commitment threshold (y-axis) increases with overshoot intensity (x-axis). Three S-curves represent systems and communities with high, medium, and low adaptive capacity: at any given overshoot intensity, lower adaptive capacity entails a higher likelihood of irreversible impacts. The S-shape is consistent with empirical damage functions reported in crop-yield, mortality, and growth-rate studies (e.g. Hultgren et al., 2025; Schoengart et al., 2025). The curves assume that adaptive capacity is mobilised; in practice, a well-documented capacity-action gap means available capacity may not translate into effective adaptation (Schubert et al., 2025), and the threshold may be crossed at lower overshoot intensities than the curves imply. The dashed curve illustrates a feedback: adaptive capacity is not static during overshoot but is shaped by whether adaptation is implemented and sustained at the pace of the evolving hazard. Where cumulative climate impacts outpace socioeconomic development, adaptive capacity erodes and the medium-capacity curve shifts leftward toward the low-capacity one. This reflects the accumulation of residual risk (the risk remaining after adaptation efforts; O'Neill et al., 2022), which compounds during the exceedance phase and may drive systems and communities across the socioeconomic commitment threshold.

---

[2] Throughout this paper, 'losses and damages' (lowercase) denotes the impact phenomenon, adverse climate consequences not avoided through mitigation or adaptation, while 'Loss and Damage' (capitalised) denotes the UNFCCC policy architecture. Within losses and damages, we distinguish losses (non-recoverable, non-compensable) from damages (recoverable or compensable); committed socioeconomic impacts as defined here correspond to the losses arising under overshoot pathways.

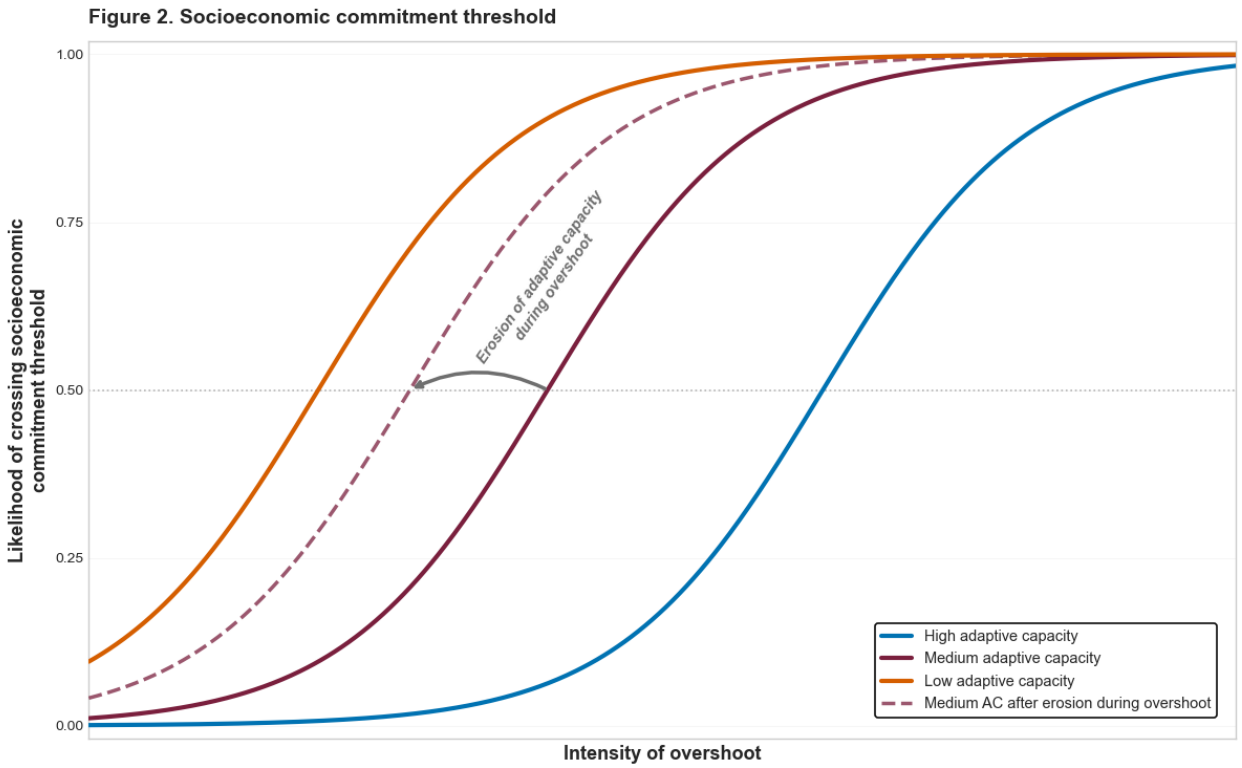

Figure 2. Socioeconomic commitment threshold

Figure 2. *Socioeconomic commitment threshold as a function of overshoot intensity. The likelihood of crossing the threshold (y-axis) increases with overshoot intensity (x-axis) and decreases with adaptive capacity. Three illustrative S-curves represent systems and communities with high (blue), medium (burgundy), and low (orange) adaptive capacity. The dashed curve shows how the medium-capacity curve shifts leftward where cumulative climate impacts erode adaptive capacity during the overshoot period. Curve positions, slopes, and separations are illustrative of qualitative behaviour, not a specific parameterisation.*

Three socioeconomic mechanisms govern whether overshoot stress crosses the commitment threshold: non-substitutability, threshold-crossing, and lock-in. They map onto the hard and soft adaptation limits framework (Dow et al., 2013; IPCC, 2022, Annex II; Thomas et al., 2021). Non-substitutability corresponds to a hard limit: no adaptive action can avert loss of life, species extinction, or cultural loss. Threshold-crossing describes the conversion of soft limits, where options remain but are constrained, into hard limits under cumulative overshoot stress (Theokritoff et al., 2023). Lock-in identifies an overshoot-specific source of limits, where otherwise reversible impacts become bounded by path dependencies generated during the exceedance phase. All three mechanisms can be activated by reversible as well as persistent biophysical changes.

- *Non-substitutability* characterises losses that cannot be compensated by economic recovery or restored by improved conditions, regardless of adaptive capacity. The magnitude of overshoot is the primary dimension: any single event exceeding a lethal or destructive threshold produces irreversible loss (Schleussner et al., 2024; Urban, 2024; Chen et al., 2025). Duration compounds losses through repeated events, but the defining feature of this mechanism is that irreversibility does not require the erosion of adaptive capacity: a single event is sufficient.

- *Threshold-crossing* occurs when acute or cumulative shocks exhaust the coping capacity of a socioeconomic system, pushing it past the point of recovery with available resources. Unlike non-substitutability, the loss is not inherent in what is damaged but contingent on whether the affected system retains sufficient resources to recover. The primary driver is overshoot magnitude relative to adaptive capacity, compounded by duration where repeated shocks prevent inter-event recovery (Hultgren et al., 2025; Schleussner et al., 2024). Rate of exceedance modulates the outcome by compressing the time available for adaptation between shocks.

- *Lock-in* occurs when physical, economic, institutional, or behavioural reconfiguration during the exceedance phase creates barriers that prevent reversal even after conditions improve. Duration is the primary dimension: the longer the exceedance phase, the deeper the reconfiguration and the higher the reversal barriers. Hard or grey infrastructure illustrates the mechanism clearly: coastal defences, water supply systems, and urban flood protection are sized to peak-phase hazards with multi-decadal design lives, and each investment raises the cost of switching back. The same logic applies to crop portfolios, design standards, retrofitting, land tenure arrangements, and settlement patterns, all of which adjust to peak-phase conditions (IDMC, 2025; O’Neill et al., 2022). At household level, lock-in operates through behavioural adaptation, such as cooling infrastructure that will not be removed even if temperatures decline.

The severity of lock-in scales with the duration of the exceedance phase and the extent of physical reconfiguration undertaken in response to peak conditions. For tight, within-century overshoots where peak warming is clustered within a few tenths of a degree, much adaptation will be neither precisely tailored to peak conditions nor a source of dominant reversal barriers on the way down; threshold-crossing and non-substitutability are likely the stronger mechanisms here. Lock-in becomes dominant for overshoots that do not reverse within-century, for hard/grey infrastructure with multi-decadal design lives, and for household-level behavioural adaptation such as cooling infrastructure installed for peak conditions. Lock-in under an overshoot pathway is distinct from maladaptation (IPCC, 2022, Annex II) in that it can result from well-designed adaptation to peak-phase conditions: the adaptation is appropriate when implemented but creates reversal barriers when conditions change. Overcoming lock-in during the decline phase may require systemic reconfiguration of the kind discussed in the transformative adaptation literature (Fedele et al., 2019); the overshoot framing adds a temporal dimension that makes the depth of lock-in trajectory-dependent.

Table 2 maps these three mechanisms to specific examples, identifying for each the primary and modulating overshoot dimensions, the biophysical driver type (reversible or persistent), and the pathway through which recovery is blocked. The biophysical driver column shows that each mechanism can be activated by reversible as well as persistent change; the modulating dimensions column shows that overshoot dimensions are not exclusive to single mechanisms.

Table 2. Mechanisms of socioeconomic irreversibility: examples, overshoot dimensions, and recovery barriers

Mechanism	Example of impact	Primary overshoot dimension(s)	Modulating overshoot dimension(s)	Biophysical driver type	Why recovery is blocked
Non-substitutability	Loss of life from heat extremes, flooding, and climate-related disease (Schleussner et al., 2024)	Magnitude (any event exceeding lethal threshold)	Duration (cumulative mortality from repeated events)	Reversible (heat extremes) or persistent	Loss is inherently irreversible; no substitute exists
	Species extinction eliminates ecosystem services underpinning livelihoods (Urban, 2024; Meyer et al., 2022)	Magnitude and duration (permanent habitat degradation)	Rate of exceedance (compresses species' range-shift capacity)	Reversible or persistent	Extinction is permanent; services cannot be reconstituted in full
	Loss of cultural heritage, place-based identity, and traditional food systems; (Chen, Z. et al., 2025; O'Neill et al., 2022)	Magnitude (destruction of physical or social substrate)	Duration (prolonged disruption severs intergenerational transmission)	Reversible or persistent	No economic substitute; loss is inherent in the nature of what is valued
Threshold crossing	Successive crop failures deplete household assets and seed stocks, forcing permanent land	Magnitude and duration (repeated shocks exceeding coping capacity)	Rate of exceedance (compresses adaptation time between shocks)	Reversible (heat extremes, precipitation shifts)	Coping resources exhausted; no capital base for re-entry

	abandonment (Hultgren, A. et al., 2025; Schleussner et al., (2024)				
	Climate-driven infrastructure failure; indirect costs compound direct damage (Karagiannakis et al., 2024)	Magnitude and duration (exceeds design tolerances; repeated failures compound losses)	Rate of exceedance (compresses repair and rebuilding windows)	Reversible or persistent	Economic base for reconstruction eroded
Lock-in	Permanent displacement from sustained drought or repeated flooding; livelihoods collapse, land tenure reassigned, social networks dissolve (IDMC, 2025)	Duration and magnitude (sustained stress drives reconfiguration)	Rate of exceedance (compresses window for planned relocation)	Reversible or persistent	Demographic, legal, and social structures reconfigured; return barriers too high
	Involuntary immobility; exceedance phase depletes resources needed for relocation (O'Neill et al., 2022)	Duration (progressive resource depletion)	Magnitude (severity of conditions in place)	Reversible or persistent	Resources for autonomous adaptation or relocation exhausted; populations trapped
	Coastal settlement abandonment under committed SLR;	Magnitude	Duration (continued SLR commitment extends exposure)	Persistent	Physical conditions do not reverse; sunk costs lock in spatial configuration

	infrastructure path dependencies prevent flexible reallocation (Mengel et al., 2018)				

4.2 Typology of overshoot socioeconomic outcomes

The three mechanisms produce qualitatively different outcomes depending on whether the underlying biophysical change is reversible or persistent. Table 3 cross-tabulates biophysical change with socioeconomic impacts to yield a four-cell typology of overshoot outcome, formalising the dynamics in Figures 1b and 1c.

Two quadrants in Table 3 merit particular attention because they challenge the implicit assumption that biophysical reversibility implies socioeconomic reversibility. The bottom-left quadrant, socioeconomic overshoot legacy, captures the paper’s central thesis: that a reversible biophysical change can trigger permanent socioeconomic loss. The examples developed in Table 2 (successive crop failures triggering livelihood collapse, excess heat mortality) all fall here when the underlying biophysical driver is reversible. What defines this quadrant is not the persistence of the hazard but the crossing of the socioeconomic commitment threshold: in Figure 2, it corresponds to systems and communities that have crossed the threshold at a given overshoot intensity, regardless of whether the biophysical driver subsequently reverses.

The top-right quadrant, permanent adaptation challenge, captures the converse: persistent biophysical change need not produce irreversible socioeconomic loss, provided the affected system has sufficient adaptive capacity to sustain a permanent reconfiguration. In principle, managed retreat from committed sea-level rise in a well-resourced coastal city could illustrate this, though successful cases at scale remain rare (Hanna et al., 2019). This quadrant is available only to high-capacity systems and communities, mapping directly onto existing inequalities. The same persistent biophysical change that constitutes a permanent adaptation challenge for a wealthy city constitutes existential loss (bottom-right quadrant) for a low-lying small island state with no alternative for retreat, or for glacier-dependent communities with no alternative water source. This asymmetry is not incidental to the framework; it is its core implication: overshoot does not distribute its permanent legacies uniformly, and the determinants of which quadrant a system or community occupies are primarily socioeconomic rather than biophysical.

Both bottom-row quadrants produce irreversible losses and damages, but they differ in cause and therefore in the policy interventions that could have prevented them. The bottom-left quadrant (socioeconomic legacy) reflects a failure of adaptation under conditions that were biophysically recoverable, and is governed by the socioeconomic commitment threshold. The bottom-right quadrant (existential loss) reflects a failure of mitigation efforts that could have avoided triggering these biophysical conditions. The distinction matters for attributing responsibility and for the design of policy responses, which cluster on mitigation, adaptation, and Loss and Damage instruments respectively.

Table 3. Typology of overshoot socioeconomic outcomes: biophysical persistence and socioeconomic irreversibility

	Reversible biophysical changes	**Persistent biophysical changes**
Reversible socioeconomic impacts	**Temporary adaptation challenge.** The system endures stress during the exceedance phase but recovers as conditions improve, owing to sufficient adaptive capacity. Examples: heat mortality management through early-warning systems; crop stress absorbed through varietal switching where financial and institutional capacity permits. In principle, adaptation to peak conditions could leave systems with more robust infrastructure post-overshoot than before; realisation of this requires capacity, foresight, and institutional continuity that are themselves concentrated in already-advantaged contexts.	**Permanent adaptation challenge.** The biophysical state is permanently altered, but the system adapts to maintain functionality through sustained reconfiguration. Available only to high-capacity systems and communities; the same persistent change constitutes existential loss where resources for sustained reconfiguration are absent. Example: managed retreat from committed sea-level rise in well-resourced settings.

Irreversible socioeconomic impacts	**Socioeconomic legacy.** The system crosses its adaptive capacity threshold, and losses are inherently non-recoverable, even as the biophysical change recedes. This is the defining quadrant for the socioeconomic commitment threshold. Examples: livelihood collapse from repeated drought; excess heat mortality.	**Existential loss**. The biophysical environment is permanently altered beyond all adaptation limits. Examples: small island states facing permanent coastal flooding; glacier loss permanently eliminating meltwater supply for downstream communities; coral reef collapse removing the ecological and economic base of dependent communities.

5. Concluding remarks

An overshoot pathway leaves lasting legacies that temperature decline alone cannot erase: higher sea levels, diminished glaciers, lost species, permanent changes to coastal communities, and severe impacts on livelihoods. The decline phase will initially manifest as reduced frequency of record and non-record-breaking extremes, but non-linear responses introduce distinct hazards absent from the exceedance phase: reduced meltwater runoff during glacier regrowth lags declining temperature by decades (Schuster et al., 2025; Jóhannesson et al., 1989), and retained ocean heat generates novel hydrological conditions (Marshall et al., 2025). The permanent exceedance counterfactual produces strictly worse outcomes: for every system not yet past the socioeconomic commitment threshold, each degree-year of avoided overshoot preserves recovery potential and prevents further losses.

The feasibility of sustained temperature decline is the first-order uncertainty in any overshoot pathway (Figure 1a). Decline depends on sustained CDR at scale (Smith et al., 2024), yet the financial, institutional, and governance resources required for CDR are precisely those eroded by the overshoot itself. Land competition intensifies as displaced populations require resettlement and degraded agricultural systems require restoration. A substantial share of national climate pledges risks over-reliance on land-based CDR (Dooley et al., 2024), with land requirements estimated at around one billion hectares, comparable to current global cropland area (Land Gap, 2025). This raises major feasibility concerns and risks overstepping multiple planetary boundaries (Prütz et al., 2026; Deprez et al., 2024). Distributional consequences compound this: the post-2050 CDR burden, land-use implications, and opportunity costs of diverted finance fall disproportionately on regions already bearing the brunt of overshoot impacts (Pelz et al., 2025), and due-diligence obligations under international law may constrain state reliance on CDR (Rajamani et al., 2026). The result is a feasibility feedback loop running backwards through the three-layer cascade: the more severe the overshoot, the greater the irreversible socioeconomic losses, the fewer the resources for CDR, and the longer the decline phase, which further raises the probability of crossing further irreversibility thresholds.

Second-order uncertainties concern the layers through which the trajectory translates into outcomes (Figures 1b, 1c). The boundary between reversible and persistent biophysical change is state-dependent: recovery capacity depends on initial conditions, rate of exceedance, and interactions between slow Earth system processes (Roldán-Gómez et al., 2025; Pfleiderer et al., 2024). Threshold behaviour, such as in ice sheets and coral reefs, introduces poorly constrained discontinuities (Armstrong McKay et al., 2022; Wunderling et al., 2024). Overshoot will also interact with biodiversity loss, resource depletion, and conflict in ways that are poorly understood but could amplify irreversibility by further eroding adaptive capacity. The socioeconomic commitment threshold is governed by adaptive capacity, which is itself dynamic: vulnerability, governance, and financial reserves shift during overshoot (Serdeczny et al., 2024; Andrijevic et al., 2023), and the three mechanisms interact in context-specific ways. The S-curves in Figure 2 are therefore conceptual, not predictive, and subject to deep uncertainty on both axes.

Committed socioeconomic impacts as defined here correspond to the irreversible component of losses and damages: the losses arising under overshoot pathways, as distinct from damages that can be recovered or compensated. The framework contributes to the Loss and Damage architecture in three ways: it identifies the mechanisms through which harms become non-recoverable, formalises the conditions under which temporary exceedance crosses into irreversibility, and exposes a governance gap. Declining temperature may be read as evidence the crisis is resolving even as the distribution of permanent harm worsens: political will for sustained CDR investment and Loss and Damage finance in high-emitting nations may weaken precisely as irreversible legacies accumulate in vulnerable regions. Because these losses fall predominantly where historical responsibility is lowest (Ganti et al., 2026), their recognition bears on attribution questions central to Loss and Damage policy. Overshoot governance must therefore integrate Loss and Damage mechanisms with adaptation investment and CDR deployment, rather than treating them as separate policy tracks.

The distribution of overshoot's permanent legacies is not uniform but structured by existing inequalities. Low-income, climate-vulnerable countries face higher risks of irreversible impacts through lower adaptive capacity; within countries, marginalised communities bear disproportionate risk. The framework's core implication, that which quadrant a system occupies in Table 3 is determined primarily by socioeconomic rather than biophysical factors, means overshoot concentrates its permanent costs among the populations least responsible for the emissions that produced it. This inequity has a temporal dimension: some cohorts will experience the elevated impacts of the exceedance phase without benefiting from decline-phase improvements within their lifetimes, creating a distinct form of intergenerational injustice (Thiery et al., 2021).

The three-layer framework, the commitment threshold, and the typology identify where, for whom, and through what mechanisms temporary exceedance produces permanent harm. Applying the typology across the Representative Key Risks assessed in IPCC AR6 WGII (O'Neill et al., 2022; Appendix II) would test its generalisability, revealing where irreversibility mechanisms compound and where adaptive capacity determines the quadrant in which a given biophysical change lands. This requires impact modelling under overshoot scenarios and empirical characterisation of adaptive capacity. Future work should also calibrate the commitment threshold for specific systems and communities, and quantify the feasibility feedback loop between overshoot severity and CDR capacity. The framework assumes a stylised trajectory with well-defined phases. In practice, internal climate variability may amplify or obscure the overshoot signal at regional scales, particularly where magnitude is limited. The three mechanisms, however, operate under any warming trajectory producing cumulative stress, and the commitment threshold can be crossed under noisy, non-monotonic paths.

For many systems and communities, returning temperatures to 1.5°C after overshoot will not return conditions to an equivalent state: losses committed during the exceedance phase persist. The primary policy imperative remains minimising peak warming through rapid near-term emissions reductions, because every degree-year of avoided overshoot reduces the probability of crossing socioeconomic commitment thresholds. Post-peak decline is a necessary but insufficient second imperative: each degree-year of avoided overshoot preserves recovery potential for systems and communities not yet past their thresholds.

Author contributions

A.A.K. led the study conceptualisation, developed the analytical framework, produced the figures, and wrote the original draft. E.B., A.P., C.-F.S., and R.S.-S. contributed to conceptualisation and analytical framework development. M.A., E.B., M.P., A.P., C.-F.S., and R.S.-S. contributed to reviewing successive drafts and figures.

Funding

A.A.K. was supported by the European Union’s Horizon Europe research and innovation programme under Grant Agreement No. 101081179 (DIAMOND).

E.B. was supported by the European Union’s Horizon Europe research and innovation programme under Grant Agreement No. 101081369 (SPARCCLE).

R.F.S.-S. acknowledges funding from the Quadrature Climate Foundation and the Wellcome Trust Grant No. 309112/Z/24/Z (TACTIC).

Code availability

The code underlying the figures will be made publicly available on GitHub upon publication: https://github.com/AlKhourdajie/[...]

References

1. Bevacqua, E., Schleussner, CF. & Zscheischler, J. A year above 1.5 °C signals that Earth is most probably within the 20-year period that will reach the Paris Agreement limit. Nat. Clim. Chang. 15, 262–265 (2025). https://doi.org/10.1038/s41558-025-02246-9

2. World Meteorological Organization (WMO). State of the Global Climate 2025. (WMO-No. 1342). Geneva, 2026. ISBN: 978-92-63-1129

3. Forster, P.M., C. Smith, T. Walsh, et al. (2025). ‘Indicators of Global Climate Change 2024: annual update of key indicators of the state of the climate system and human influence.’ Earth System Science Data, 17, 2641. https://doi.org/10.5194/essd-17-2641-2025

4. Foster, G. and S. Rahmstorf (2026) 'Global Warming Has Accelerated Significantly.' Geophysical Research Letters. https://doi.org/10.1029/2025GL118804

5. United Nations Environment Programme (2025). Emissions Gap Report 2025: Off target – Continued collective inaction puts global temperature goal at risk [Olhoff, A., chief editor; Lamb, W.; Kuramochi, T.; Rogelj, J.; den Elzen, M.; Christensen, J.; Fransen, T.; Pathak, M.; Tong, D. (eds)]. Nairobi. https://doi.org/10.59117/20.500.11822/48854.

6. Reisinger, A., J.S. Fuglestvedt, A. Pirani, et al. (2025). ‘Overshoot: A conceptual review of exceeding and returning to global warming of 1.5°C.’ Annual Review of Environment and Resources, 50, 185–217. https://doi.org/10.1146/annurev-environ-111523-102029

7. Roldán-Gómez, P. J., De Luca, P., Bernardello, R., and Donat, M. G.: Regional irreversibility of mean and extreme surface air temperature and precipitation in CMIP6 overshoot scenarios associated with interhemispheric temperature asymmetries, Earth Syst. Dynam., 16, 1–27, https://doi.org/10.5194/esd-16-1-2025, 2025

8. Pfleiderer, P., C.-F. Schleussner & J. Sillmann. (2024). ‘Limited reversal of regional climate signals in overshoot scenarios.’ Environmental Research: Climate, 3(1), 015005. https://doi.org/10.1088/2752-5295/ad1c45

9. Schleussner, CF., Ganti, G., Lejeune, Q. et al. Overconfidence in climate overshoot. Nature 634, 366–373 (2024). https://doi.org/10.1038/s41586-024-08020-9

10. Yang, YM., Shin, J., Park, JH. et al. Reduced mid-latitude El Niño-related precipitation due to southern ocean warming under abrupt CO2 change scenarios. Clim Dyn 64, 3 (2026). https://doi.org/10.1007/s00382-025-07944-w

11. Chimuka, V. R., and K. Zickfeld. (2026). 'Asymmetry in carbon cycle feedbacks and transient climate response under positive and negative CO2 emissions.' EGUsphere [preprint]. https://doi.org/10.5194/egusphere-2025-6405

12. Zickfeld, K., Azevedo, D., Mathesius, S. et al. Asymmetry in the climate–carbon cycle response to positive and negative CO2 emissions. Nat. Clim. Chang. 11, 613–617 (2021). https://doi.org/10.1038/s41558-021-01061-2

13. UNFCCC. (2025). 'Global Mutirão: Uniting humanity in a global mobilization against climate change (draft decision).' Conference of the Parties Serving as the Meeting of the Parties to the Paris Agreement on Its Seventh Session, Held in Belém from 10 to 21 November 2025. Retrieved April 14, 2026, from https://unfccc.int/sites/default/files/resource/cma2025_L24_adv.pdf

14. Marshall, A., E. Grubert and S. Warix (2025) 'Temperature Overshoot Would Have Lasting Impacts on Hydrology and Water Resources.' *Water Resources Research*. https://doi.org/10.1029/2024WR037950

15. Meyer, A. L. S., J. Bentley, R. C. Odoulami, A. L. Pigot and C. H. Trisos (2022) 'Risks to biodiversity from temperature overshoot pathways.' Philosophical Transactions of the Royal Society B: Biological Sciences, 377(1857), 20210394. https://doi.org/10.1098/rstb.2021.0394

16. Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu, 2021: Ocean, Cryosphere and Sea Level Change. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362, doi:10.1017/9781009157896.011.

17. Mengel, M., Nauels, A., Rogelj, J. et al. Committed sea-level rise under the Paris Agreement and the legacy of delayed mitigation action. Nat Commun 9, 601 (2018). https://doi.org/10.1038/s41467-018-02985-8

18. Schuster, L., Maussion, F., Rounce, D.R. et al. Irreversible glacier change and trough water for centuries after overshooting 1.5 °C. Nat. Clim. Chang. 15, 634–641 (2025). https://doi.org/10.1038/s41558-025-02318-w

19. Fouillet, A., G Rey, V Wagner, K Laaidi, P Empereur-Bissonnet, A Le Tertre, P Frayssinet, P Bessemoulin, F Laurent, P De Crouy-Chanel, E Jougla, and D Hémon (2008). ‘Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave.’ International Journal of Epidemiology, 37(2), 309–317. https://doi.org/10.1093/ije/dym253

20. Schoengart, S., M Schwarz, J Schwaab, F Pretis, P Peiderer, and C-F Schleussner (2025). ‘Temporary warming, lasting losses: Economic damages from climate overshoot may be irreversible within this century.’ Research Square (preprint). https://doi.org/10.21203/rs.3.rs-7241437/v1

21. O’Neill, B., M. van Aalst, Z. Zaiton Ibrahim, L. Berrang Ford, S. Bhadwal, H. Buhaug, D. Diaz, K. Frieler, M. Garschagen, A. Magnan, G. Midgley, A. Mirzabaev, A. Thomas, and

R. Warren, 2022: Key Risks Across Sectors and Regions. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2411–2538, doi:10.1017/9781009325844.025.

22. Schleussner, C.-F., P. Pfleiderer, M. Andrijevic, M. M. Vogel, F. E. L. Otto, and S. I. Seneviratne. (2021). 'Pathways of climate resilience over the 21st century.' Environmental Research Letters 16(5). https://doi.org/10.1088/1748-9326/abed79

23. Ritchie, P. D. L., N. J. Steinert, J. F. Abrams, H. Alkhayuon, C. W. Arnscheidt, N. Bochow, R. R. Chapman, J. Clarke, D. P. Dennis and J. F. Donges (2026) ‘The implications of overshooting 1.5°C on Earth system tipping elements - a review.’ Environmental Research Letters, 21(4), 043001. https://doi.org/10.1088/1748-9326/ae3cad

24. Armstrong McKay, D. I., A. Staal, J. F. Abrams, R. Winkelmann, B. Sakschewski, S. Loriani, I. Fetzer, S. E. Cornell, J. Rockström and T. M. Lenton (2022) 'Exceeding 1.5°C global warming could trigger multiple climate tipping points.' *Science*, 377(6611). https://doi.org/10.1126/science.abn7950

25. Ranasinghe, R., A.C. Ruane, R. Vautard, N. Arnell, E. Coppola, F.A. Cruz, S. Dessai, A.S. Islam, M. Rahimi, D. Ruiz Carrascal, J. Sillmann, M.B. Sylla, C. Tebaldi, W. Wang, and R. Zaaboul, 2021: Climate Change Information for Regional Impact and for Risk Assessment. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson- Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1767–1926, doi:10.1017/9781009157896.014

26. Hegerl, G., et al. (in preparation). High impact events, tipping points, and irreversible regional impact. Manuscript in preparation for *Reviews of Geophysics*. Assessment is led by World Climate Research Programme (WCRP).

27. Bochow, N., Poltronieri, A., Robinson, A. *et al.* Author Correction: Overshooting the critical threshold for the Greenland ice sheet. *Nature* 623, E18 (2023). https://doi.org/10.1038/s41586-023-06852-5

28. Wunderling, N., A. S. von der Heydt, Y. Aksenov, S. Barker, R. Bastiaansen, V. Brovkin, M. Brunetti, V. Couplet, T. Kleinen, C. H. Lear, J. Lohmann, R. M. Roman-Cuesta, S. Sinet, D. Swingedouw, R. Winkelmann, P. Anand, J. Barichivich, S. Bathiany, M. Baudena, J. T. Bruun, C. M. Chiessi, H. K. Coxall, D. Docquier, J. F. Donges, S. K. J. Falkena, A. K. Klose, D. Obura, J. Rocha, S. Rynders, N. J. Steinert and M. Willeit (2024) 'Climate tipping point interactions and cascades: a review.' *Earth System Dynamics*, 15(1), pp. 41–74. https://doi.org/10.5194/esd-15-41-2024

29. de Vrese, P., Brovkin, V. Timescales of the permafrost carbon cycle and legacy effects of temperature overshoot scenarios. Nat Commun 12, 2688 (2021). https://doi.org/10.1038/s41467-021-23010-5

30. Simpson, N. P., K. J. Mach, A. Constable, J. Hess, R. Hogarth, M. Howden, J. Lawrence, R. J. Lempert, V. Muccione, B. Mackey, M. G. New, B. O'Neill, F. Otto, H.-O. Pörtner, A. Reisinger, D. Roberts, D. N. Schmidt, S. Seneviratne, S. Strongin, M. van Aalst, E. Totin and C. H. Trisos (2021) 'A framework for complex climate change risk assessment.' One Earth, 4(4), pp. 489–501. https://doi.org/10.1016/j.oneear.2021.03.005

31. Theokritoff, E., van Maanen, N., Andrijevic, M. et al. Adaptation constraints in scenarios of socio-economic development. Sci Rep 13, 19604 (2023). https://doi.org/10.1038/s41598-023-46931-1

32. Thiery, W., S. Lange, J. Rogelj, C.-F. Schleussner, L. Gudmundsson, S. I. Seneviratne, M. Andrijevic, K. Frieler, K. Emanuel, T. Geiger, D. N. Bresch, F. Zhao, S. N. Willner, M. Büchner, J. Volkholz, N. Bauer, J. Chang, P. Ciais, M. Dury, L. François, M. Grillakis, S. N. Gosling, N. Hanasaki, T. Hickler, V. Huber, A. Ito, J. Jägermeyr, N. Khabarov, A. Koutroulis, W. Liu, W. Lutz, M. Mengel, C. Müller, S. Ostberg, C. P. O. Reyer, T. Stacke and Y. Wada (2021) 'Intergenerational inequities in exposure to climate extremes.' Science, 374(6564), pp. 158–160.

33. Mechler, R., L. M. Bouwer, T. Schinko, S. Surminski, and J. Linnerooth-Bayer, eds. (2019). Loss and damage from climate change: Concepts, methods and policy options. https://link.springer.com/book/10.1007/978-3-319-72026-5

34. Hultgren, A., Carleton, T., Delgado, M. *et al.* Impacts of climate change on global agriculture accounting for adaptation. *Nature* 642, 644–652 (2025). https://doi.org/10.1038/s41586-025-09085-w

35. Schubert, A., A. von Streit, and M. Garschagen. (2025). 'Unravelling the capacity–action gap in flood risk adaptation.' *Natural Hazards and Earth System Sciences* 25, 1621–1653. https://doi.org/10.5194/nhess-25-1621-2025

36. Dow, K., Berkhout, F., Preston, B. et al. Limits to adaptation. Nature Clim Change 3, 305–307 (2013). https://doi.org/10.1038/nclimate1847

37. IPCC, 2022: Annex II: Glossary [Möller, V., R. van Diemen, J.B.R. Matthews, C. Méndez, S. Semenov, J.S. Fuglestvedt, A. Reisinger (eds.)]. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2897–2930, doi:10.1017/9781009325844.029.

38. Thomas, A., E. Theokritoff, A. Lesnikowski, D. Reckien, K. Jagannathan, R. Cremades, D. Campbell, E. T. Joe, A. Sitati, C. Singh, A. C. Segnon, B. Pentz, J. I. Musah-Surugu, C. A. Mullin, K. J. Mach, L. Gichuki, E. Galappaththi, V. I. Chalastani, I. Ajibade, R. Ruiz-Diaz, C. Grady, M. Garschagen, J. Ford, K. Bowen, and Global Adaptation Mapping Initiative Team. (2021). 'Global evidence of constraints and limits to human adaptation.' Regional Environmental Change 21, article 85.

39. Urban, M. C. (2024) 'Climate change extinctions.' Science, 386(6726), pp. 1123–1128. https://doi.org/10.1126/science.adp4461

40. Chen, Z., Gao, Q., Wu, Y. *et al.* World Cultural Heritage sites are under climate stress and no emissions mitigation pathways can uniformly protect them. *Commun Earth Environ* 6, 628 (2025). https://doi.org/10.1038/s43247-025-02603-8

41. IDMC (2025). Global Report on Internal Displacement 2025. https://www.internal-displacement.org/global-report/grid2025/

42. Fedele, G., C. I. Donatti, C. A. Harvey, L. Hannah, and D. G. Hole. (2019). 'Transformative adaptation to climate change for sustainable social-ecological systems.' Environmental Science & Policy 101, 116–125. https://doi.org/10.1016/j.envsci.2019.07.001

43. Karagiannakis, G., M. Panteli and S. Argyroudis (2024) 'Fragility Modeling of Power Grid Infrastructure for Addressing Climate Change Risks and Adaptation.' *WIREs Climate Change*. https://doi.org/10.1002/wcc.930

44. Hanna, C., I. White, and B. Glavovic. (2019). 'Managed retreat in practice: Mechanisms and challenges for implementation.' Oxford Research Encyclopedia of Natural Hazard Science. https://doi.org/10.1093/acrefore/9780199389407.013.350

45. Jóhannesson, T., Raymond, C., & Waddington, E. (1989). Time-Scale for Adjustment of Glaciers to Changes in Mass Balance. Journal of Glaciology, 35(121), 355–369. https://doi.org/10.3189/S002214300000928X

46. Smith, S. M., Geden, O., Gidden, M. J., Lamb, W. F., Nemet, G. F., Minx, J. C., Buck, H., Burke, J., Cox, E., Edwards, M. R., Fuss, S., Johnstone, I., Müller-Hansen, F., Pongratz, J., Probst, B. S., Roe, S., Schenuit, F., Schulte, I., Vaughan, N. E. (eds.) The State of Carbon Dioxide Removal 2024 - 2nd Edition. DOI 10.17605/OSF.IO/F85QJ (2024)

47. Dooley, K., Christiansen, K.L., Lund, J.F. et al. Over-reliance on land for carbon dioxide removal in net-zero climate pledges. Nat Commun 15, 9118 (2024). https://doi.org/10.1038/s41467-024-53466-0

48. Land Gap (2025) The Land Gap Report 2025, University of Melbourne. Available at: https://www.landgap.org/

49. Prütz, R., Rogelj, J. , Ganti, G. , Price, J., Warren, R., Forstenhäusler, N., Wu, Y., Augustynczik, A.L.D., Wögerer, M., Krisztin, T. , Havlík, P. , Kraxner, F., Frank, S. , Hasegawa, T., Doelman, J.C., Daioglou, V., Humpenöder, F., Popp, A. & Fuss, S. (2026). Biodiversity implications of land-intensive carbon dioxide removal. Nature Climate Change 16, 155-163. 10.1038/s41558-026-02557-5.

50. Deprez, A., P. Leadley, K. Dooley, P. Williamson, W. Cramer, J.-P. Gattuso, A. Rankovic, E. L. Carlson and F. Creutzig (2024) 'Sustainability limits needed for CO2 removal.' Science, 383(6682), pp. 484–486. https://doi.org/10.1126/science.adj6171

51. Pelz, S., G. Ganti, R. Lamboll, M. J. Gidden and others (2025) 'Using net-zero carbon debt to track climate overshoot responsibility.' Proceedings of the National Academy of Sciences of the United States of America (PNAS), 122(13), e2409316122. https://doi.org/10.1073/pnas.2409316122

52. Rajamani, L., White, E., Rogelj, J., Prütz, R., Wetzer, T., Wood, M., & Stuart-Smith, R. F. (2026). Legal guardrails on states' dependence on carbon dioxide removal to meet climate targets. Climate Policy, 1–15. https://doi.org/10.1080/14693062.2025.2599861

53. Serdeczny, O., M. Andrijevic, C. Fyson, T. Lissner, I. Menke, C.-F. Schleussner, E. Theokritoff, and A. Thomas. (2024). 'Climatic risks to adaptive capacity.' Mitigation and Adaptation Strategies for Global Change 29, article 10.

54. Andrijevic, M., Schleussner, CF., Crespo Cuaresma, J. et al. Towards scenario representation of adaptive capacity for global climate change assessments. Nat. Clim. Chang. 13, 778–787 (2023). https://doi.org/10.1038/s41558-023-01725-1

55. Ganti, G. et al. (2026). Exceeding 1.5°C requires rethinking accountability in climate policy. Nature, 649, 1107–1109. DOI: 10.1038/d41586-026-00247-y

Appendix I: Mapping Climate-Impact Drivers onto Socioecological Effects

This appendix provides brief definitions for the Climatic Impact-Driver (CID) categories referenced in this section. The definitions are adapted from the IPCC AR6 Working Group I report, specifically Chapter 12 and its associated Table 12.1.

Heat and Cold

1. Mean air temperature: Mean surface air temperature and its diurnal and seasonal cycles.
2. Extreme heat: Episodic high surface air temperature events potentially exacerbated by humidity.
3. Cold spell: Episodic cold surface air temperature events potentially exacerbated by wind.
4. Frost: Freeze and thaw events near the land surface and their seasonality.

Wet and Dry

1. Mean precipitation: Mean precipitation and its diurnal and seasonal cycles.
2. River flood: Episodic high water levels in streams and rivers driven by basin runoff and the expected seasonal cycle of flooding.
3.
4. Heavy precipitation and pluvial flood: High rates of precipitation and resulting episodic, localized flooding of streams and flat lands.
5. Landslide: Ground and atmospheric conditions that lead to geological mass movements, including landslide, mudslide and rockfall.
6. Aridity: Mean conditions of precipitation and evapotranspiration compared to potential atmospheric and surface water demand, resulting in low mean surface water, low soil moisture and/or low relative humidity.
7. Hydrological drought: Episodic combination of runoff deficit and evaporative demand that affects surface water or groundwater availability.
8. Agricultural and ecological drought: Episodic combination of soil moisture supply deficit and atmospheric demand requirements that challenges the vegetation’s ability to meet its water needs for transpiration and growth. Note: ‘agricultural’ vs. ‘ecological’ term depends on affected biome.
9. Fire weather: Weather conditions conducive to triggering and sustaining wildfires, usually based on a set of indicators including temperature, soil moisture, humidity and wind. Note: distinct from wildfire occurrence and area burned.

Wind

1. Mean wind speed: Mean wind speeds and transport patterns and their diurnal and seasonal cycles.
2. Severe wind storm: Episodic severe storms including extratropical cyclone wind storms, thunderstorms, wind gusts, derechos and tornadoes.
3. Tropical cyclone: Strong, rotating storm originating over tropical oceans accompanied by high winds, rainfall and storm surges.
4. Sand and dust storm: Storms causing the transport of soil and fine dust particles.

Snow and Ice

1. Snow, glacier and ice sheet: Snowpack seasonality and characteristics of glaciers and ice sheets including calving events and meltwater.
2. Permafrost: Permanently frozen deep soil layers, their ice characteristics, and the characteristics of seasonally frozen soils above.
3. Lake, river and sea ice: The seasonality and characteristics of ice formations on the ocean and freshwater bodies of water.
4. Heavy snowfall and ice storm: High snowfall and ice storm events including freezing rain and rain-on-snow conditions.
5. Hail: Storms producing solid hailstones.
6. Snow avalanche: Cryospheric mass movements and the conditions of collapsing snowpack.

Coastal

1. Relative sea level: The local mean sea surface height relative to the local solid surface.
2. Coastal flood: Flooding driven by episodic high coastal water levels that result from a combination of relative sea level rise, tides, storm surge and wave setup.
3. Coastal erosion: Long term or episodic change in shoreline position caused by relative sea level rise, nearshore currents, waves and storm surge.

Open Ocean

1. Mean ocean temperature: Mean temperature profile of ocean through the seasons, including heat content at different depths and associated stratification.
2. Marine heatwave: Episodic extreme ocean temperatures.
3. Ocean acidity: Profile of ocean water pH levels and accompanying concentrations of carbonate and bicarbonate ions.
4. Ocean salinity: Profile of ocean salinity and associated seasonal stratification. Note: distinct from salinization of freshwater resources.
5. Dissolved oxygen: Profile of ocean water dissolved oxygen and episodic low oxygen events.

Other

1. Air pollution weather: Atmospheric conditions that increase the likelihood of high particulate matter or ozone concentrations or chemical processes generating air pollutants. Note: distinct from aerosol emissions or air pollution concentrations themselves.
2. Atmospheric CO2 at surface: Concentration of atmospheric carbon dioxide (CO2) at the surface. Note: distinct from overall radiative effect of CO2 as greenhouse gas.
3. Radiation at surface: Balance of net shortwave, longwave and ultraviolet radiation at the Earth’s surface and their diurnal and seasonal patterns.

Appendix II: Representative Key Risks

The table is based on Table 16.6 | Climate-related representative key risks (RKRs), based on IPCC AR6 WGII, Chapter 16, O’Neill et al., (2022).

Code	Representative key risk	Scope
RKR-A	Risk to low-lying coastal socio-ecological systems	Risks to ecosystem services, people, livelihoods and key infrastructure in low-lying coastal areas, and associated with a wide range of hazards, including sea level changes, ocean warming and acidification, weather extremes (storms, cyclones), sea ice loss, etc.
RKR-B	Risk to terrestrial and ocean ecosystems	Transformation of terrestrial and ocean/coastal ecosystems, including change in structure and/or functioning, and/or loss of biodiversity.
RKR-C	Risks associated with critical physical infrastructure, networks and services	Systemic risks due to extreme events leading to the breakdown of physical infrastructure and networks providing critical goods and services.
RKR-D	Risk to living standards	Economic impacts across scales, including impacts on gross domestic product (GDP), poverty and livelihoods, as well as the exacerbating effects of impacts on socioeconomic inequality between and within countries.
RKR-E	Risk to human health	Human mortality and morbidity, including heat-related impacts and vector-borne and waterborne diseases.
RKR-F	Risk to food security	Food insecurity and the breakdown of food systems due to climate change effects on land or ocean resources.
RKR-G	Risk to water security	Risk from water-related hazards (floods and droughts) and water quality deterioration. Focus on water scarcity, water-related disasters and risks to indigenous and traditional cultures and ways of life.
RKR-H	Risks to peace and to human mobility	Risks to peace within and among societies from armed conflict as well as risks to low-agency human mobility within

		and across state borders, including the potential for involuntarily immobile populations.