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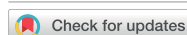
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Overshoot pathways: reversible biophysical change, irreversible socioeconomic impacts

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Keywords: temperature overshoot, socioeconomic commitment threshold, committed socioeconomic impacts, losses and damages, adaptation limits, carbon dioxide removal

Abstract

Exceeding global warming of 1.5 °C in the near term is now unavoidable. An overshoot pathway, in which exceedance is followed by decline to or below the threshold through net-negative emissions, is now the only remaining route back to 1.5 °C. Permanent exceedance forecloses the recovery from climate impacts that an overshoot pathway may permit, yet even an overshoot pathway leaves lasting legacies. To characterise the reversibility of temporary overshoot impacts, we propose a three-layer analytical framework distinguishing hazards (with four dimensions: magnitude, duration, rate of exceedance, and rate of decline), biophysical responses (reversible vs persistent change), and socioeconomic outcomes (reversible vs irreversible impact). We introduce the socioeconomic commitment threshold, endogenous to the overshoot trajectory: how much overshoot intensity a system can experience before the losses it accumulates persist after temperatures decline, explained by three mechanisms: non-substitutability, threshold-crossing, and lock-in. A typology linking biophysical persistence with socioeconomic irreversibility illustrates how 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 rather than biophysical factors, except where permanent biophysical change exceeds adaptation limits. For systems and communities with low adaptive capacity, overshoot concentrates irreversible legacies even where temperatures subsequently decline, placing equity and justice at the centre of overshoot assessment.

1. Introduction

Exceeding global warming of 1.5 °C is no longer a distant prospect: the first year above 1.5 °C has been recorded (Bevacqua *et al* 2025, WMO 2026). The remaining carbon budget for a 50% probability of limiting warming to 1.5 °C stands at roughly 130 GtCO₂ from the start of 2026, equivalent to about three years of current emissions (Forster *et al* 2026). Warming has increased 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 a peak, then a 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 CO₂, is now the only remaining route back to 1.5 °C. Without sustained

reductions and removals, exceedance becomes permanent, and more consequences 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 (Pfleiderer *et al* 2024, Schleussner *et al* 2024, Roldán-Gómez *et al* 2025), some regions continuing to warm as global temperature declines (Yang *et al* 2026), in addition to asymmetries in carbon cycle feedbacks and transient climate response (Zickfeld *et al* 2021, Chimuka and Zickfeld 2026). 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. How long such impacts persist is not a new question in economics. The empirical damage literature distinguishes impacts on the level of output (Kalkuhl and Wenz 2020), from impacts on its growth rate (Dell *et al* 2012) and identifies this persistence as an open question and a central barrier to quantifying the benefits of mitigation (Piontek *et al* 2021). Persistence, however, cuts across that distinction rather than mapping onto it. A growth rate effect can reverse as temperatures decline, while a loss incurred in the level of output, including non-market losses such as a destroyed ecosystem, can be permanent. The framework developed here therefore addresses persistence directly, specifying the mechanisms and conditions under which the persistent case arises. 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 overshoot intensity is paramount, since the dimensions of the overshoot hazards (magnitude, duration, rate of exceedance and rate of decline; with peak magnitude matters first among the four dimensions) 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: sustained CDR at scale can deliver net-negative CO₂ only once rapid and deep reductions have brought gross emissions close to

zero. Without both, 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 hazards (temperature trajectory and overshoot dimensions), the biophysical responses (reversible vs persistent change), and the socioeconomic outcomes (reversible vs irreversible impacts). We introduce a *socioeconomic commitment threshold*: how much overshoot intensity a given system can experience before the losses it accumulates persist after temperatures decline, explained 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. Cumulative exposure, rapid warming, non-substitutability, threshold-crossing, and erosion of adaptive capacity are not unique to an overshoot pathway; they operate under any warming trajectory. What is specific to an overshoot pathway is the return phase, which introduces the rate of decline as a fourth hazard dimension and the resulting irreversible impacts despite the decline in temperature. The framework identifies the conditions under which biophysical persistence and socioeconomic irreversibility decouple, a possibility that arises only under an overshoot pathway because socioeconomic losses persist after temperatures decline, and provides a typology for assessing

where and for whom overshoot pathways create 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 (the extent by which peak temperature exceeds a threshold; distinct from absolute peak warming that governs threshold-dependent systems), 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 temperature 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 and 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 (Meyer *et al* 2022, Marshall *et al* 2025). 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) may experience lower cumulative impact and recover rapidly 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). Adaptive capacity, the ability of a system or community to adjust to stress, moderate harm, and recover (Dow *et al* 2013, Klein *et al* 2014), determines how much cumulative impact can be absorbed before recovery is blocked. This coping ceiling is a limit to adaptation in the established sense, illustrated in our figure as the adaptive capacity threshold (dash-dot): the level of cumulative impact above which recovery is blocked through threshold-crossing, lock-in, or non-substitutability (section 4). The threshold is a property of the system, and it is dynamic: where cumulative impacts outpace development gains, financial and institutional resources are depleted, and the threshold erodes during the exceedance phase (Smit and Wandel 2006, Schleussner *et al* 2021, O'Neill *et al* 2022). 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).

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.

3. From hazard to biophysical response

3.1. Characterising the overshoot pathways hazard

The four dimensions of overshoot pathways hazard shape biophysical and socioeconomic outcomes through distinct impact signatures. Magnitude determines whether critical thresholds are crossed in

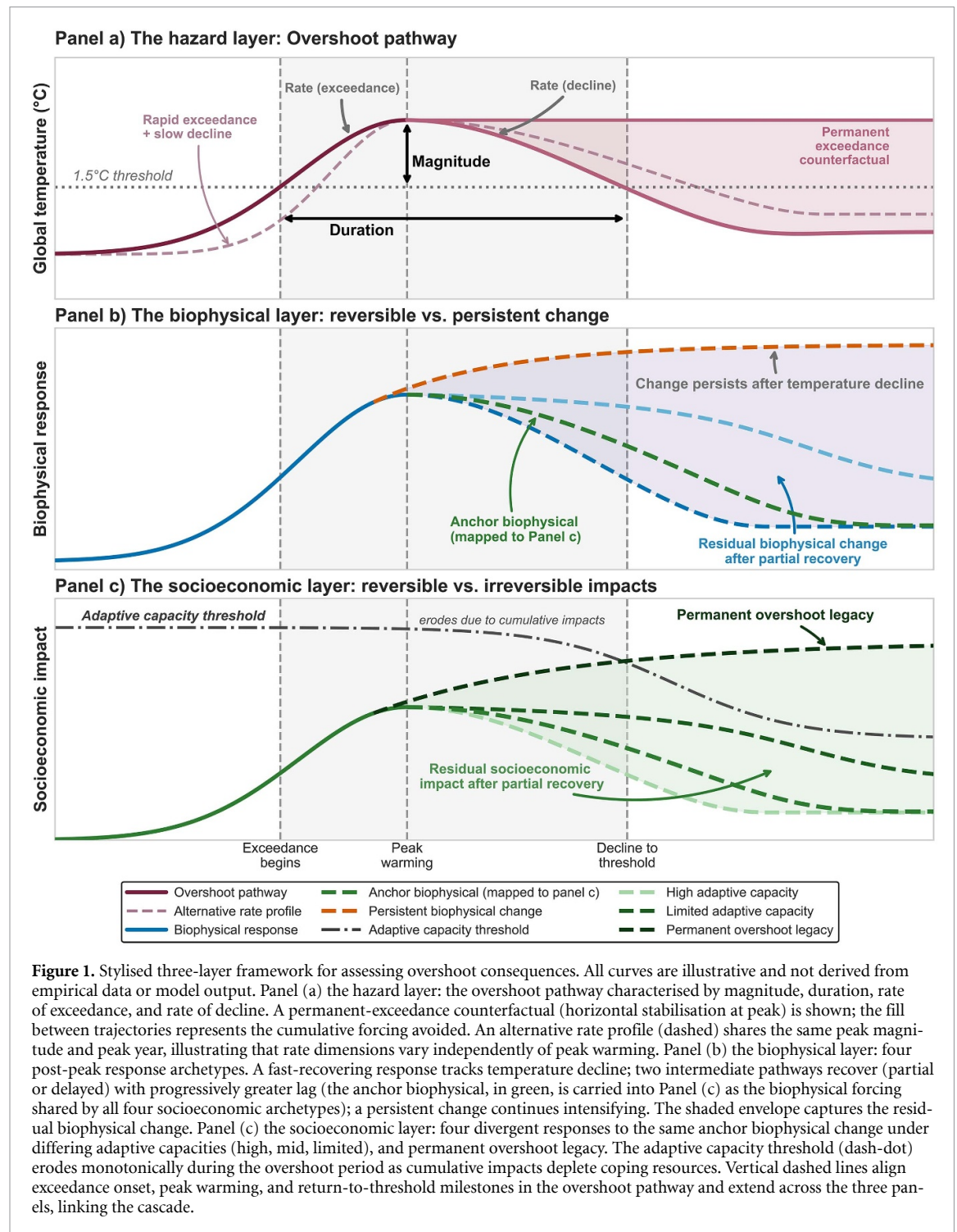


Figure 1. Stylised three-layer framework for assessing overshoot consequences. All curves are illustrative and not derived from empirical data or model output. Panel (a) the hazard layer: the overshoot pathway characterised by magnitude, duration, rate of exceedance, and rate of decline. A permanent-exceedance 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 warming. Panel (b) the biophysical layer: four post-peak response archetypes. A fast-recovering response tracks temperature decline; two intermediate pathways recover (partial or delayed) 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.

biophysical systems (e.g. warm-water coral collapse above $\sim 1.5^\circ\text{C}$) and socioeconomic ones (e.g. infrastructure failure beyond design tolerances). Note that, for threshold-dependent systems, magnitude is expressed as absolute peak warming rather than exceedance above 1.5°C . Duration governs cumulative exposure and contributes to whether systems and communities are pushed beyond their recovery capacity. 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. This is not specific to overshoot pathways; it operates under any rapid warming. 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 new hazards absent from the warming phase (section 5).

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 it is the absolute level that is decisive: warm-water coral reef collapse is driven primarily by whether temperature exceeds $\sim 1.5^\circ\text{C}$ (Armstrong McKay *et al* 2022, Schleussner *et al* 2024). Two trajectories with identical degree-years but different temporal profiles will produce different impacts: the integral treats a brief, high peak and a prolonged, lower exceedance as equivalent, but they are not, either for rate-sensitive systems or for systems whose impacts scale non-linearly with warming. 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 A 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 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* 2026): 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.

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 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 CID, 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

⁷ Also sensitive to cumulative exposure (degree-years); see Wunderling *et al* (2024).

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

Mechanism	Primary overshoot dimensions	Metric	Examples
Threshold behaviour and hysteresis	Magnitude	Peak warming	Coral reef collapse; ice sheet loss; tipping cascades ⁷
Physical inertia and commitment	Cumulative exposure	Degree-years	Sea-level rise; glacier mass loss; permafrost thaw

decades is effectively irreversible for the generation that experiences it Thiery *et al* 2021.

The likelihood that a given socioeconomic impact becomes irreversible increases with overshoot intensity and decreases with adaptive capacity (figure 2). The same overshoot pathway therefore produces different outcomes across systems and communities of differing adaptive capacity. For any one system, the hazards experienced during overshoot translate into cumulative socioeconomic impact through continued exposure, rising vulnerability, and eroding response capacity. Some of that impact reverses as conditions ease; some does not. We call the point at which it stops reversing the *socioeconomic commitment threshold*: how much overshoot intensity a given system can experience before the losses it accumulates persist after temperatures decline. The threshold is overshoot-specific, because a loss that outlasts the decline is only definable where a decline occurs. It is endogenous to the overshoot trajectory: as the adaptive capacity erodes during the exceedance phase, less overshoot is needed to commit a given loss, and the threshold falls as the overshoot continues.

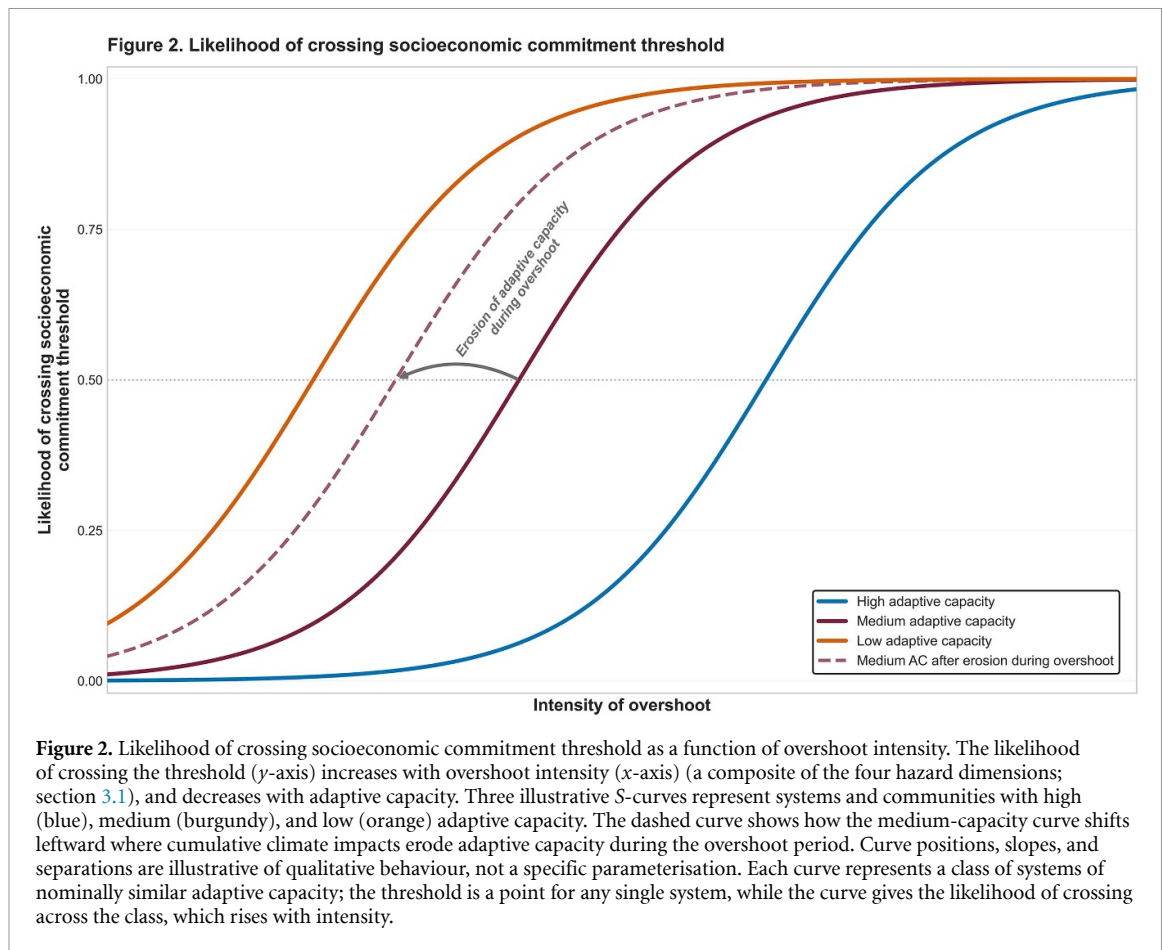
The ultimate result is *committed socioeconomic impacts*, analogous to committed warming or committed sea-level rise in the physical climate system, but explained by three distinct socioeconomic mechanisms described below. Committed socioeconomic impacts constitute the irreversible component of losses and damages (Mechler *et al* 2019) arising under overshoot pathways⁸. 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.

Figure 2 illustrates the likelihood of crossing the socioeconomic commitments threshold as a function of overshoot intensity, a stylised composite

of the overshoot pathways dimensions described 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). 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 the overshoot phase (section 2) 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.

Three socioeconomic mechanisms explain why losses stop reversing, and so determine where a system's commitment threshold lies: non-substitutability, threshold-crossing, and lock-in. They map onto the hard and soft adaptation limits framework (Dow *et al* 2013, Klein *et al* 2014, 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 sunk costs or path dependencies generated during the exceedance phase (Haasnoot *et al* 2024). In other words, the adjustments a system makes to cope with the peak, such as hard coastal

⁸ 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.



defences or new water infrastructure, are costly to undo, so it stays locked to its exceedance-phase configuration even after temperatures decline. 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. The primary driver is overshoot magnitude relative to adaptive capacity, compounded by duration where repeated shocks prevent inter-event recovery (Schleussner *et al* 2024, Hultgren *et al* 2025). Rate of exceedance modulates the outcome by compressing the time

available for adaptation between shocks. The two mechanisms differ in kind: non-substitutability is loss intrinsic to what is destroyed, which no capacity can avert (a hard adaptation limit by nature), whereas threshold-crossing is loss contingent on resource exhaustion, which sufficient capacity could have averted (a soft adaptation limit converted to hard).

- *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: 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 (O'Neill *et al* 2022, IDMC 2025). At the household level, lock-in operates through infrastructure adaptation, such as cooling equipment that will not be removed even if temperatures decline.

Lock-in takes two forms that fall on different systems. Sunk-cost lock-in presupposes that adaptation succeeded: the peak-tailored infrastructure described above is expensive to reverse, and building it at all is resource-intensive, so this form concentrates in high-capacity systems. Path-dependency lock-in arises where adaptation failed or was never available: displacement, involuntary immobility, and the reassignment of land tenure reconfigure a system through forced adjustment rather than deliberate investment, concentrating in low-capacity systems. This distinction locates the widely documented adaptation deficit (Fankhauser and McDermott 2014) in the second form: where little peak-tailored infrastructure exists to be stranded, the decline phase is first experienced as relief, and lock-in operates through the barriers left by forced reconfiguration rather than through sunk costs.

For low, within-century overshoots where peak warming is contained 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, so sunk-cost lock-in is weak, and threshold-crossing and non-substitutability are likely the stronger mechanisms. Path-dependency lock-in is not bounded in the same way: forced reconfiguration follows from stress that exhausts coping capacity rather than from investment tailored to the peak, so it can operate in low-capacity systems even under a modest overshoot magnitude. Nonetheless, grey infrastructure and household-level commitments with multi-decadal design lives generate some sunk-cost lock-in, so its depth rather than its presence scales with the duration of exceedance; it becomes the dominant mechanism only for overshoots that do not reverse within the century. Sunk-cost lock-in is also 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 (Kates *et al* 2012, 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.

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 1(b) and (c).

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 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 two forms of lock-in fall on either side of these: sunk-cost lock-in in a high-capacity system is typically a permanent adaptation challenge, a cost absorbed through reconfiguration, whereas path-dependency lock-in in a low-capacity system, driven by forced displacement for instance with no capacity to recover, is a socioeconomic legacy. 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, except where permanent biophysical change exceeds adaptation limits.

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 <i>et al</i> 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 <i>et al</i> 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 <i>et al</i> 2025; O'Neill <i>et al</i> 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 abandonment (Hultgren <i>et al</i> 2025; Schleussner <i>et al</i> 2024)	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
	Climate-driven infrastructure failure; indirect costs compound direct damage (Karagiannakis <i>et al</i> 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 <i>et al</i> 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; infrastructure path dependencies prevent flexible reallocation (Mengel <i>et al</i> 2018)	Duration	Magnitude (extent of committed sea-level rise)	Persistent	Physical conditions do not reverse; sunk costs lock in spatial configuration

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. Example: managed retreat from committed sea-level rise in well-resourced settings.
Irreversible socioeconomic impacts	Socioeconomic legacy. During exceedance, cumulative impact overtakes the system's adaptive capacity threshold, and loss is committed: it persists as the biophysical change recedes. 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, loss of identity and cultural heritage.

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.

5. Conclusions and policy implications

5.1. Conclusions

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 (Jóhannesson *et al* 1989, Schuster *et al* 2025), and retained ocean heat generates novel hydrological conditions (Marshall *et al* 2025). A full account of decline-phase hazards would require treating the descent on its own terms rather than as the mirror of the ascent; that is beyond the scope of this paper. Relative to an overshoot pathway, permanent exceedance forecloses recovery: for every system not yet past the socioeconomic commitment threshold, each degree-year of avoided overshoot preserves recovery potential and prevents further committed losses.

The framework contributes three things. It separates the hazard, the biophysical response, and the socioeconomic outcome, so that reversibility is assessed at each layer rather than assumed to propagate from one to the next. It introduces the *socioeconomic commitment threshold* to identify where temporary temperature exceedance leads to permanent socioeconomic loss. And it provides a typology showing that a reversible biophysical change can produce irreversible socioeconomic loss, while a persistent biophysical change need not, where adaptive capacity is sufficient. The central implication is distributional: which quadrant of table 3 a system or community occupies is determined primarily by socioeconomic rather than biophysical factors, except

where permanent biophysical change exceeds adaptation limits, so an overshoot pathway concentrates its permanent legacies where adaptive capacity is lowest.

These contributions are subject to uncertainty at each layer. The boundary between reversible and persistent biophysical change is state-dependent (Pfleiderer *et al* 2024, Roldán-Gómez *et al* 2025), and threshold behaviour in systems such as ice sheets and coral reefs introduces poorly constrained discontinuities (Armstrong McKay *et al* 2022, Wunderling *et al* 2024). The socioeconomic commitment threshold is governed by adaptive capacity, which is itself dynamic as vulnerability, governance, and financial reserves shift during overshoot (Andrijevic *et al* 2023, Serdeczny *et al* 2024). The S-curves in figure 2 are therefore conceptual, not predictive. Applying the typology across the Representative Key Risks assessed in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Working Group II (O'Neill *et al* 2022; See appendix B) would test its generalisability and reveal where irreversibility mechanisms compound. This requires impact modelling under overshoot scenarios, empirical characterisation of adaptive capacity, and calibration of the commitment threshold for specific systems and communities. The commitment threshold is defined only where temperatures decline. Nothing requires that decline to be smooth: a noisy, non-monotonic descent commits losses in the same way, since what matters is the cumulative overshoot experienced before the decline, not the shape of the path.

5.2. Policy implications

Several policy implications follow, each a corollary of the framework. First, the feasibility of sustained temperature decline is the first-order uncertainty in any overshoot pathway (figure 1(a)), and it follows directly from the cascade described in this paper. Decline depends on sustained CDR at scale (Edwards *et al* 2026), yet the financial, institutional, and governance resources it requires are precisely those eroded by the overshoot itself. 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), raising legal and feasibility concerns and risking multiple planetary boundaries (Deprez *et al* 2024, Prütz *et al* 2026, 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 irreversibility thresholds.

Second, committed socioeconomic impacts correspond to the irreversible component of losses and

damages (Mechler *et al* 2019), as distinct from damages that can be recovered or compensated. This distinction exposes a governance gap: declining temperature may be read as evidence that the crisis is resolving even as the distribution of permanent harm worsens, so political will for sustained CDR investment and Loss and Damage finance may weaken precisely as irreversible legacies accumulate. Overshoot governance should therefore integrate Loss and Damage mechanisms, adaptation investment, and CDR deployment for net-negative emissions rather than treating them as separate policy tracks.

Third, these legacies are not distributed uniformly. Because which quadrant a system occupies is determined primarily by socioeconomic factors rather than biophysical ones, except where permanent biophysical change exceeds adaptation limits. Therefore, an overshoot pathway concentrates its permanent costs among the populations least responsible for the emissions that produced them (Pelz *et al* 2025), and among cohorts who experience the exceedance phase without living to benefit from decline-phase recovery, creating a distinct form of intergenerational injustice (Thiery *et al* 2021). The same asymmetry applies to the response: the capacity to cut emissions rapidly, to finance adaptation, and to sustain CDR is concentrated among those most responsible for the overshoot and least exposed to its permanent legacies.

For many systems and communities, returning temperatures to 1.5 °C after overshoot will not restore conditions to an equivalent state: many losses committed during the exceedance phase persist. Two imperatives follow. The first is to minimise overshoot intensity, with peak magnitude first among the four dimensions; in the near term this means rapid emissions reductions, because every degree-year of avoided overshoot lowers the probability of crossing socioeconomic commitment thresholds. The second, necessary but not sufficient on its own, is to manage the decline phase: sustaining the reductions and removals that bring temperatures down preserves recovery potential for systems and communities not yet past their thresholds. Reducing the magnitude and duration of exceedance and managing the descent are all necessary and will be significant challenges, but near-term mitigation is the immediate lever.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Code availability

The code underlying the figures is available publicly on GitHub: https://github.com/AlKhourdajie/Overshoot_irreversible_socioeconomic_impacts/tree/main.

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Appendix A. 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. Heavy precipitation and pluvial flood: High rates of precipitation and resulting episodic, localized flooding of streams and flat lands.
4. Landslide: Ground and atmospheric conditions that lead to geological mass movements, including landslide, mudslide and rockfall.
5. 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.
6. Hydrological drought: Episodic combination of runoff deficit and evaporative demand that affects surface water or groundwater availability.
7. 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.

8. 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 B. Representative key risks (RKR)

The table is based on table 16.6 | Climate-related 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.

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