

From AMOC weakening to socio-ecological impacts: a systematic review of Earth-system risk pathways

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Systematic Review

Keywords: AMOC weakening, Earth-system tipping points, socio-ecological impacts, systematic evidence map

Posted Date: October 9th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11078570/v1>

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Additional Declarations: The authors declare no competing interests.

Abstract

The Atlantic Meridional Overturning Circulation (AMOC) redistributes Atlantic heat, salt, and carbon. Meltwater forcing and warming can weaken it, reducing northward heat transport, producing a North Atlantic “warming hole”, shifting the Intertropical Convergence Zone southward, and reorganising monsoons and rainfall. These responses propagate into biogeochemistry, ecosystems, and human systems. This evidence map synthesises peer-reviewed impact literature using reproducible, query-based Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) screening of 2 672 Web of Science records published in 2000–2025. We retained 246 studies and coded consequences across seven domains: regional climate, extremes, ocean biogeochemistry and productivity, terrestrial and marine biodiversity, agriculture and food security, human health, and societal vulnerability. Three structural biases emerge. First, idealised freshwater “hosing” often imposes fluxes far above realistic meltwater input; explicit meltwater experiments remain a small minority. Second, physical climate dominates (208 of 246 studies), while agricultural, health, and societal evidence is sparse and largely conceptual. Third, research concentrates in the North Atlantic, Europe, and North America; dedicated human-impact assessments remain particularly sparse across populous, climate-vulnerable tropical regions where monsoon and rainfall disruption could have major human consequences. Linking physical mechanisms to downstream impacts and identifying evidence gaps supports physically grounded, cross-sectoral, geographically inclusive assessment of AMOC weakening as an Earth-system tipping element.

1 Introduction

The Atlantic Meridional Overturning Circulation (AMOC) redistributes heat, salt, and carbon, sustaining North Atlantic mildness and influencing tropical rainfall and African and Asian monsoons (Vellinga and Wood 2002). Warming and Greenland meltwater lower surface density and may substantially weaken overturning this century (Caesar et al. 2018, 2021; Boers 2021).

Coupled Model Intercomparison Project (CMIP) models generally simulate gradual weakening through 2100 under greenhouse forcing without imposed meltwater (Rugenstein et al. 2013; Jackson et al. 2015); idealised freshwater experiments and recent analyses suggest possible abrupt collapse (Liu et al. 2017; Ditlevsen and Ditlevsen 2023; van Westen et al. 2024; Loriani et al. 2025). Hosing and coupled ice-sheet experiments examine freshwater-driven decline (Manabe and Stouffer 2000; Stouffer et al. 2006; Swingedouw et al. 2006, 2007a), which alters hemispheric temperatures, tropical rainfall, monsoons, productivity, sea level, and storm tracks (Vellinga and Wood 2002, 2008; Mulitza et al. 2008; Jackson et al. 2015; Ben-Yami et al. 2024). Downstream fisheries, crop, disease-vector, and human-exposure literature remains fragmented across disciplines.

Palaeoclimate slowdowns accompanied Northern Hemisphere cooling and southward tropical-rainfall shifts (Manabe and Stouffer 2000; Alley et al. 2003; Alvarez-Solas et al. 2010, 2019). Heinrich-stadial

iceberg discharge freshened the North Atlantic, suppressed deep-water formation, and motivated early modelling. This review instead addresses contemporary and future impacts.

Existing reviews emphasise mechanisms or individual sectors. We map the full cross-sectoral evidence from 2000–2025 peer-reviewed literature, coding impacts, representation of AMOC decline, models, forcings, and regions.

2 Physical background

Supplementary Fig. S1 summarises the physical cascade.

2.1 From freshwater to a weakened circulation

Dense-water formation in the subpolar North Atlantic and Nordic Seas drives the deep southward return flow. Surface warming, enhanced high-latitude precipitation and runoff, Arctic sea-ice loss, and Greenland meltwater lower surface density (Swingedouw et al. 2007a; Swingedouw et al. 2009, 2021). Imposed freshwater weakens or halts overturning, with responses depending on flux magnitude and location (Manabe and Stouffer 2000; Stouffer et al. 2006). Slowdown fingerprints appear in observed sea-surface temperatures (Caesar et al. 2018, 2021), while projections show continued twenty-first-century weakening without explicit meltwater forcing (Jackson et al. 2015).

2.2 The atmospheric response

A weakened AMOC transports less heat northward, and the climate system responds first by cooling the North Atlantic and the surrounding continents while the Southern Hemisphere warms, the inter-hemispheric contrast known as the bipolar seesaw (Manabe and Stouffer 2000; Levermann et al. 2007).

Bjerknes compensation partly offsets reduced ocean heat transport through a strengthened Hadley circulation and altered mid-latitude eddies (Drijfhout 2010; Hu et al. 2013; Yang et al. 2015).

Compensation is of the order of half the extratropical oceanic anomaly: net North Atlantic cooling persists while atmospheric circulation reorganises beyond the basin. The subpolar “warming hole”, linked directly to AMOC decline, reshapes the jet and storm tracks (Brayshaw et al. 2009; Drijfhout et al. 2012; Gervais et al. 2019; Rousi et al. 2021).

2.3 The oceanic response

Reduced convection and stronger near-surface stratification restrict nutrient supply to the sunlit layer and the along-gyre nutrient stream sustaining subpolar productivity; redistributed heat and carbon alter anthropogenic CO₂ uptake (Kwiatkowski et al. 2019). Adjustment of the along-shore density gradient raises northeastern North American sea level independently of thermal expansion (Yin et al. 2009; Krasting et al. 2016) (Sections 4.6 and 4.10).

2.4 Global teleconnections

Northern tropical Atlantic cooling shifts the Intertropical Convergence Zone southward, weakening the West African monsoon and Sahel rainfall (Mulitza et al. 2008; Defrance et al. 2017) and reducing South and East Asian monsoon precipitation (Lu and Dong 2008; Yu et al. 2009; Sandeep et al. 2020). Through the Walker circulation and inter-basin feedbacks, it also changes El Niño–Southern Oscillation amplitude and character, although models disagree on the sign (Timmermann et al. 2005; Dong and Sutton 2007; Xie et al. 2008; Williamson et al. 2018).

2.5 Lessons from the past

Deglacial reconstructions show nearly or completely eliminated overturning during Heinrich event H1 and the Younger Dryas, followed by rapid recovery (McManus et al. 2004). Model and proxy studies link Heinrich-stadial behaviour to North Atlantic freshwater and iceberg forcing (Menviel et al. 2008; Alvarez-Solas et al. 2010, 2019). These episodes support possible abrupt transitions and multiple circulation regimes and motivated idealised experiments.

3 Materials and methods

This systematic evidence map uses reproducible, PRISMA-guided searching and screening to characterise literature coverage and structure, without appraising individual studies' evidential strength or estimating pooled effects.

3.1 Search strategy

We searched the Web of Science Core Collection on 15 January 2026 for publications through 31 December 2025. A master Boolean query combined AMOC terminology ("AMOC", "Atlantic meridional overturning", "thermohaline circulation", "Gulf Stream System"), weakening/collapse conditions ("weakening", "slowdown", "collapse", "shutdown", "hosing", "freshwater forcing"), and generic impacts. Three thematic queries reused the AMOC and condition blocks with vocabularies for agriculture/food security, ocean productivity/biogeochemistry, and societal risks including economy, migration, and health, to counter under-retrieval outside climate disciplines. The master, agriculture, ocean, and societal queries returned 2 035, 93, 278, and 266 records, respectively: 2 672 in total. Full strings appear in the Supplementary Material.

3.2 Screening and selection

DOI deduplication removed 471 of 2 672 records, leaving 2 201; excluding 110 outside 2000–2025 left 2 091. Titles, abstracts, and author keywords were screened for (i) explicit AMOC weakening or collapse and (ii) a direct or indirect environmental, ecological, or socio-economic consequence. Exclusions comprised no AMOC–impact link (670), purely palaeoclimatic studies (553), mechanisms without assessed impacts (428), and other reasons including editorials and off-topic retrievals (176), leaving 264. Four eligible studies known to the author but missed through indexing/keyword mismatches were added under the same inclusion and coding criteria. All four used the same bias-corrected ice-sheet meltwater framework (C4) as other corpus studies. Full texts were sought for 268 records.

Of these, 256 full texts were obtained and 12 unretrievable. Ten were excluded: three palaeoclimatic/observational studies without future impact assessment, two outside the eligible period, four preprints/grey-literature documents, and one unusable scanned report. All **246 retained studies** (Fig. 1) were read in full and coded; Supplementary Table S1 summarises the corpus, provided in full in Appendix A.

3.3 Coding framework

All 246 studies were coded for representation of AMOC decline, driving model/dataset, freshwater magnitude and nature, scenario/design, impact domains, regions, and principal quantitative consequences.

The representation of the AMOC decline was classified into five mutually exclusive conditions, which prove central to the analysis that follows:

- **C1 – idealised freshwater hosing or imposed shutdown:** the circulation is forced to weaken or collapse by a prescribed, idealised freshwater flux applied to the North Atlantic, or by an imposed shutdown.
- **C2 – scenario-emergent weakening without explicit meltwater forcing:** the AMOC weakens as an emergent response within a standard greenhouse-gas scenario run (CO₂, RCP, or SSP forcing), with no added meltwater.
- **C3 – abrupt emergent collapse:** an abrupt collapse emerges within a model without idealised hosing, for example in a high-resolution or tipping-point simulation that crosses a threshold of its own accord.
- **C4 – explicit ice-sheet meltwater forcing:** an ice-sheet meltwater perturbation, typically from Greenland, is superimposed on a scenario run. The plausibility of such experiments varies with the imposed flux, its duration, and its location, and should be assessed case by case (Section 4.1).
- **C5 – no self-contained AMOC simulation:** the study does not simulate an AMOC change itself. Two sub-types are distinguished: **C5a** studies that nevertheless quantify impacts using an externally prescribed AMOC trajectory (for example, integrated-assessment or impact models driven by a published weakening scenario), and **C5b** conceptual studies, reviews, perspectives, and adaptation frameworks. Where the distinction is not material to a given result, the two are reported together as C5.

We note that a study coded C5 is not thereby weak evidence: a C5a assessment may rest on a quantitative, model-derived AMOC trajectory, whereas C5b studies are conceptual. The frequency of C5b, rather than C5 as a whole, is what indicates a reliance on conceptual rather than simulation-based evidence.

Impact domains were coded, allowing multiple domains per study, into seven categories: base climate (the mean temperature, precipitation, and circulation response); extremes (heatwaves, cold spells,

droughts, floods, and storms); biogeochemistry (ocean carbon, productivity, deoxygenation, nutrients, and fisheries); biodiversity (species, habitats, and ecosystems); agriculture and food security; human health; and society, comprising migration, economy, and conflict. Regions were coded from a fixed list spanning the major ocean basins and continents.

3.4 Use of assisted tools and validation

A rule-based large-language-model screener (Claude Sonnet 4, claude-sonnet-4-20250514, Anthropic) screened titles and abstracts through the API using a fixed system prompt and coding grid, reproduced in the Supplementary Material. It assigned *Include*, *Exclude*, or *Maybe* and preliminary condition, domain, region, and related codes, excluding palaeoclimate-only, mechanism-only, and absent AMOC–impact links. The author adjudicated every *Maybe* on the full record and audited a random 10% sample of other decisions. A second inductive pass (Claude Sonnet 4, claude-sonnet-4-6) checked concrete impacts in retained abstracts and derived thematic keywords. Models classified and extracted stated information; they did not interpret results or write article text.

The author read every full text retained for assessment, verified coding and every quantitative value against the source, and resolved remaining ambiguities. No inter-rater reliability statistic was computed for this single-author map. Search strings, prompts, coding grid, included/excluded screening records, and scripts are released for independent reassessment (Supplementary Material). The author takes responsibility for coding, analysis, and conclusions. Figures use standard plotting libraries to visualise coded data; no generative image tools were used.

4 Results

4.1 How the community represents an AMOC decline

Across the 246 studies, the way an AMOC decline is brought about is markedly uneven. Idealised hosing collapses (C1) are the most common approach, accounting for 104 studies (42%), followed by passively diagnosed slowdowns within standard greenhouse-gas scenario runs (C2, 83 studies, 34%). Explicit meltwater-forced experiments (C4), in which an ice-sheet discharge is superimposed on a scenario, represent only 21 studies (9%), and abrupt collapses emerging without imposed hosing (C3) a further 7 (3%). The remaining 31 studies (13%) are conceptual (C5) and simulate no AMOC change of their own. The evidence base is thus dominated by the two approaches that either impose a decline by construction (C1) or diagnose it as an emergent response to greenhouse forcing (C2); experiments imposing explicit ice-sheet meltwater forcing remain a small minority.

The contrast becomes sharper when the magnitude of the imposed freshwater forcing is examined (Fig. 2). Here the statistical unit is the individual experiment rather than the study, since a single publication may report several hosing experiments at different fluxes; the distribution therefore describes experimental practice rather than a per-study average. Among hosing experiments (C1), the prescribed flux has a median of 0.5 Sv and ranges up to 100 Sv, one to three orders of magnitude larger

than any physically plausible meltwater input. Explicit meltwater experiments (C4), by contrast, cluster around a median of 0.16 Sv, of the same order as the freshwater fluxes used to represent enhanced Greenland discharge in hosing protocols, which are typically set at around 0.1 Sv (Stouffer et al. 2006; Swingedouw et al. 2013), above the present-day Greenland Ice Sheet net mass loss, which is of order 0.005–0.01 Sv depending on the averaging period (Otosaka et al. 2023). Whether fluxes of this size overestimate the forcing, or instead compensate for the widely reported low sensitivity of many models to freshwater perturbation, linked to a common bias in the simulated Atlantic freshwater transport, remains debated (Liu et al. 2017). The magnitude in Sverdrups is, moreover, only a partial measure of the forcing: a flux sustained over several centuries delivers far more total freshwater than the same flux applied briefly, so the integrated forcing (in Sv-years) can differ even at equal peak magnitude. With that caveat, a substantial fraction of the corpus studies the impacts of an AMOC collapse driven by freshwater fluxes far outside the range the real climate system could deliver. This is a legitimate way to probe the physical response of the circulation and to establish a worst-case envelope, but it means that much of what is known about AMOC impacts has been learned from experiments designed to guarantee a collapse rather than to represent a physically plausible or projected trajectory. The distinction matters for interpretation: an impact robustly simulated under 0.5 Sv of idealised hosing cannot be assumed to generalise to the range of scenario-emergent and explicit-meltwater experiments represented in C2 and C4.

4.2 Growth and temporal evolution of the field

The corpus has grown unevenly and has changed in character over time (Supplementary Fig. S2). The first decade (2000–2009, 62 studies) was dominated by idealised hosing: 41 of these early studies are C1, against only 6 passive CMIP slowdowns. The balance shifts in the following decade (2010–2019, 71 studies), where passive slowdowns (C2, 31 studies) overtake hosing (C1, 23). The most recent period (2020–2025) accounts for 113 studies, nearly half the corpus, and is characterised by the continued rise of C2 (46 studies) alongside a marked increase in conceptual work (C5, 14 studies), with a pronounced peak in 2025. This trajectory reflects a change in how the community frames the problem: from an early phase treating AMOC collapse as an idealised thought experiment, toward a recent phase in which a weakening AMOC is diagnosed within standard projections and increasingly assessed through the lens of tipping-point risk and its societal implications.

4.3 The disciplinary imbalance

The impacts studied are concentrated overwhelmingly in physical climate. Counting every domain a study addresses, base climate appears in 208 of the 246 studies, far ahead of ocean biogeochemistry (73), extremes (64), society (54), biodiversity (37), agriculture (36), and human health (10). When only the primary domain of each study is counted, the imbalance is starker still: 205 studies treat base climate as their main focus, and every other domain, combined, accounts for 41. Figure 3 cross-tabulates the experimental condition against the impact domain and reveals a second structural feature: the societal and health literatures rest disproportionately on conceptual studies. Of the 54 studies touching on

society, 21 are conceptual (C5); of the 10 touching on health, 6 are. The domains closest to human welfare are thus the least grounded in physical simulation, relying instead on perspectives, integrated assessment, and expert judgement. Physical-climate impacts, by contrast, are supported across all experimental approaches.

4.4 Regional climate response

Base climate is by far the most studied domain (208 studies), and the mean response is also the most consistently reported across the corpus. We summarise it by theme, reserving temperature and precipitation *extremes* for Section 4.5.

North Atlantic cooling and the bipolar seesaw.

The most consistent signal is a cooling of the North Atlantic and the surrounding continents, set against a weaker warming of the Southern Hemisphere. In the earliest coupled hosing experiment, a collapse produced a Northern Hemisphere cooling of 1–2 °C on average, reaching 8 °C locally over the northwestern Atlantic, with European temperatures falling 1–3 °C and a Southern Hemisphere warming of a few tenths of a degree (Vellinga and Wood 2002). Later experiments confirmed the pattern and quantified its dependence on the degree of weakening: a THC reduction from 15 to 8 Sv cooled the North Atlantic by more than 3 °C and lowered European winter temperatures by around 1.7 K (Jacob et al. 2005), while a full shutdown cooled the United Kingdom by 3–5 °C in the first decade (Wood et al. 2003). Multi-model hosing at 0.1 Sv yielded an ensemble-mean weakening near 30%, with cooling of up to 3 °C south of Greenland but no complete shutdown (Stouffer et al. 2006). More recent simulations sharpen the upper bound: an abrupt collapse in a high-resolution model cooled the sea surface by up to 10 °C near western Europe, with regional temperature trends exceeding 1 °C per decade during the transition (van Westen et al. 2024), and a 43% weakening under quadrupled CO₂ offset the global-warming signal by 0.3 °C globally but by 2.4 °C over the subpolar North Atlantic (Bellomo and Mehling 2024). The explicit meltwater-forcing experiments recover the same seesaw at more moderate amplitude: a 0.1 Sv perturbation in an IPSL configuration weakened the AMOC by about 40% and cooled the Northern Hemisphere by 0.2–0.8 °C north of 25°N (Swingedouw et al. 2009).

Southward shift of the tropical rain belt.

Cooling of the northern tropical Atlantic displaces the Intertropical Convergence Zone southward, a response that appears almost universally across conditions and models. It accompanies the cooling in the classic hosing runs (Vellinga and Wood 2002; Wood et al. 2003), in intermediate-complexity collapses where the Southern Hemisphere warms by up to 2 °C (Menviel et al. 2008), and in GFDL experiments where the THC falls from 16 to about 4 Sv (Zhang and Delworth 2005). The southward shift redistributes precipitation on a hemispheric scale, drying the northern tropics and moistening parts of the Southern Hemisphere, and it is the mechanism through which AMOC weakening reaches the monsoon systems.

Monsoon weakening.

The corpus documents a consistent weakening of the monsoons that depend on cross-equatorial moisture transport. A collapse weakens the Indian and West African monsoons in idealised runs (Wood et al. 2003), and dedicated experiments quantify the effect: monsoonal moisture export falls by around 23% under an RCP8.5 collapse (Yu et al. 2018). The explicit meltwater case is anchored by work in the Sahel, where an AMOC reduced by 60–90% of its initial value lowered boreal-summer precipitation by 10–60% over 2030–2060 relative to RCP8.5 (Defrance et al. 2017). Because these monsoon responses bear directly on agriculture and water availability, they recur in Sections 4.8 and 4.10.

4.5 Extremes

Temperature and precipitation extremes respond to an AMOC decline in ways that are often counter-intuitive, because the regional cooling can offset the background warming rather than add to it. The corpus (64 studies) reveals a picture more nuanced than a simple intensification of hazards.

A cooling that reshapes, rather than removes, temperature extremes.

Because a weakened AMOC cools the Northern Hemisphere, it can *reduce* some warm extremes while sharply increasing cold ones. The most detailed account comes from European hydroclimate: under a collapsed circulation, the one-in-ten-year cold-night extreme over northwestern Europe falls from -4.4°C to -34.3°C , and further still under stronger forcing (van Westen and Baatsen 2025). Idealised collapse in the United States lowers the ten-year extreme-cold return level by 3.4°C at Chicago and 5.6°C at New York (Yin and Zhao 2021). Yet the same experiments show that the response is not a uniform increase in cold hazard: in one European study a 60% AMOC reduction cooled mean winter minima by 7.2°C and yet the cold-spell-duration index *decreased*, because the shift of the whole temperature distribution changed its shape as well as its mean (Meccia et al. 2024). This is the central subtlety of the extremes literature: an AMOC decline does not simply make everything more extreme, it redistributes which extremes matter, tilting the balance from heat toward cold over the North Atlantic sector.

Drought and drying.

The southward shift of the rain belt and the reorganisation of the mid-latitude circulation drive widespread drying. A collapse produces a drier European hydroclimate; in the Netherlands, dry-season intensity increases by around 28% under RCP4.5 with a collapsed AMOC relative to its corresponding pre-industrial reference (van Westen et al. 2025). Observational analyses already identify a significant drying trend over central and southern Europe across 1902–2020 (Ionita et al. 2022). Changes in atmospheric circulation regimes compound the effect: a reorganisation toward more anticyclonic flow west of the British Isles raises the risk of summer drought over western and central Europe (Rousi et al. 2021).

Storms, circulation regimes, and compound events.

A weakened AMOC shifts the North Atlantic jet and storm tracks, altering the frequency of the circulation regimes that bring damaging weather. The same regime changes that increase summer drought risk also raise the frequency of zonal, flood-prone regimes over northwestern Europe in winter (Rousi et al. 2021). Conceptual and synthesis studies increasingly link AMOC slowdown to the clustering of high-impact events, framing recent European storm and flood episodes within this circulation context (Graham et al. 2023). Coastal extremes are further amplified by the dynamical sea-level response, examined in Section 4.10.

4.6 Ocean biogeochemistry and productivity

Ocean biogeochemistry is the second most studied domain (73 studies), and the best developed of the non-climate sectors. A weakened AMOC reorganises the physical supply of nutrients, oxygen, and carbon to the ocean interior, with consequences that are large, quantified, and increasingly consistent across models.

Decline in primary production.

The clearest signal is a fall in marine primary production, concentrated in the North Atlantic. Under explicit ice-sheet meltwater forcing, global net primary production declines by 3.2 PgC yr^{-1} (9%), rising to 4.5 PgC yr^{-1} under extreme melt, with an additional loss of 0.8 PgC yr^{-1} in the North Atlantic alone and productivity reduced by $30\text{--}70 \text{ gC m}^{-2} \text{ yr}^{-1}$ in the subtropical gyre and eastern-boundary upwelling regions (Kwiatkowski et al. 2019). The decline is driven by increased stratification and a shoaling mixed layer that starves the sunlit zone of nutrients, and it propagates up the food web: a coupled model projects total system biomass falling by 2–4% on top of the background climate signal (Boot et al. 2025), and community structure shifts as diatoms give way to smaller phytoplankton, with diatom biomass dropping to around a quarter of its initial value and export production at 100 m falling by more than half in the subpolar North Atlantic (Lee et al. 2025).

Reduced carbon uptake.

By slowing the transport of carbon-rich surface water into the deep Atlantic, a weakened AMOC reduces the ocean's uptake of anthropogenic CO_2 . Estimates of the effect span the range of forcings: ocean carbon storage falls by 3.9–12.4 PgC by 2100 under an intermediate scenario, enough to add 0.26–0.81% to global warming (Schaumann and Alastrué de Asenjo 2025), while idealised collapses project far larger long-term redistribution of dissolved inorganic carbon into the deep Atlantic over centuries to millennia (Liu et al. 2023; Schmittner and Boling 2025). A subtlety emerges in the explicit meltwater case: in one such experiment the circulation and biology changes that would reduce uptake by 29.9 PgC were 89% offset by the accompanying salinity changes, leaving only a small net effect (Swingedouw et al. 2007b). The magnitude of the carbon-cycle feedback therefore depends sensitively on how the AMOC decline is forced.

Deoxygenation and nutrient supply.

The physical response also redistributes oxygen and nutrients. Modelling and observations agree on subsurface deoxygenation in the North Atlantic, with oxygen declines already detected on the Scotian Shelf and at Cabot Strait over recent decades (Claret et al. 2018), and basin-scale losses that a slowing circulation modulates (Palter and Trossman 2018; Tagklis et al. 2020). Nutrient pathways are cut at their source: the Gulf Stream nitrate transport falls by 35% under a twenty-first-century slowdown (Whitt 2019), Arctic export production declines by around half with a threefold drop in surface nitrate (Fu et al. 2020), and the reduced nutrient advection to the Labrador Shelf is visible in a sustained shift in algal nitrogen isotopes (Doherty et al. 2021).

Fisheries.

Comparatively few studies carry these biogeochemical changes through to living marine resources, and those that do are largely conceptual. A collapse of North Atlantic plankton to below half its initial biomass would propagate to commercially important stocks such as cod (Gosling 2013), and equatorial Atlantic upwelling, which sustains regional fisheries, weakens markedly under a meltwater-forced collapse (Freire-Souza et al. 2025). The step from a modelled productivity decline to a quantified fisheries impact is, however, rarely taken.

4.7 Terrestrial and marine biodiversity

Thirty-seven studies address biodiversity, spanning range contractions, habitat loss, biome shifts, and the reorganisation of marine communities. Although fewer than for climate or biogeochemistry, several provide quantified, species-level projections that make this one of the more concrete impact domains.

Species range contractions.

The most frequently quantified results concern the contraction of species ranges, and two of them isolate the AMOC contribution explicitly by comparing runs with and without a circulation collapse. For amphibians, the median range contraction under RCP8.5 reaches 51% with full dispersal and 74% without, and adding a hosing-induced collapse increases those contractions by a further 25–50% in the Nearctic and around 50% in the Palearctic (Velasco et al. 2021). Across a broader set of plant and animal species, median geographic-range reductions grow from 35% by 2030 to 78% by 2070 under RCP8.5 alone, and are amplified further once a meltwater-driven AMOC weakening is superimposed, with complete range loss for a fifth of the modelled species (Ureta et al. 2022). These two studies are among the clearest demonstrations in the corpus that an AMOC decline adds materially to the biodiversity loss expected from warming alone.

Habitat loss and biome shifts.

At the community and biome scale, cooling and drying reorganise vegetation. In Europe, an inactive AMOC projects the extinction of Norway spruce across 77% of its current distribution, against 43% under an active circulation, with tree-species diversity declining in 84% of grid cells (Heubel et al. 2025). Idealised cooling shifts European vegetation from temperate broadleaf toward boreal conifer dominance

(Higgins and Schneider 2005), and terrestrial productivity falls, with Sahel net primary production reduced by around 38% in one early assessment (Higgins and Vellinga 2004). The Amazon is a recurring focus, though with a sign that depends on the balance between AMOC-driven wetting and warming-driven drying: several studies find that an AMOC collapse *increases* southern-Amazon rainfall and can delay the forest-to-savanna transition (Ciemer et al. 2021; Nian et al. 2023), while others emphasise loss of moist-forest habitat and the decline of cold- and moist-affinity taxa in northern Amazonia (Akabane et al. 2024).

Marine community reorganisation.

In the ocean, the productivity changes of Section 4.6 translate into shifting species distributions. The centre of mass of silver hake tracks the Gulf Stream position closely and has shifted poleward over four decades (Nye et al. 2011), and rapid northwestern-Atlantic warming under a weakening AMOC, up to three times the global rate in a high-resolution model, drives the redistribution of commercially and ecologically important species (Saba et al. 2016). At the base of the food web, community structure shifts from diatoms toward smaller phytoplankton (Lee et al. 2025), altering the energy available to higher trophic levels.

4.8 Agriculture and food security

Agriculture appears in 36 studies, but as a *primary* focus in only three. This thinness is itself a result: despite the direct dependence of agriculture on the monsoon and rainfall changes documented in Section 4.4, few studies carry the physical signal through to crops or food systems, and those that do cluster on two very different cases, the European breadbasket and the Sahel.

Loss of cultivation zones.

The most striking projections concern the potential loss of major crop-growing areas. A conceptual assessment finds that an AMOC collapse could eliminate around half of global wheat and maize cultivation zones over decades, with Europe hardest hit (Wescombe et al. 2025). A more detailed integrated study quantifies this as a 25% loss of suitable wheat area and 16% of maize area from the AMOC collapse alone, rising to roughly 50% of both once combined with 2.5 °C of warming (Laybourn et al. 2023). For the United Kingdom, where the cooling and drying are most direct, an AMOC collapse cuts the arable share of agricultural land from 32% to 7%, reducing agricultural output by around 346 million GBP per year (Ritchie et al. 2020), a figure corroborated by an independent assessment reporting 3.4 °C of cooling, a summer rainfall reduction of 123 mm, and arable land cut to about a fifth of its current extent (Benton 2020).

Monsoon-driven food risk in the tropics.

The physically most consequential agricultural pathway runs through the monsoons. A dedicated multi-monsoon assessment finds West African monsoon rainfall falling by 29% and Indian monsoon rainfall by 19% under a collapse, with shorter wet seasons and longer dry seasons (Ben-Yami et al. 2024). The

explicit meltwater case is anchored in the Sahel, where an AMOC reduced by 60–90% lowers growing-season precipitation by 10–60% and could remove up to 1.1 million km² of cultivable sorghum area (Defrance et al. 2017). These tropical food-security risks fall on populations far more vulnerable than those of the European cases, yet they rest on far fewer dedicated studies.

4.9 Human health

Human health is the least studied domain in the entire corpus: it appears in only 10 of the 246 studies, and in most of these it is mentioned in passing within a broader review or economic assessment rather than analysed in its own right (Gosling 2013; Laybourn et al. 2023; Loriani et al. 2025). Six of the ten are conceptual (C5). The near-absence of dedicated AMOC–health research is one of the most consequential findings of this review, because the health burden of monsoon failure, food insecurity, and shifting disease vectors would fall on the populations least represented elsewhere in the corpus.

The few quantified signals.

Where health outcomes are quantified, the results are pointed. A shutdown producing 3 °C of cooling over northwestern Europe is estimated to cause around 5 500 additional temperature-related deaths per year in the Netherlands alone, alongside shifts in disease vectors (Martens et al. 2010). The temperature-mortality relationship is, however, double-edged: because the regional cooling opposes greenhouse warming, an AMOC slowdown acts predominantly to *attenuate* future European heatwaves and the mortality associated with them (Duarte et al. 2025), so the net effect on thermal-stress deaths depends on the balance between reduced heat mortality and increased cold mortality (Hayashi et al. 2010).

Vector-borne disease.

Within the eligible 2000–2025 corpus, the clearest dedicated AMOC–health study concerns malaria. By slowing the AMOC and shifting the African rain belt southward, accelerated Greenland melt is projected to *reduce* malaria prevalence by 4–8% over the Sahel and by up to 16% over the East African plateaus, while *increasing* it by 6–14% over southern Africa and lengthening the transmission season there by one to three months (Chemison et al. 2021). This redistribution, rather than uniform change, illustrates precisely the kind of health consequence that an AMOC-focused analysis can reveal and that a warming-only study would miss.

4.10 Societal vulnerability, economy, and sea level

Fifty-four studies address societal dimensions, making this the largest of the non-climate domains, but its composition is distinctive: it leans heavily on conceptual work (21 of the 54 are C5) and concentrates on two well-defined strands, macroeconomic assessment and coastal sea-level rise, while the more diffuse questions of migration and conflict remain almost unquantified.

Economic cost.

The macroeconomic literature is dominated by integrated-assessment modelling. A global estimate puts the direct GDP loss from a shutdown at around 0.1% by 2100, but this small aggregate hides a highly uneven distribution: national impacts reach -3.65% of GDP for Iceland and -2.52% for Denmark, while a few economies, such as Egypt, are projected to benefit (Link and Tol 2011). This unevenness, rather than the modest global mean, is the substantive economic result. Other assessments frame the AMOC as a tail risk to be avoided: optimal carbon-tax pathways that internalise the collapse rise steeply once its damages are counted (Mastrandrea and Schneider 2001), and stabilisation scenarios show the collapse can be avoided at sufficiently low concentrations (Mori et al. 2006). The sectoral economic studies of Section 4.8 (British arable land, crop zones) provide some of the few bottom-up damage estimates.

Dynamical sea-level rise.

The most consistently reported societal impact is coastal, and it is concentrated on the northeastern seaboard of North America. Because a weakened AMOC raises sea level dynamically along that coast, independently of thermal expansion, projections place additional rise at New York City of 0.15–0.23 m by 2100 depending on scenario (Yin et al. 2009), with further increments under added Greenland melt (Schleussner et al. 2011). Observational work links the recent Gulf Stream weakening to accelerated coastal sea-level rise, with a correlation of $R = -0.85$ between transport and coastal sea level (Ezer et al. 2013), and recent acceleration exceeding 10 mm yr^{-1} along the U.S. Southeast and Gulf coasts (Yin 2023). This coastal signal is where AMOC decline most directly threatens dense, high-value human settlement.

Migration, conflict, and adaptation limits.

Beyond economics and sea level, the societal literature thins markedly. Migration and conflict are named as plausible consequences of monsoon failure and food insecurity in conceptual and review studies, but almost never quantified. A recent assessment emphasises that the speed and magnitude of an AMOC-driven cooling could exceed the limits of feasible adaptation in Europe, invoking both soft and hard adaptation constraints (Biesbroek et al. 2025). Such framings signal a shift toward treating AMOC collapse as a governance and adaptation problem, but the empirical basis for its social consequences remains slight.

4.11 Geographic mismatch between physical evidence and human-impact research

The final axis of the synthesis is spatial: where the impacts fall, and where the evidence for them has been produced. The two do not coincide.

A distinctive impact signature in each region.

Read across the corpus, the reviewed studies assign a characteristic set of impacts to each part of the world (Supplementary Fig. S4). The Arctic and the subpolar North Atlantic carry the strongest physical

signal, with surface cooling and sea-ice loss dominating, set against the paradoxical warming of the Nordic Seas dipole. Northwestern Europe shares the cooling and adds drying and shifts in storminess. Along the northeastern coast of North America the signature is overwhelmingly one of dynamical sea-level rise. The tropics tell a different story: over the Sahel and West Africa the dominant impacts are monsoon and rainfall decline, over the Amazon a contested change in precipitation, and over South and East Asia a weakening of the monsoon. East Africa is the one region where the corpus records a health signal, the redistribution of malaria. This regional patterning is the substantive synthesis that Supplementary Fig. S4 makes visible.

Effort concentrated away from likely impact.

Research effort is concentrated in the North Atlantic, Europe, and North America, while dedicated human-impact assessments remain comparatively sparse across several populous and climate-vulnerable tropical regions where AMOC-driven monsoon disruption could have major consequences (Supplementary Fig. S3). Africa appears in 54 studies but predominantly for its base-climate response (48), with its societal (14) and health (8) dimensions barely addressed; the same pattern holds for South America. The regions where the physical signal is best understood are therefore not those where potentially large human consequences remain most poorly quantified. The tropical monsoon belt, home to large and highly exposed populations, is studied mainly for its mean climatology and rarely for what a rainfall collapse would mean for the people who live there.

The synthesis map (Supplementary Fig. S4) brings these threads together, placing the dominant documented impact of each region in its geographic context. It serves as a visual summary of the sectoral results of Sections 4.4–4.10 and, read against Supplementary Fig. S3, of the mismatch between where impacts concentrate and where they have been studied.

5 Discussion

Hosing legitimately isolates circulation responses and bounds worst cases. However, effects under collapse-guaranteeing forcing cannot be assumed for more modest, physically plausible or projected weakening (Section 4.1). Impact magnitude, and sometimes sign, depends on forcing, as illustrated by the salinity offset of reduced carbon uptake in an explicit meltwater experiment.

Physical-climate dominance and reliance on conceptual societal and health studies weaken the chain to human outcomes (Section 4.3). Health is primary in effectively one eligible study. Rare studies closing the chain include malaria redistribution driven by a meltwater-forced African rain-belt shift.

A post-cut-off qualitative study supports this diagnosis: interviews with 17 transdisciplinary experts identified uncertainties in AMOC-collapse health consequences and potential effects on healthcare preparedness, psychosocial health, food security, infrastructure, and societal resilience in Germany (Mirow 2026). Published after 31 December 2025, it contributes neither to the corpus nor to quantitative counts, but illustrates emerging cross-sectoral health research.

Geographic bias compounds these limitations: northern physical-climate evidence is richest, while human impacts remain poorly quantified across populous, vulnerable tropical regions (Section 4.11). Together, the biases favour northern regions' mean physical response to unrealistically strong forcing over downstream consequences of more plausible scenario-emergent or explicit-meltwater weakening. Policy-relevant evidence is thinnest where potentially large human consequences remain least quantified; assessments risk precision within a narrow physical regime.

Cross-sectoral assessment is nevertheless achievable. Explicit meltwater studies trace circulation decline through climate, biogeochemistry, biodiversity, agriculture, and society (Kuhlbrodt et al. 2009; Hu et al. 2011), or couple Greenland forcing to ocean and cryosphere responses (Golledge et al. 2019; Sadai et al. 2020). A sustained line using one Earth system model with bias-corrected meltwater forcing extends from Sahel rainfall and agriculture (Defrance et al. 2017) to climate zones (Defrance et al. 2020), ocean production (Kwiatkowski et al. 2019), biodiversity (Velasco et al. 2021; Ureta et al. 2022), and malaria (Chemison et al. 2021, 2022). Despite individual-model limitations, these studies demonstrate physically consistent impact chains reaching the Global South.

The priority is to complement physical diagnostics with explicit, scenario-consistent meltwater impact chains extending into agriculture, health, and society across vulnerable tropical and Southern-Hemisphere regions. Compound assessments of interacting drought, food insecurity, disease, and displacement are almost absent, although the largest human risks are likely there. Coordinated multi-model experiments and next-generation Earth system models can improve forcing; downstream and geographic coverage require treating the AMOC as a driver of consequences for people least equipped to absorb them. These priorities connect Climate Action (SDG 13), Good Health and Well-Being (SDG 3), Zero Hunger (SDG 2), and Sustainable Cities and Communities (SDG 11) to usable AMOC risk assessment.

Four complementary queries in one database may still miss literature elsewhere. Validation of LLM-assisted screening and extraction is detailed in Section 3. Without formal risk-of-bias or quality appraisal, counts measure coverage, not evidential strength: conceptual perspectives and multi-model intercomparisons each count once. Excluding the four manually added studies reduces C4 from 21 to 17 and the corpus from 246 to 242, with marginal changes (health 10 to 9; biogeochemistry 73 to 72) and unchanged qualitative conclusions. Primary-domain and regional classifications remain coarse measures of literature structure.

6 Conclusions

This review synthesised 246 studies of the impacts of a weakened or collapsed AMOC, coding each for how the decline was represented, which model and forcing produced it, and which domains and regions it concerned. Three findings stand out. The circulation is most often perturbed by idealised hosing at fluxes far above any plausible meltwater input, while experiments incorporating explicit ice-sheet meltwater forcing remain a small minority. The evidence is heavily weighted toward the physical climate,

with agriculture, health, and society thinly covered and resting largely on conceptual work. And research effort is concentrated in the North Atlantic and Europe, leaving the evidence comparatively sparse across several populous and climate-vulnerable tropical regions where AMOC-driven monsoon disruption could have major human consequences.

These are not fully independent gaps: the least realistic forcings, the best-studied physical domains, and the best-resourced northern regions tend to combine, so the impact evidence appears thinnest for the regions and sectors where potentially large human consequences of an AMOC decline remain poorly quantified. This limits the usefulness of the current literature for risk assessment, however rich it is as physical science.

Closing this gap is within reach. Coordinated multi-model experiments using explicit, scenario-consistent meltwater protocols, together with the next generation of Earth system models, can complement idealised hosing with more plausible trajectories, and a small but growing body of explicitly meltwater-forced, cross-sectoral work already shows that impact chains reaching into the Global South are achievable. Our recommendation is that the field should rebalance its priorities by complementing further physical-climate diagnostics with physically consistent, explicitly meltwater-forced impact assessments that extend into agriculture, health, and society and that resolve the populous and climate-vulnerable tropical and Southern-Hemisphere regions where potentially large human consequences remain poorly quantified. That reorientation is what would turn a mature physical understanding of the AMOC into an assessment of its consequences commensurate with the stakes.

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Figures

PRISMA 2020 flow -- Socio-ecological impacts of a weakened AMOC

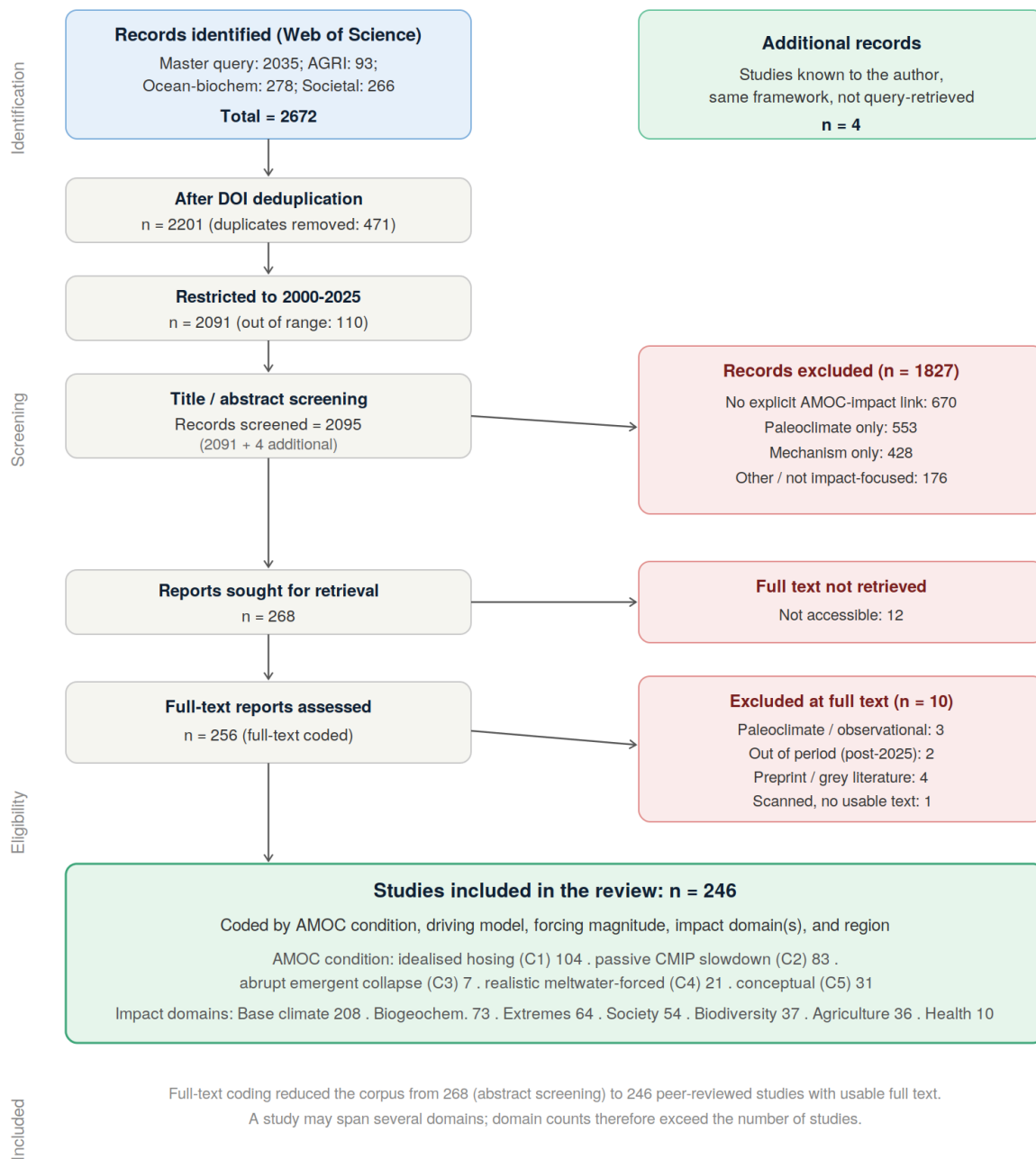


Figure 1

PRISMA 2020 flow diagram for the systematic evidence map. From 2 672 records identified across the master and thematic Web of Science queries, 246 studies were retained after deduplication, title/abstract screening, and full-text assessment. Four further studies known to the author to meet the inclusion criteria, but not retrieved by the queries (indexing and keyword mismatches) and applying the same meltwater-forcing framework as other corpus studies, were added under the same criteria

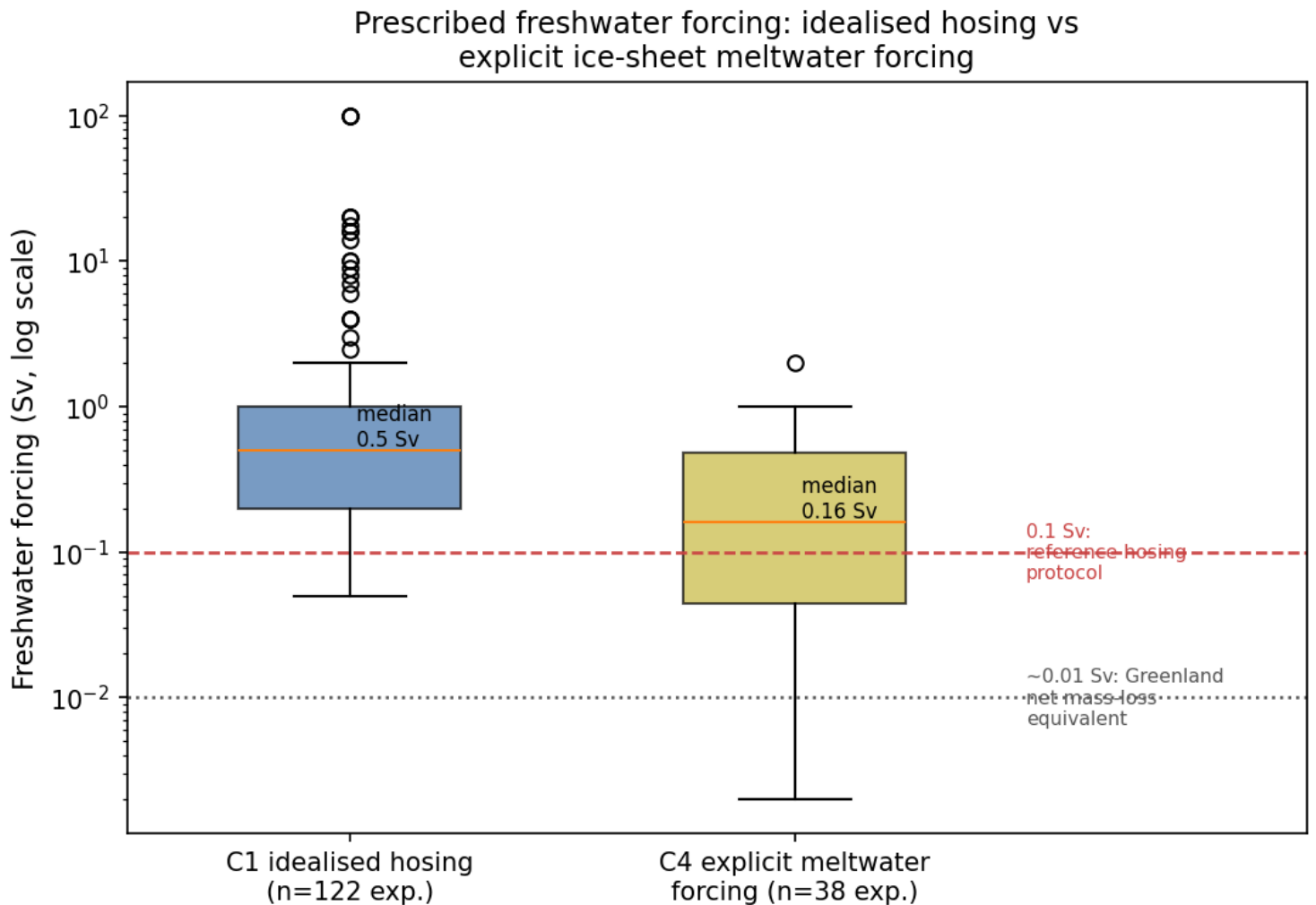


Figure 2

Magnitude of the prescribed freshwater forcing, on a logarithmic scale, for idealised hosing experiments (C1) versus explicit ice-sheet meltwater-forcing experiments (C4). Idealised hosing has a median of 0.5 Sv and reaches values up to 100 Sv, far above any physically plausible meltwater flux, whereas explicit meltwater forcing clusters near 0.16 Sv. For reference, two horizontal lines are shown: the commonly used reference hosing value of 0.1 Sv (dashed) and present-day Greenland Ice Sheet net mass loss, of order 0.005–0.01 Sv depending on the averaging period (dotted). The statistical unit is the individual experiment

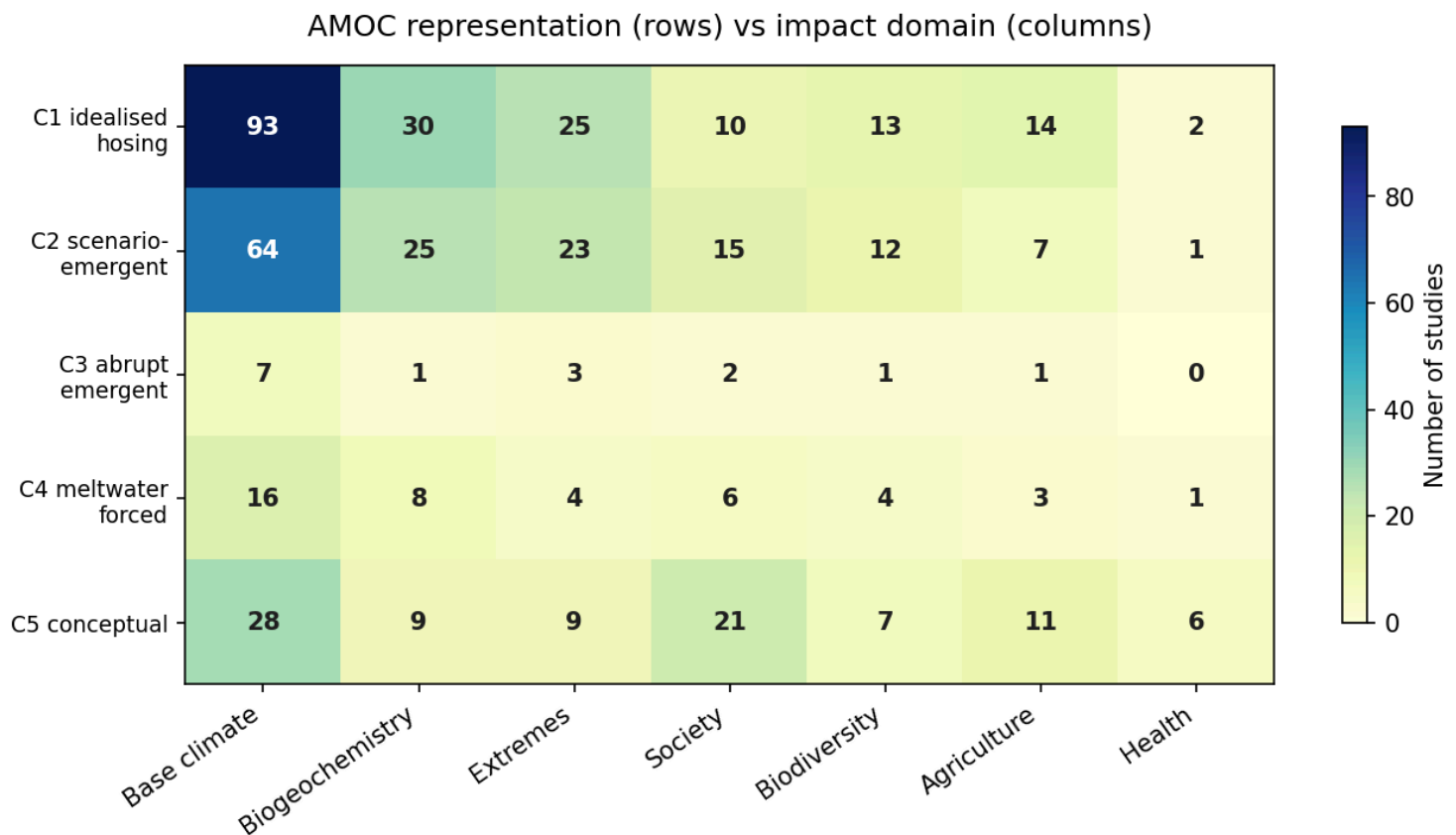


Figure 3

How the AMOC is perturbed (rows) versus which impacts are studied (columns), across the 246-study corpus. Cell values are study counts. Physical-climate impacts dominate every experimental approach, whereas societal and health impacts rest disproportionately on conceptual studies (C5) rather than on physical AMOC simulations