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CRYOSPHERE

The cryosphere beyond a planetary safe operating space

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The cryosphere plays a vital role in regulating planetary dynamics and habitability, yet it remains unclear whether its essential functions remain within a safe operating space (SOS) amid Anthropocene change. Here, we propose a cryosphere SOS and systematically evaluate its contributions to Earth system resilience using the planetary boundaries framework. Multiple lines of evidence indicate an accelerating and partly irreversible loss of cryospheric integrity, driven by amplifying feedbacks. Key cryospheric control variables either have left or are committed to departing from Holocene-like conditions. We conclude that the cryosphere has breached its SOS and is on a trajectory that locks in long-term risks for human societies and ecosystems. Safeguarding planetary resilience therefore requires explicit consideration of cryosphere change and its interactions across the Earth system.

The concept of safe operating space (SOS) has been used to define the environmental limits within which humans and ecosystems can thrive while maintaining the stability and resilience of the Earth system (*1*, *2*). The cryosphere, the frozen components of the Earth system including ice sheets, mountain glaciers, sea ice, snow cover, and permafrost, plays an irreplaceable role in regulating Earth system energy, water, carbon, and methane cycles (*3*–*6*). Its capacities for thermal inertia, phase change buffering, albedo feedback, carbon storage, and frozen water storage have been crucial for maintaining relatively stable climate and ecological conditions (*7*, *8*). The cryosphere has also been recognized as part of the planetary commons, along with the atmosphere, hydrosphere, biosphere, and lithosphere (*9*), underscoring shared responsibilities for maintaining planetary resilience and justice. Yet, despite its importance, no planetary SOS has been defined for the cryosphere.

The cryosphere is influenced by both natural variability and external forcing across timescales ranging from seasons to millions of years. Natural variability can contribute to substantial cryosphere change. However, the rapid and widespread cryosphere changes observed since the mid- to late twentieth century are predominantly attributable to anthropogenic climate change (*10*, *11*), with additional contributions from regional human disturbances, including black carbon deposition, infrastructure development, and other land-use activities (*12*, *13*). Consequently, these changes have far-reaching impacts for water availability, ecosystems, land surfaces, oceans, and climate from local to global scales (*5*, *14*). Several cryosphere elements also exhibit tipping behavior: once critical thresholds are crossed, they undergo essentially irreversible state shifts within human-relevant timescales. Cryosphere changes thus have the potential to compromise Earth system resilience—the capacity of the Earth system to maintain life-supporting conditions (*15*–*19*), and a systematic assessment of Earth system resilience changes arising from cryosphere decline is urgently needed. The absence of a cryosphere-specific SOS limits policymakers' capacity to govern cryosphere sustainability, hindering risk awareness, communication, and decision-making.

The planetary boundaries (PB) framework is an established approach for defining a planetary SOS (*1*, *2*, *20*, *21*). The Holocene, i.e., the past 11,700 years, serves as the reference state for PB assessments, as it was characterized by relatively stable planetary conditions under which human civilizations emerged and flourished (*22*–*25*). The PB framework comprises nine boundaries, each grounded in an Earth system component defined by one or more control variables that indicate the risk of transitioning away from Holocene-like conditions (*20*) (Fig. 1A). Boundary values are set conservatively, following the precautionary principle, and positioned at the lower end of the zone of increasing risk (*21*, *26*). Together, the boundaries directly represent nine key Earth system processes that regulate planetary function and stability, i.e., biosphere integrity, climate change, stratospheric ozone depletion, atmospheric aerosol loading, freshwater change, ocean acidification, land-system change, biogeochemical flows, and the introduction of novel entities (i.e., anthropogenically introduced materials, substances, or lifeforms). While the cryosphere is not yet explicitly included in the PB framework, a growing body of research shows that cryosphere functions critically underpin Earth system stability and resilience through cryo-climatic, cryo-ecological, and cryo-hydrological regulation (Fig. 1B, supplementary text, and table S1).

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Here, we propose a cryosphere SOS consistent with PB principles and assess its current status (Fig. 1C). We first identify and evaluate candidate cryosphere control variables through literature review, expert elicitation, iterative discussion, and consensus-based methods guided by PB criteria (materials and methods). Four control variables are identified—land ice volume, sea ice area, snow cover area, and permafrost temperature—to capture key cryosphere functions that regulate Earth system resilience (Fig. 1D). We then assess the cryosphere's departure from Holocene-like conditions and the implications for Earth system resilience. Rather than serving as a direct estimate of physical tipping points or irreversible thresholds, the proposed cryosphere SOS is precautionary and risk-based. We conclude by outlining research priorities to better understand the cryosphere-driven Earth system risks, and by discussing the governance relevance of recognizing cryosphere SOS transgression within global sustainability frameworks.

Assessment of cryosphere's SOS

We assess the cryosphere SOS in three steps: i) quantifying departures from Holocene-like baseline conditions for four control variables (materials and methods); ii) evaluating the Earth system's capacity to remain within these bounds; and iii) assessing boundary transgression by integrating baseline departures, Earth system resilience, and committed cryosphere change under climate stabilization.

Baseline departure

Baseline departure is defined as values falling below the 5th percentile of baseline distribution for land ice volume, sea ice area, and snow cover area (lower bound), and exceeding the 95th percentile for permafrost temperature. These baseline bounds are used to quantify departures from Holocene-like baseline variability and serve as an important input to the subsequent boundary transgression assessment. Where available, the full Holocene is used to define baseline variability; otherwise, mid-Holocene or pre-industrial conditions are applied in this initial assessment (*26*, *27*).

For land ice, the control variable is defined as the global integrated ice volume, encompassing mountain glaciers, the Greenland Ice Sheet, and the Antarctic Ice Sheet. Holocene time series of global land ice volume and its components were reconstructed using two independent estimates of ice mass variability (*28*, *29*) and recent ice volume assessments (approximately 2010) (*30*–*32*). The lower 5th percentile of Holocene variability for global land ice is estimated at 27.48 (90% CrI: 26.85–27.79) $\times 10^6$ Gt, comprising 2.67 (2.56–2.74) $\times 10^6$ Gt for Greenland (the ice sheet + peripheral glaciers), 24.69 (24.19–24.85) $\times 10^6$ Gt for Antarctica (the ice sheet and peripheral glaciers), and 0.08 (0.04–0.17) $\times 10^6$ Gt for global mountain glaciers (excluding Greenland and Antarctic peripheral glaciers). Analysis for 1850–2018 (Fig. 2A, fig. S1, and Table 1) shows that current global land ice volume, and each of its components, remains above this lower bound.

For sea ice, the control variable is represented by the annual-mean total area across both hemispheres. As baseline references, we use the mid-Holocene (CESM2 simulation spanning 700 years, beginning ~6 ka BP) and pre-industrial (1850–1899) periods, due to a lack of continuous Holocene reconstructions (Table 1). Departures for 1850–2024 and 1900–2024 reveal a clear and accelerating divergence (Fig. 2B). A persistent departure of global sea ice from baseline envelopes emerged around the 1980s, with the Arctic's departure in the 1990s and the Antarctic following in the mid-to-late 2010s (fig. S2).

For snow cover, the control variable is the global annual-mean snow-covered area. Similar to sea ice, baselines for snow cover are derived from a CMIP6 CESM2 mid-Holocene simulation and pre-industrial simulations (Table 1). Analyses for 1850–2024 and 1900–2024 show a consistent decline in annual-mean global snow-covered area beginning in the mid-1980s, with a permanent departure from both baselines evident by the early 1990s (Fig. 2D)—in agreement with IPCC AR6 assessments (*11*).

For permafrost, the control variable is expressed as the mean annual ground temperature (MAGT) within the spatial domain of the maximum preindustrial permafrost region (*33*). Baseline conditions are derived from the CESM2 mid-Holocene simulation and ISIMIP preindustrial multi-model simulations (Table 1). Global permafrost MAGT has warmed steadily since pre-industrial times, with a clear departure from the pre-industrial variability envelope emerging in the 1980s (Fig. 2C). Both CESM2 and ISIMIP models indicate consistent warming trends, although absolute temperature values differ between models. The global permafrost area is also shrinking beyond both baseline envelopes (fig. S3).

Earth system resilience

The cryosphere underpins Earth system resilience—the capacity of the planet to maintain or recover to Holocene-like conditions despite anthropogenic perturbations. Assessing cryosphere SOS transgression therefore requires evaluating Earth system resilience alongside departures of the proposed control variables from Holocene-like conditions. Here, we examine cryosphere-related feedbacks and tipping dynamics from continental to planetary scales as indicators of Earth system resilience across the four cryosphere components. Based on the available evidence, we conclude that Earth system resilience is compromised due to the dominance of amplifying feedbacks over stabilizing ones, and the irreversible and cascading risks of activating cryosphere-controlled tipping elements (Fig. 3).

First, land ice retreat introduces several powerful amplifying feedbacks (Fig. 3A). One is the melt–albedo feedback, where melting ice exposes darker surfaces, reducing albedo and increasing solar absorption, thereby reinforcing further melt (*36*). Ice darkening through algal blooms and deposition of light-absorbing impurities – including dust (from natural and increasingly anthropogenic sources), black carbon, and other anthropogenic particulates – further amplifies this feedback (*37*–*40*). A second is the melt–elevation feedback (*41*): as surface melt lowers the elevation of glaciers and ice sheets, they are exposed to warmer air masses with enhanced sensible and latent heat exchange. This effect, further exacerbated by reduced orographic snowfall, accelerates additional melt (*42*). Paleoclimate evidence and modelling studies also show that once critical thresholds are crossed, marine ice sheet instability can trigger self-sustaining retreat of the West Antarctic Ice Sheet (WAIS) (*43*, *44*), while marine ice cliff instability may further accelerate disintegration (*45*, *46*). Mountain glaciers exhibit their own set of local-scale amplifying feedbacks, including ice thinning, shrinking accumulation zones, surface darkening, and altered snow redistribution (*34*). Although some stabilizing feedbacks partially offset land ice loss—such as transient snowfall increasing under warming conditions (*47*–*49*) and the long-term influence of glacial isostatic adjustment acting over millennia (*50*)—these effects to date have not counteracted the dominant amplifying feedbacks and are not expected to do so in the foreseeable future (*34*). The overall dominance of these amplifying mechanisms drives far-reaching consequences: global sea-level rise, disruption of oceanic and atmospheric circulation, reduced freshwater provision, and cascading ecological impacts (*51*). The Greenland Ice Sheet, West Antarctic Ice Sheet, East Antarctic subglacial basins, and East Antarctic Ice Sheet have been designated as planetary tipping elements (Fig. 3B), and mountain glaciers are recognized as regional tipping elements (*17*, *34*). The progressive activation of these tipping

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elements would mark a fundamental and potentially irreversible degradation of Earth System resilience.

Second, sea ice declines in the Arctic and Antarctic similarly exhibit potent feedback behavior. Increased summer and autumn sea ice ablation darkens the ocean surface through expanding melt ponds and open water, amplifying atmospheric and oceanic heating via both melt–albedo and ice–ocean heat flux feedbacks (*52*). Although Arctic summer sea ice declines approximately linearly with warming because of counteracting negative feedback (*53*), the sea ice system may nevertheless exhibit regional thresholds and abrupt transitions. For Arctic sea ice, a notable threshold occurred in 2007, when the flushing of thick, multi-year ice left a thinner, younger ice pack, altering the trajectory of the decline (*54*). Post-2007 variability has been strongly influenced by atmospheric dynamics, including phases of the Arctic Oscillation, and by the geometric constraints of the Arctic Ocean (*55*). Model projections show a nearly ice-free Arctic summer by the 2040s, marking a shift toward a thinner, more transient summer ice cover (*56*). In the Antarctic, the extreme sea ice decline observed over the past decade has been interpreted by some studies as an abrupt change, potentially lying outside the range of natural variability (*54*, *57*, *58*). Oceanic changes—including warmer circumpolar deep water and a saltier surface layer—have accelerated ice loss (*58*). Classic albedo feedbacks now pose concerns for Antarctic summers, as reduced ice coverage delays winter refreezing. Both gradual and abrupt losses of polar sea ice substantially erode planetary resilience by amplifying global and regional warming, exacerbating weather and climate extremes, disrupting oceanic circulation, and driving irreversible ecological impacts. Despite lacking conclusive evidence for self-sustained irreversibility (*59*) and being thus excluded from the list of major tipping elements with a high confidence (*34*), sea ice plays an important role in mediating transitions towards (or from) Earth tipping elements (*34*, *35*).

Third, snow cover losses are also amplified by the albedo feedback (Fig. 3A): reduced albedo increases net shortwave radiation absorption, which in turn intensifies surface warming and accelerates snowmelt (*60*–*62*). While global climate models often treat hemispheric snow cover loss as a largely linear response to global mean temperature (*11*), the system also exhibits non-linear regional thresholds (*63*) and phase shifts (*11*, *64*). For example, as continental interiors cross the 0°C threshold earlier in spring, seasonal snowmelt shifts from a gradual decline to a highly synchronized, abrupt regional pulse (*63*). A pervasive regional decoupling has also emerged between mountain snowmelt dynamics and downstream streamflow generation (*65*). Ultimately, the accelerated degradation of snow cover destabilizes adjacent cryosphere components, disrupts regional hydrological and ecological systems, and alters planetary energy balance (*61*, *65*)—collectively eroding the planetary resilience that sustains Holocene-like conditions.

Fourth, permafrost thaw introduces an additional, powerful carbon–climate feedback (Fig. 3A). Model projections suggest that emissions from thawing permafrost could contribute an additional 0.05–0.7°C of global warming by 2100 under low- to high-CO_2 emission scenarios (*66*, *67*). Paleoclimate reconstructions reveal strong coupling between permafrost carbon stocks and climate; following the last deglaciation, northern soils lost more than 300 Pg C, reaching a minimum in the early Holocene before progressively accumulating towards pre-industrial levels (*68*). Methane released from thawing permafrost may contribute up to 50% of the total radiative forcing associated with permafrost carbon emissions (*69*). Thermokarst processes, triggered by local disturbances, rapid warming, or extreme events, can further accelerate thaw, greenhouse gas emissions, and landscape and ecosystem disruptions through self-amplifying feedbacks (*70*, *71*). Subsea permafrost thaw may also accelerate as declining sea ice reduces oceanic insulation and altered circulation brings warmer waters onto continental shelves (*72*). Although permafrost lacks a single global threshold and is therefore not classified as a global tipping element with high confidence, it nonetheless operates as a tipping system at the regional scale (*34*) (Fig. 3B). Owing to the slow formation of permafrost and the sustained microbial decomposition of thawed organic matter, much of the carbon loss and landscape disruption are likely irreversible on centennial-to-millennial horizons (*73*), thereby severely compromising Earth system resilience the maintain Holocene-like conditions.

In addition, cryosphere-related feedbacks and tipping dynamics are interconnected, both within the cryosphere and across other Earth system domains (*19*, *74*), many of which are destabilizing (*34*, *35*), further undermining Earth system resilience.

Boundary transgression

Given the compromised resilience of the Earth system, cryosphere boundary positions should be defined conservatively. Here, we provisionally adopt the upper or lower bounds of the baseline variability envelope as precautionary boundary positions (Table 1), recognizing that they are intended as risk-based indicators rather than physically derived stability limits (*20*, *26*, *27*).

Applying these baseline bounds, an SOS for global integrated land ice requires volumes above 27.48×10^6 Gt, including $>24.69 \times 10^6$ Gt in Antarctica, $>2.67 \times 10^6$ Gt in Greenland, and $> 0.08 \times 10^6$ Gt in global mountain glaciers. A planetary SOS for sea ice corresponds to a global annual-mean area $> 19.8 \times 10^6$ km^2, with $>9.7 \times 10^6$ km^2 in the Arctic and $> 9.8 \times 10^6$ km^2 in the Southern Ocean. For snow cover, the SOS corresponds to a global annual-mean area of 38.8×10^6 km^2. For terrestrial permafrost, the SOS is provisionally set at MAGT < -6.6°C, derived from the ISIMIP multi-model mean and the maximum pre-industrial permafrost extent (1850–1899). Together, these boundaries delineate a safe cryospheric state that supports Earth system resilience by maintaining stabilizing feedbacks and minimizing the risk of crossing critical tipping points.

Cryosphere components differ markedly in adjustment timescales owing to their distinct responses to external forcings: snow and sea ice adjust quickly and remain near equilibrium with current climate, whereas permafrost and land ice respond over much longer periods, from decades to millennia. Our cryosphere SOS framework integrates both fast- and slow-responding components to assess Earth system risks: fast-responding components act as leading indicators of functional degradation, whereas slow-responding components represent long-term commitments and potentially irreversible consequences. These contrasting response times have important implications for assessing boundary transgressions. While near-equilibrium sea ice and snow cover offer a direct basis for evaluation, out-of-equilibrium land ice and permafrost necessitate an explicit accounting of committed future losses already locked in under contemporary climate conditions. Indeed, even if anthropogenic emissions ceased immediately, land ice and permafrost shrinkage would persist. Existing estimates indicate that, under current disequilibrium, global mountain glaciers (excluding Greenland and Antarctic peripheral glaciers) are committed to an ice loss of 37 (*21*–*54*) $\times 10^3$ Gt (*75*), the Greenland Ice Sheet is committed to a loss of $0.1 \pm 0.025 \times 10^6$ Gt (*76*). The Antarctica Ice Sheet is committed to a loss of approximately 0.5×10^6 Gt by 2500 (*77*), with depletion persisting for millennia (*45*). Consequently, the integrated committed loss driven by contemporary disequilibrium could far exceed 0.64×10^6 Gt, placing global land ice

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well beyond the Holocene variability envelope. Committed permafrost loss across the twentieth century has been estimated at 3.4 ± 2.3 million km^2 (*78*). Our assessment of the permafrost SOS has not yet considered the rapid thaw in subsea permafrost underlying the Arctic Ocean—remnants of terrestrial permafrost later submerged by postglacial sea-level rise (*79*).

We conclude that the cryosphere has already transgressed its planetary SOS considering baseline departure, committed losses, and deterioration in cryosphere-mediated Earth system functions. Sea ice, snow cover, and permafrost have currently departure from their Holocene-like baselines, while land ice is committed to such departure. Cryosphere change and SOS transgressions are inherently nonlinear processes, shaped by external forcing, internal system dynamics, feedback mechanisms, tipping behavior, and interactions with other Earth system components.

Towards global cryosphere sustainability

In this study, we propose a cryosphere SOS based on the planetary boundaries framework, and assessed the extent to which the cryosphere's essential functions remain compatible with Earth system resilience. We identified four control variables—land ice volume, sea ice area, snow cover area, and permafrost temperature—and found they are departing from Holocene-like baseline conditions. Moreover, changes across many cryosphere subsystems are associated with self-amplifying feedbacks, tipping dynamics, and non-linear impacts on the Earth system's overall capacity to maintain Holocene-like states. Hence, we provisionally conclude that the cryosphere has already breached, or committed to crossing its proposed SOS. Maintaining and restoring Earth System resilience now requires urgent global action to halt and reverse greenhouse gas and black carbon emissions, and to reduce the effects of local human disturbances such as infrastructure expansion in cryospheric regions.

Research frontiers

Our SOS assessment remains provisional, highlighting the need to better constrain cryosphere control variables and deepen understanding of their role in Earth system resilience. First, there are still large uncertainties regarding the quantification of both Holocene-like baseline and current status, stemming from critical gaps in mechanistic understanding, observation and reconstruction, and model parameterization (*11*). Due to the logistical challenges of operating in harsh cryospheric environments, the cryosphere remains sparsely observed, with limited spatial and temporal coverage (*11*). This constrains mechanistic understanding and leaves the cryosphere underrepresented in Earth System modeling (*80*). Strengthening observation networks, remote sensing, paleoclimate reconstructions, and data assimilation is essential for advancing cryosphere modelling and digital twins (*81*), and ultimately for improving cryosphere SOS assessments. In particular, an improved quantification of Holocene ranges of variability likewise requires close collaboration across cryosphere science, Earth system modelling, and paleosciences (*21*). A deeper understanding of the cryosphere's interactions and cascading feedbacks across the Earth system is also essential for a robust SOS assessment. Multidisciplinary and coupled modelling approaches are urgently needed to improve the quantification of cross-sphere interactions and nonlinear dynamics, and to identify thresholds beyond which cryosphere perturbations could drive irreversible large-scale transitions (*11*, *34*, *51*). Evaluating the hysteresis and committed loss of cryosphere components is critical for assessing their boundary transgressions, which further requires accounting for the impacts of temperature-overshoot trajectories (*34*, *82*, *83*). Additional research is needed to quantify the impacts of human perturbation on cryosphere boundary transgression, and to understand how governance and management interventions can modulate the cryosphere's contributions to Earth system resilience and human well-being.

Integration within the PB framework

The cryosphere SOS may potentially be incorporated into the PB framework in two ways: (1) integrating cryosphere control variables within existing PBs, or (2) establishing a dedicated tenth boundary for cryosphere change. Integration into existing boundaries would be most relevant for climate change, freshwater change, and land system change, yet each has conceptual limitations. The climate change boundary focuses primarily on atmospheric variables (radiative forcing and atmospheric CO_2 concentration), and supplementing these with cryosphere control variables could capture the unique dynamics and hysteresis of cryosphere processes; however, this will overlook the cryosphere's hydrological and ecological functions beyond its climate functions. The freshwater change boundary could treat the cryosphere as frozen water, but would overlook cryosphere-specific feedbacks and timescales. The land system change boundary considers boreal regions, but it insufficiently represents cryospheric processes that extend beyond terrestrial forest systems. Given its unique systemic role, the cryosphere is therefore a strong candidate for a tenth PB, supported by extensive evidence that the cryosphere's distinctive properties and functions fundamentally regulate Earth system stability and resilience. Following further evaluation, a dedicated cryosphere boundary can serve as a robust indicator of planetary state, provide a clearer message for communication, and guide strategies to prevent abrupt and irreversible cryosphere and Earth system transitions.

In addition, significant harm to people can occur well before planetary SOS boundaries are crossed, with profound implications for interspecies, intergenerational, and intragenerational justice (*84*–*86*). Human societies depend heavily on the services provided by the cryosphere (*3*, *5*), and the impacts of cryosphere change are often experienced first and most acutely at local or regional scales. For example, even before global land ice has exceeded its SOS, mountain glacier retreat has already generated significant regional risks through its effects on hydrological systems (*87*), including increasing glacial hazards and adverse impacts on water resources. Future work could further consider defining a Safe and Just Operating Space (SJOS) for the cryosphere—one that combines precautionary biophysical limits with justice considerations to minimize harm and deprivation for humans and other beings.

Governance relevance

The proposed cryosphere SOS boundaries can be translated for actors across scales to establish time-bound targets and strategies (*88*). The land ice boundary guides strategies to counter irreversible ice loss, sea-level rise, climate instability, and freshwater scarcity. The sea ice boundary informs strategies to stabilize regional and global climate, protect marine ecosystems, and manage shipping and resource extractions. The snow cover boundary highlights strategies to regulate Earth's radiation and water balance, and sustain snow-dependent ecosystems. The permafrost boundary emphasizes strategies to manage resource extraction and infrastructure development over cold regions, maintain landscape stability and prevent large CO_2 and CH_4 releases that would accelerate warming for centuries. Together, these boundaries provide essential guidance for maintaining a stable and resilient cryosphere, thereby supporting planetary health and enabling sustainable human development.

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This cryosphere SOS assessment responds in a timely manner to urgent needs among policymakers, governments, and change agents to mitigate cryosphere change and associated Earth system risks. Notably, the United Nations' designation of 2025 as the International Year of Glaciers' Preservation, and 21 March as World Glacier Day, signals growing global recognition of the cryosphere's vital role in climate and water systems. The juxtaposition of the Decade of Action for Cryospheric Sciences (2025–2034), the UN Ocean Decade's Antarctica InSync initiative (2025–2030), and the fifth International Polar Year (2032–2033) offers unprecedented opportunities for coordinated international action. Several national governments have already enacted legislation to protect cryosphere domains, such as Argentina's Glacier Protection Law and China's Ecological Conservation Law for the Qinghai–Tibet Plateau.

Humanity depends on the cryosphere for climate stability, ecological integrity, freshwater security, and coastal protection. Neglecting the cryosphere would lead to a profound underestimation of planetary risks. In contrast, establishing a cryosphere SOS clarifies its critical and unique contributions to Earth system resilience, strengthens science–policy communication, and informs global sustainability governance. Integrating this framework into decision-making will enable coordinated actions among scientists, policymakers, and communities to preserve the frozen foundations of a habitable Earth.

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SUPPLEMENTARY MATERIALS

science.org/doi/10.1126/science.aef5636
Materials and Methods; Supplementary Text; Figs. S1 to S3; Tables S1 to S6; References (*90–139*)

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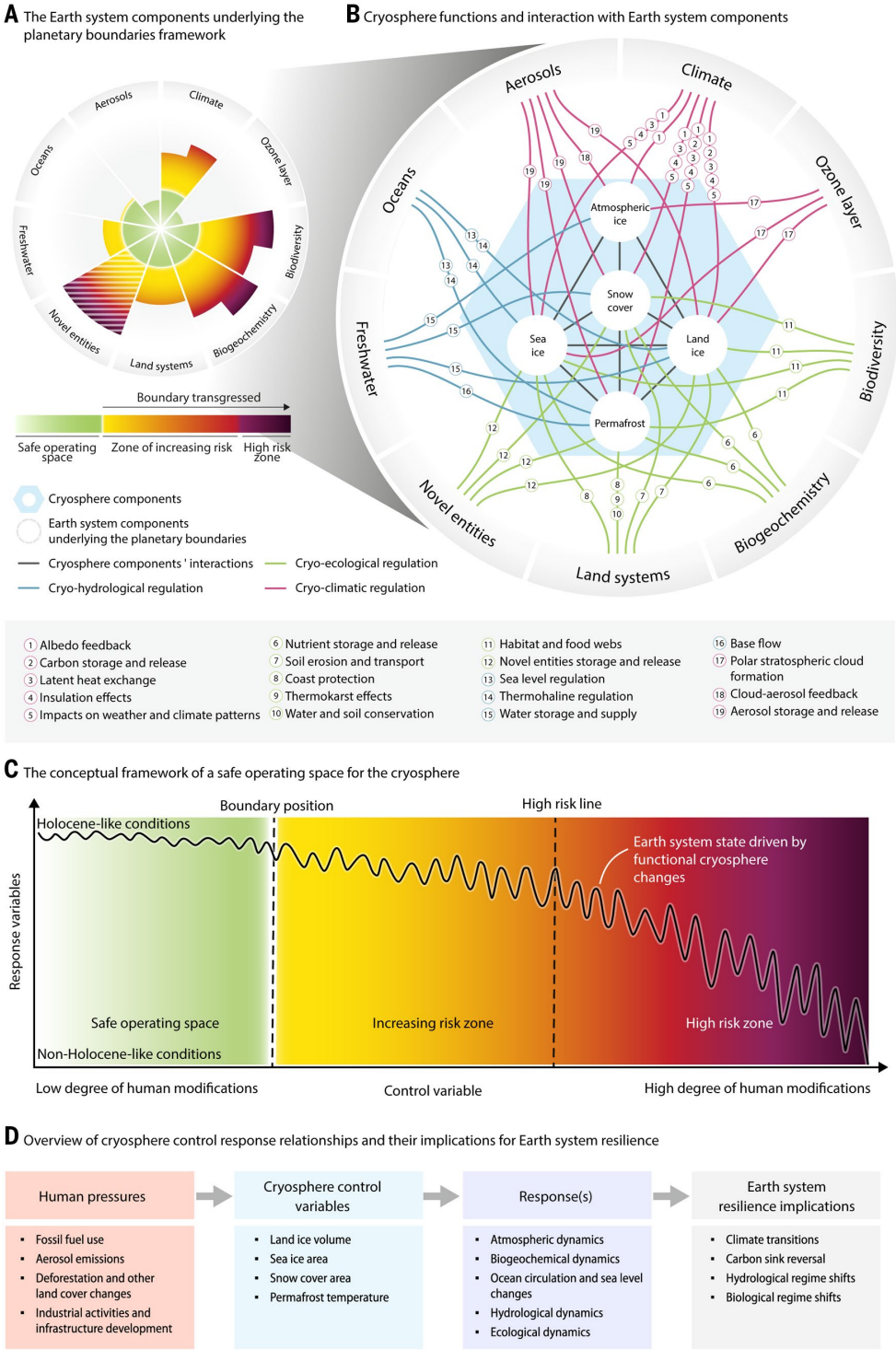


Fig. 1. The Earth system functions of the cryosphere and the conceptual framework of a safe operating space (SOS) for the cryosphere. (**A**) The Earth system components that underlie the planetary boundaries (PB) framework(1,2,20). (**B**) The role of cryosphere components in maintaining the functions of other Earth system components through cryo-climatic, cryo-hydrological, and cryo-ecological regulation. (**C**) Conceptual framework of an SOS for the cryosphere, consistent with the planetary boundaries framework. The boundary delineates Holocene-like, stable conditions from states of increased Earth system risk in the Anthropocene. Cryosphere changes and their boundary transgressions are generally nonlinear processes shaped by external forcing, internal system configurations, feedback and tipping dynamics, and interactions with other Earth system components. "High degree of human modification" indicates that the magnitude and rate of contemporary cryosphere change are strongly influenced by human activities and have exceeded the range expected from natural variability alone. (**D**) Cryosphere control–response relationships considered in the selection of control variables. Collectively, the panels illustrate how human pressures drive changes in cryosphere functions, which further affect Earth system resilience.

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Table 1. Overview of control variables for cryosphere sub-systems, including their baseline upper/lower bounds, boundary position, the current status, and committed loss under current disequilibrium. Control variables in bold are proposed for SOS assessment, and remaining variables are included for reference. The Greenland and Antarctic peripheral glaciers are considered part of the ice sheets, and not as mountain glaciers. Note: For the baseline upper and lower bounds as well as current value, 90% confidence interval (values in parentheses) is reported where available. The lower mid-Holocene baseline bound for sea ice and snow cover is derived from the 700-year CESM2 mid-Holocene experiment (beginning ~6,000 years ago). The boundary positions are provisionally defined as the upper 95th percentile for permafrost MAGT (based on the ISIMIP multi-model mean and within the spatial domain of the maximum preindustrial permafrost region), the lower 5th percentile of the entire Holocene baseline for land ice, and the lower 5th percentile of the mid-Holocene baseline for sea ice and snow cover area. Boundary transgression is assessed by current value for the fast-responding components, sea ice and snow cover, and additionally considers committed loss (rightmost column) for the slower-responding components, land ice and permafrost. Current values are determined from the latest available datasets: land ice from reconstructed data in this study (for the year 2018), sea ice and snow cover from satellite and ERA5-Land observations (for the year 2024), and permafrost mean temperature from the multi-model mean of the ISIMIP3b simulation round (the average value from 2000 to 2014, 90% confidence interval in parentheses), see materials and methods. MAGT refers to mean annual ground temperature. Committed land ice loss is based on refs. (*32*–*35*). To the best of our knowledge, there are yet no estimates of the committed changes for global permafrost temperature.

		Baseline upper/lower bounds [95th percentile (upper bound) for permafrost and 5th (lower bound) for others]					
Sub-system	**Control variables (unit)**	**Entire Holocene (11.7 ka B.P. to 1849)**	**Mid-Holocene (7 to 5 ka B.P.)**	**Pre-industrial (1850–1899)**	**Boundary position of SOS**	**Current value**	**Committed loss under current disequilibrium**
Land ice	**Global land ice volume** (10^6 Gt)	27.48 (26.85–27.79)	27.62 (26.99–29.51)	-	min. 27.48	27.63	>0.64
	Mountain glacier volume (10^6 Gt)	0.08 (0.04–0.17)	0.08 (0.04–0.19)	-	min. 0.08	0.08	0.037 (0.021–0.054)
	Greenland ice volume (10^6 Gt)	2.67 (2.56–2.74)	2.67 (2.55–2.73)	-	min. 2.67	2.75	0.1 ± 0.025
	Antarctic ice volume (10^6 Gt)	24.69 (24.19–24.85)	24.85 (24.38–26.59)	-	min. 24.69	24.79	>0.5
Sea ice	**Global annual-mean area** (10^6 km^2)	-	19.8	20.0 (15.2–21.9)	min. 19.8	16.5	-
	Arctic annual-mean area (10^6 km^2)	-	9.7	10.2 (9.0–11.5)	min. 9.7	8.7	-
	Antarctic annual-mean area (10^6 km^2)	-	9.8	9.5 (6.3–11.1)	min. 9.8	7.9	-
Snow cover	**Global annual-mean area** (10^6 km^2)	-	38.8	38.3 (34.5–42.9)	min. 38.8	35.9	-
Permafrost	**Global permafrost MAGT** (°C)	-	-	−6.6 (−7.1 – −6.2)	max. -6.6	−5. (−6.0 – −5.3)	?
	Global permafrost area (10^6 km^2)			14.8 (13.7–15.7)	min. 14.8	13.7 (13.4–14.1)	3.4 ± 2.3

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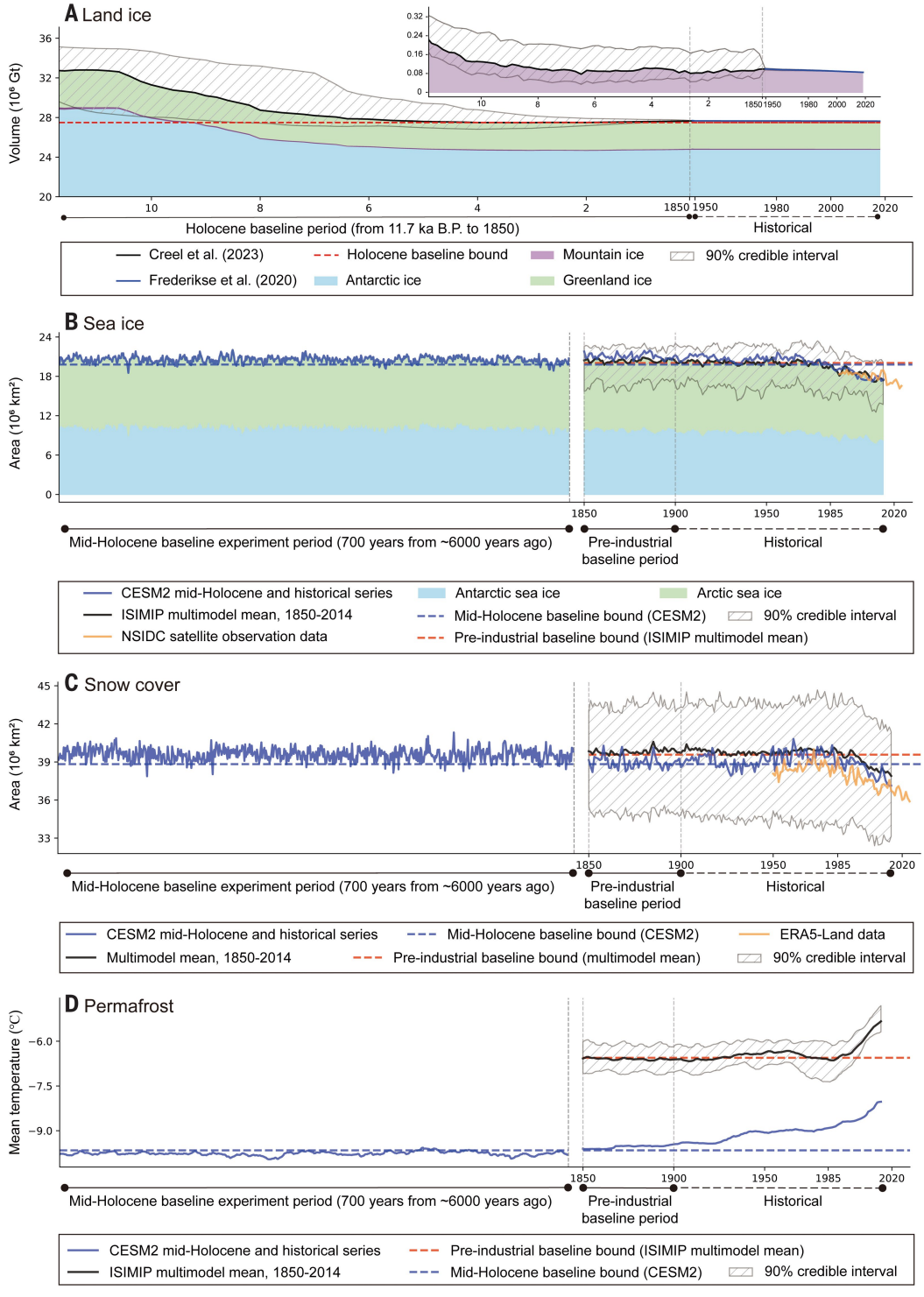


Fig. 2. Departure from the Holocene-like baseline variability envelope of cryosphere control variables. (**A**) Global integrated land ice volume, representing the sum of ice volumes from Antarctica, Greenland, and global mountain glaciers (further shown in inset). The Greenland and Antarctic peripheral glaciers are integrated with the ice sheets, rather than being counted as mountain glaciers. (**B**) Global annual-mean sea ice area, defined as the combined total of Arctic and Antarctic sea ice. (**C**) Global annual-mean snow cover area. (**D**) Mean annual ground temperature (MAGT), averaged over the spatial domain of the maximum preindustrial permafrost region (1850–1899). MAGT is defined as the ground temperature at the depth of minimum annual thermal amplitude; permafrost regions are those with negative mean annual ground temperatures. All panels show departures of cryosphere control variables from the Holocene-like baseline variability envelope, illustrating the progressive divergence of cryosphere components from their stable Holocene states.

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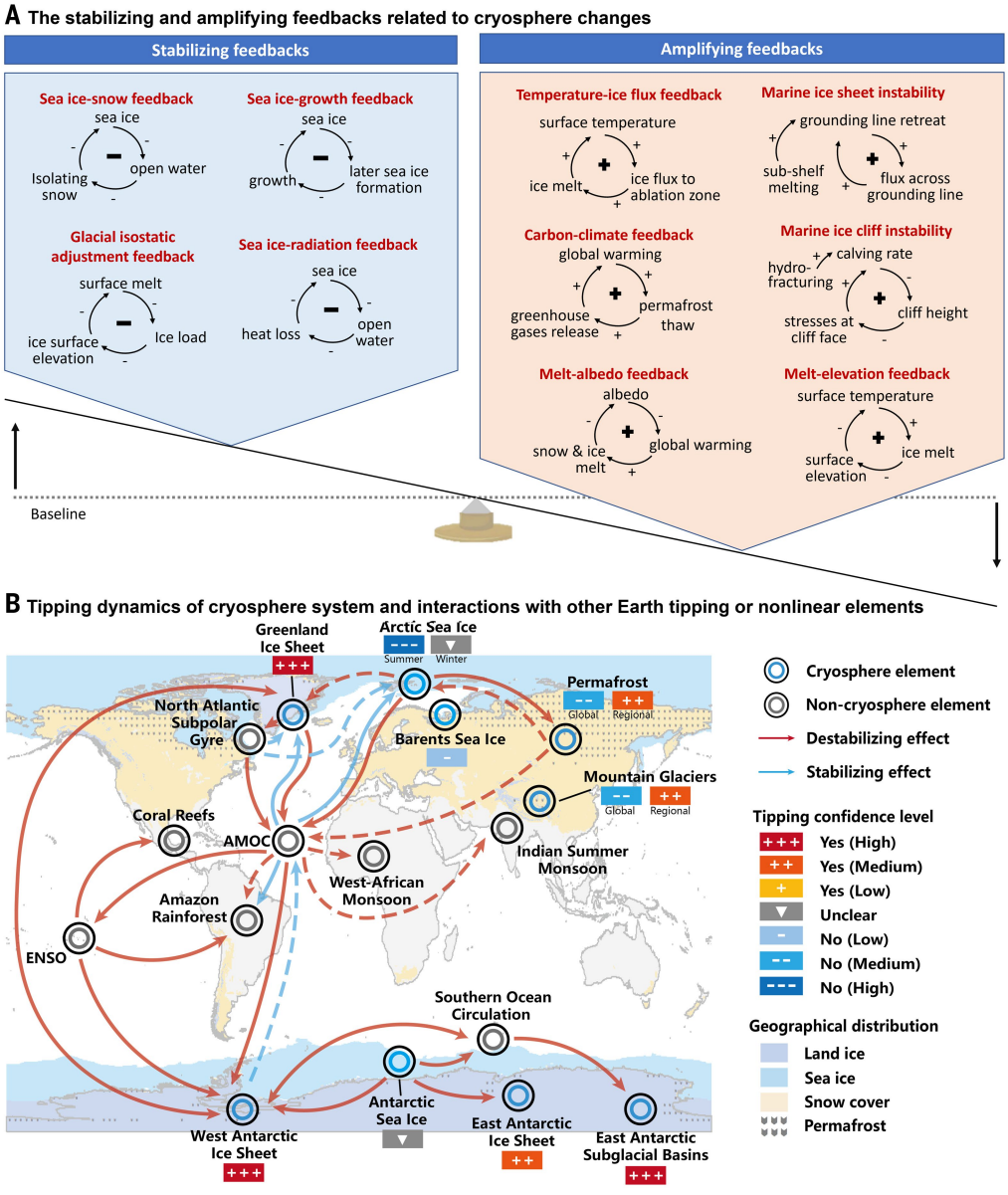


Fig. 3. Impacts of cryosphere changes on the self-regulatory biophysical capacity of the Earth system (Earth system resilience). (**A**) Major stabilizing and amplifying feedbacks associated with cryosphere changes. Shown are the most relevant and extensively studied feedback mechanisms (*34*); additional feedbacks may exist. (**B**) Tipping dynamics of cryosphere components and their interactions with other Earth tipping or nonlinear elements, illustrating stabilizing (blue) and destabilizing (red) linkages, modified from refs. (*34*,*35*). The interactions with regional cryosphere tipping elements are not shown for clarity, and dashed lines represent very limited evidence for destabilizing and stabilizing effects. Together, the panels highlight how feedbacks and tipping interactions within the cryosphere can weaken the Earth system's resilience and drive departures from Holocene-like conditions.

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The cryosphere beyond a planetary safe operating space

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