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Reconsidering the drivers of ice-shelf collapse

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Antarctic ice shelves face increasing collapse risk as environmental stresses intensify. Long-term weakening, ocean-induced thinning, and loss of stabilizing sea ice can drive disintegration yet are mostly missing from models which only consider surface melt-driven fracturing, limiting accuracy of projections.

Beyond surface melt

Antarctica's floating ice shelves have a key role in maintaining ice-sheet stability by buttressing its grounded ice[1]. The loss of this buttressing capacity through thinning, weakening and retreat of confined ice shelves can trigger dynamic acceleration of upstream ice, leading to increased mass loss and contribution to global sea-level rise[2–5]. Extensive ice-shelf loss therefore represents a potential tipping point for future irreversible Antarctic Ice Sheet retreat[6].

Ice shelf collapse is the catastrophic and irreversible disintegration of a floating ice shelf[7–9]. This is distinct from periodic advance-retreat cycles, which comprise the natural stable state and permit ice-shelf regrowth. Since the beginning of the satellite era, at least ten ice shelves have been observed to collapse, either rapidly within days to weeks[10,11] or through multiple decadal weakening phases[12,13].

The majority of observed collapses have occurred on the Antarctic Peninsula and have been attributed to surface meltwater-driven hydrofracturing, whereby surface ponding and drainage exert pressure that opens crevasses and fractures through the ice[8,14–18]. This mechanism is represented in current ice-sheet models and is parametrized by prescribed thresholds of liquid water at the surface; ice shelves are identified as susceptible to hydrofracture-driven failure based upon their annual liquid water availability[19–22] but the mechanism itself is not yet resolved in a physically realistic manner. By contrast, growing satellite evidence from the past two decades shows that many collapses have occurred in the absence of significant surface melt, highlighting a broader suite of pre-conditioning drivers that remain misrepresented in models, as spatial accuracy or temporal resolution are often insufficient to capture these adequately. These drivers often act over longer timescales and include progressive structural weakening, loss of pinning-point contact, basal melting and thinning, and changes in sea-ice and ocean-swell regimes[13,23–25]. That these drivers are not well-represented in models limits our capacity to forecast when and where future collapses may occur and introduces significant uncertainty into projections of Antarctica's contribution to sea-level rise.

Observations of diverse ice-shelf collapse drivers

Satellite observations since the 1970s have documented numerous collapses on the Antarctic Peninsula, including Wordie, Prince Gustav, Larsen A, and Larsen B, driven by widespread surface melting and hydrofracture[2,10,14,15,26]. The 2002 Larsen B collapse remains the canonical example: the near-synchronous drainage of over 2750 meltwater lakes triggered a chain reaction of fracturing and flexure that disintegrated 3000 km² of ice shelf within days[16,27]. This event cemented meltwater-driven hydrofracture as the prevailing explanation for ice-shelf collapse and remains the only collapse process represented in continental-scale ice-sheet models, with additional factors such as ice-block fragmentation and ice-front stress redistribution likely playing a secondary role[8,28].

Yet, several major ice shelf collapses across East and West Antarctica demonstrate that surface melt is not a prerequisite for disintegration. At Cadman Glacier (Antarctic Peninsula), ocean warming-induced basal melt led to gradual ungrounding from a bedrock ridge, culminating in collapse over just three years without any observed surface ponding[11] (Fig. 1b). At Thwaites Glacier, multi-decadal weakening of the Western Ice Tongue has been linked to stress concentrations around pinning points and progressive thinning, which together reduced structural integrity (Fig. 1c[25,29–32],. Similarly, the Conger–Glenzer and Cook West Ice Shelves in East Antarctica disintegrated following decades of ocean-induced thinning and dynamic weakening and notable absence of surface melt, where previously-stabilizing pinning points became destabilizing fracture sources[13,23] (Fig. 1d). These cases collectively illustrate that ice-shelf collapse can arise from the slow evolution of internal stress fields and structural weakening, rather than being directly triggered by surface meltwater.

Sea ice and mélange play a complex role in modulating ice-shelf stability. Observations indicate that the loss of landfast sea ice can expose ice fronts to direct ocean-swell impact, enhancing rift propagation and calving[9,24,33]. The disintegration of Voyeykov Ice Shelf and several neighbouring glaciers in 2007 followed the sudden breakup of decades-old landfast sea ice and mélange[24,34] (Fig. 1a). Similarly, the collapses of the Parker Ice Tongue in 2020 and the Hektoria Glacier tongue in 2022 were preceded by multiyear sea-ice loss[32,35–37]. However, the persistence of landfast ice during the Conger–Glenzer ice shelf collapse[13] shows that sea ice alone does not guarantee stability. Modelling studies suggest that while thin landfast ice cannot directly buttress thick ice shelves[32], it plays an important secondary role by damping ocean swell and consolidating mélange, indirectly modulating the timing and rate of collapse[33,38].

Together, these observations demonstrate that Antarctic ice shelf collapse can be triggered by multiple, interacting processes, not solely by surface melt-driven hydrofracture. Structural weakening, basal melting, thinning, evolving pinning points, and the loss of stabilizing sea ice or mélange can each precondition shelves for rapid failure. Rapid retreats in both floating and grounded ice highlight that ice shelf collapse can be highly non-linear and occur over short timescales[39,40]. Yet these drivers remain largely absent from, or at least poorly represented in, continental-scale ice sheet models, and additional mechanisms not yet observed may become important in the future as the climate warms. This gap limits our ability to identify which ice shelves are most vulnerable, their potential to initiate instability at/near the grounding line, and ultimately to project their potential contributions to future sea-level rise.

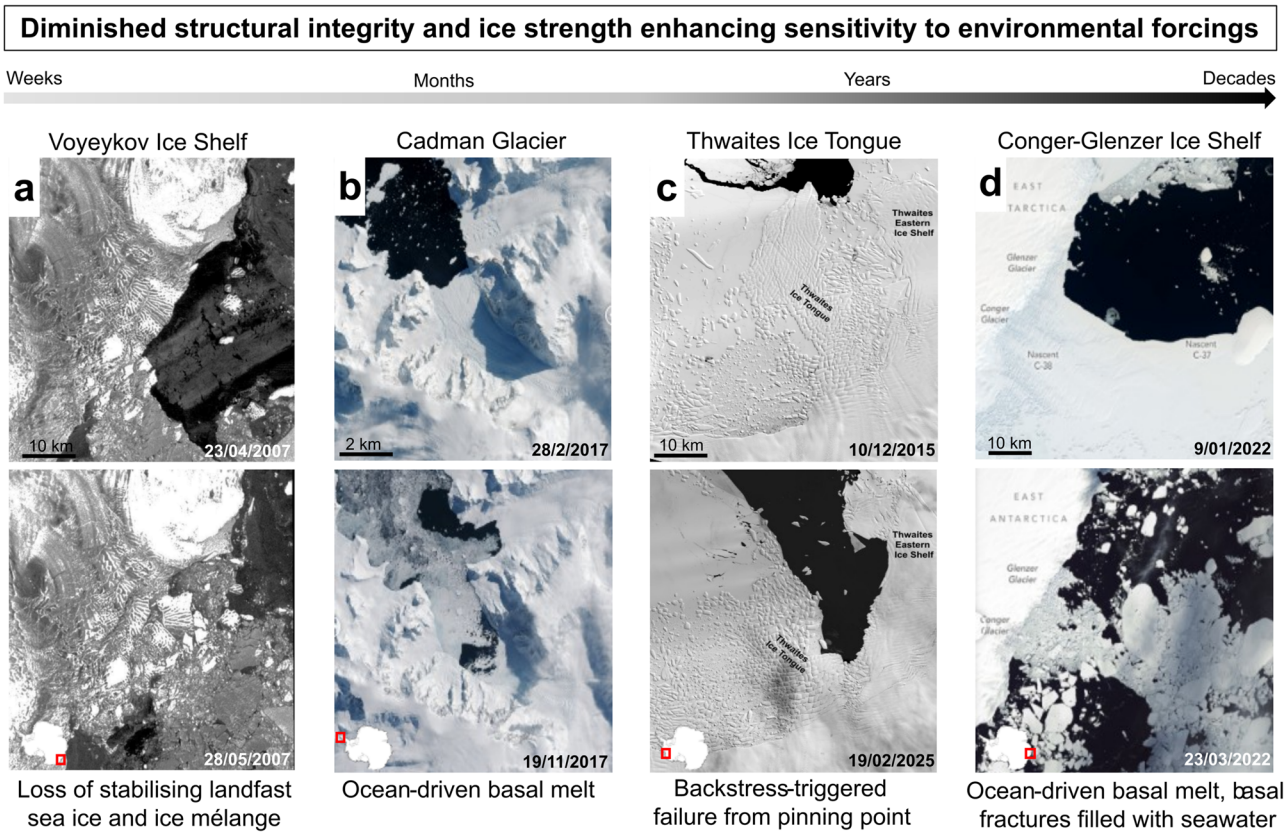


Fig. 1 | Antarctic ice-shelf collapse events, their temporal scales and varying drivers. a The Voyeykov Ice Shelf in East Antarctica partially rapidly disintegrated over a few weeks between March and May 2007. **b** Complete rapid disintegration of the Cadman Glacier Ice Shelf on the Antarctic Peninsula occurred over a 3-year period in 2021. **c** The Thwaites Ice Tongue in West Antarctica has experienced a substantial reduction in structural integrity since the early 2000s. **d** The Conger-Glenzer Ice Shelf in East Antarctica gradually collapsed over 30 years and finally disintegrated over one week in March 2022. Imagery adapted from **a** Environmental Satellite (ENVISAT) Synthetic Aperture Radar (ASAR); **b** Contains modified Copernicus Sentinel data [2017]; **c** Contains modified Copernicus Sentinel data [2015, 2025]; (d) U.S Geological Survey/NASA Landsat 8 OLI.

Towards understanding ice-shelf collapse processes

There are significant computational and technical challenges in representing ice shelf collapse in numerical models. Traditional ice-sheet models have kilometre-scale spatial resolutions, whereas ice fracture and damage occur on spatial scales of tens of metres and are key precursors to ice shelf collapse. Representing these processes requires the development of efficient parametrizations, approximations of complex physical processes with simplified variables or values. Progress has been made through the inclusion of continuum damage approaches in ice-sheet models[41–44] that are already informing parametrizations for large-scale ice sheet modelling. Using high-resolution brittle elastic fracture models to simulate realistic fracture patterns and calving processes[25,45], along with phase-field modelling of hydrofracture[46,47], is also encouraging.

Further advances must be delivered through closer collaboration between the numerical modelling and remote sensing communities. The rapid development in understanding and modelling of ice shelf collapse has been underpinned by comprehensive multi-sensor satellite observations that have captured collapse events in extraordinary detail. Greater implementation of these observations into new model physics and input parameters[32,38] provides a tangible pathway to improvement. Continued observation of ice-shelf thinning, damage, strain-rates and motion with satellite missions, such as advanced altimeters[39] and multi-frequency synthetic aperture radar[40] also essential. New measurements at higher spatial and temporal resolution have the potential to capture new ice shelf characteristics and collapse pathways that were previously unknown.

Improving parameterizations of damage and fracture associated with ocean-induced thinning and hydrofracture remains a priority, as both drivers have been widely observed and are expected to intensify in the future. However, there is also a growing need for experimental modelling that focuses on collapse processes not currently active or observed, but which may become increasingly important as the climate warms. For example, sea ice presently fringes nearly all major Antarctic ice shelves year-round, yet widespread and consistently ice-free summers are projected by the end of the century[48], and the response of ice shelves to prolonged, repeated seasonal exposure to potentially damaging ocean swell remains uncertain (e.g., refs. 9,33). Seasonal warming of the ocean surface associated with declining sea ice may also promote thermo-mechanical undercutting at the waterline of ice shelves, potentially driving frontal ablation rates of hundreds of metres to kilometres per year through buoyancy-driven calving multiplier effects (e.g., refs. 49,50). A transition toward more pronounced buoyancy-driven calving has recently been proposed to

affect thinning grounded glaciers as grounding becomes more tenuous, potentially establishing an "ice plain" configuration in which rapid retreat by buoyant calving propagates upstream of the grounding line[51]. In addition, increases in the magnitude of extreme weather events are expected[52], yet the extent to which short-lived, intense events such as atmospheric rivers will accelerate the decline of already weakening ice shelves remains unclear. There remains a need for all forms of modelled ice-shelf collapse to be improved.

Accurately representing ice-shelf collapse mechanisms in numerical models is a complex task, but remains essential for incorporating physically realistic ice shelf collapse mechanisms into continental-scale ice sheet models to produce accurate sea level projections for Antarctica. In a warming climate, it is expected that more ice shelves will collapse or significantly weaken in this century and beyond, as sea ice declines, summers become warmer, and warm Circumpolar Deep Water encroaches further towards the continent. Yet, the current generation of ice sheet models that are employed to produce sea-level projections and inform policymakers are not yet able to simulate these complex mechanisms in a way that comprehensively and dynamically represents the full range of observed collapse processes. As a result, we cannot adequately quantify how widespread future ice-shelf collapse will be. This inherently introduces a structural bias into projections that increases uncertainty and introduces a potential bias skewed toward an underestimation of sea level contributions. Improving our understanding of the drivers and monitoring the pace of current change is therefore essential to produce robust, policy relevant projections and to reduce both qualitative and quantitative uncertainties in future sea-level rise estimates for Antarctica.

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