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Antarctic surface hydrology and impacts on ice-sheet mass balance

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Melting is pervasive along the ice surrounding Antarctica. On the surface of the grounded ice sheet and floating ice shelves, extensive networks of lakes, streams and rivers both store and transport water. As melting increases with a warming climate, the surface hydrology of Antarctica in some regions could resemble Greenland's present-day ablation and percolation zones. Drawing on observations of widespread surface water in Antarctica and decades of study in Greenland, we consider three modes by which meltwater could impact Antarctic mass balance: increased runoff, meltwater injection to the bed and meltwater-induced ice-shelf fracture — all of which may contribute to future ice-sheet mass loss from Antarctica.

Surface meltwater in Antarctica is more extensive than previously thought and its role in projections of future mass loss are becoming increasingly important. As accurately projecting future sea-level rise is essential for coastal communities around the globe, understanding how surface melt may either trigger or buffer rapid changes in ice flow into the ocean is critical. We provide an overview of the current understanding of the major components of the Antarctic surface hydrology system and the distribution of melt. Using the framework of surface hydrology in Greenland, we consider the different ways in which surface hydrology can impact ice-sheet mass balance. Looking to the future, we discuss how the hydrologic systems will evolve in Antarctica as well as their impact on future changes in ice-sheet mass balance. Finally, we highlight knowledge gaps that limit our understanding of the impact of increased surface meltwater on future sea level rise.

Current distribution of meltwater

Meltwater on the surface of Antarctica was observed by early explorers, who noted the noise of running water and water seeping into their tents[1]. Today the surface melt distribution in Antarctica (Fig. 1) is determined using satellite observations[2–5] and reanalysis-forced regional climate modeling[6]. The surface meltwater production estimates derived from these two methods correspond well with in situ observations[7]. At present, the most intense melt is observed across ice shelves (Fig. 1), particularly along the Antarctic Peninsula, including the Larsen C, Wilkins and George VI ice shelves, as well as the relatively low-latitude East Antarctic ice shelves, including the West and Shackleton ice shelves. More localized, but intense, melt occurs on other East Antarctic ice shelves, including the Amery and Roi Baudouin ice shelves[7,8], where extensive surface hydrological networks develop. The two largest ice shelves, Ross and Ronne-Filchner, experience only minor surface melting. The upper elevation limit of surface melting today is generally ~1,400 m during spatially extensive, but low-magnitude, West Antarctic melt episodes[7,9], compared to a 3,200 m elevation limit in Greenland during the anomalous[10] 2012 melt events.

Liquid water on the Antarctic Ice Sheet and the floating ice shelves that buttress upstream grounded ice (Fig. 1) is found in supraglacial lakes, subsurface lakes, surface streams and rivers[1,8,11–14]. Through-ice fractures are interpreted as evidence of water having drained through ice shelves (Figs 1a and 2)[15]. Similar to terrestrial hydrologic systems, these components of the Antarctic hydrologic system store, transport and export water. In contrast to terrestrial hydrology, on ice sheets and glaciers water can refreeze with consequences for the temperature of the surrounding ice[16–18], firn or snow. Storage occurs in lakes, crevasses, in buried lakes and possibly in firn aquifers. Transport and export are less persistent and more difficult to observe than lakes[14,19,20]. Antarctic surface and subsurface hydrological systems have been studied using satellite and airborne imagery[1,8,11–14], although field-based observations are limited[8,21–23].

Surface storage of meltwater. Meltwater is stored in surface lakes on both grounded and floating ice. On grounded ice, lakes develop in areas with local-scale melt enhancement and relatively low accumulation rates; areas that are often close to rock outcrops and blue ice (for example, Shackleton Glacier; Fig. 1j)[12,14]. Similar to Greenland[20], on grounded Antarctic ice, lakes form in persistent surface depressions. The formation of surface lakes in the same location each year over decades is evidence of control by the interplay between bedrock topography and ice flow[24]. On the floating ice shelves surrounding Antarctica[8,14,19,20,25], water collects in surface depressions that move with ice flow. These surface depressions in the ice shelf are controlled by basal crevassing[26], grounding zone flow-stripe development[27], suture-zone depressions[1] and basal channels produced by ocean melting[28]. Water will fill a depression if the ice surface or near surface is impermeable. Impermeable surfaces are often associated with high melt and low snow accumulation rates[29]. Once water collects in an ice shelf depression, the basin will deepen due to both enhanced lake-bottom ablation (due to the lower albedo of the water compared to the surrounding ice/snow)[30,31], and the flexural response of the floating ice to the water load[32,33]. The largest supraglacial lake (~80 km long) is on the Amery Ice Shelf (Fig. 2e)[13,14,34].

On both grounded and floating ice, surface fractures (crevasses) can accumulate water[26], serving as another storage site for meltwater and a mechanism by which water directly impacts ice dynamics. Water-filled fractures may propagate vertically when sufficient water is available, creating through-ice fractures on Antarctica's ice shelves[32,35,36] and Greenland's floating tongues[37]. Fractures beneath

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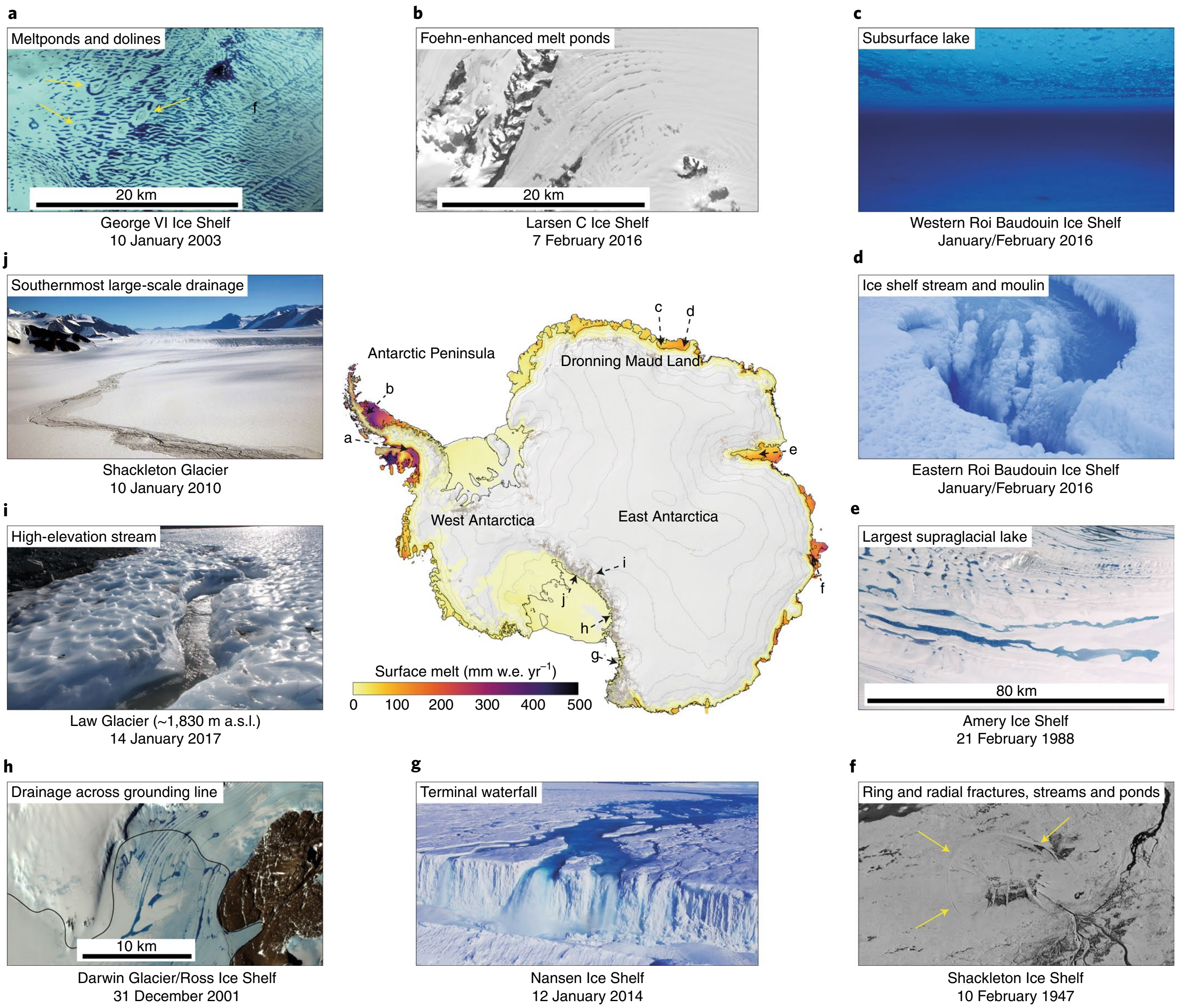

Fig. 1 | Examples of major components of surface hydrological systems located on a present-day Antarctic surface melt map. The central map shows 2000–2009 Antarctica surface melt from QuikSCAT satellite observation 7; the locations of the images in **a**–**j** are indicated. **a**, Meltwater lakes and dolines (arrows), **b**, Foehn wind-enhanced meltwater ponding. **c**, Buried lake. **d**, Moulin draining surface stream. **e**, Elongate supraglacial lake. **f**, Fractures around a drained lake. Scale unknown. **g**, Persistent waterfall draining water. **h**, Supraglacial streams transporting water across grounding line of the Darwin Glacier onto the Ross Ice Shelf. **i**, High-elevation (1,830 m) meltwater stream. **j**, Meltwater stream crossing the grounding line. Images reproduced from: US Geological Survey (**a**,**b**,**e**,**h**); ref. [8], Springer Nature Limited (**c**); Sanne Bosteels (**d**); USGS/EROS and the Polar Geospatial Center (**f**); Won Sang Lee (**g**); Mike Kaplan (**i**); John Stone (**j**).

lakes on Greenland's grounded ice drain meltwater to the ice-sheet bed by hydrofracturing[38,39]. There is no direct evidence of hydrofracture beneath lakes on grounded Antarctic ice.

Englacial storage of meltwater. Antarctic surface meltwater is stored englacially when surface lakes freeze over and are buried by snowfall[8,40]. In Antarctica, buried lakes tend to form on ice shelves close to the grounding line[8]. Since at least 1947 on the Roi Baudouin Ice Shelf, meltwater produced in areas of blue ice above and below the grounding line fills surface lakes. These lakes are buried as the ice moves towards the calving front[14]. Radar satellites, such as C-Band Sentinel-1 A and B, are capable of penetrating metres though dry snow, highlighting the promise of tracing buried lakes and other subsurface liquid water[41]. When these grounding line lakes refreeze, they form massive ice layers[29,42]. Over successive melt seasons, frozen surface lakes (now stacked ice lenses) may accumulate in dense and thick ice horizons[29]. On the Larsen C Ice Shelf, a massive ice facies >40 m thick, extending 16 km horizontally, was interpreted as a stack of frozen lakes[42]. Temperature profiles through this refrozen ice are substantially warmer due to the release of latent heat as the lakes froze, similar to the cryohydrologic warming described across Greenland[17].

In Greenland, perennial firn aquifers store water in environments similar to where buried supraglacial lakes form[43]. Water in these firn aquifers is stored in a porous matrix of ice crystals. No Antarctic firn aquifer has been sampled yet, but beneath massive ice facies on Larsen C, a second ~45-m-thick ice unit has been interpreted as a percolation-type facies of water-infiltrated firn[42].

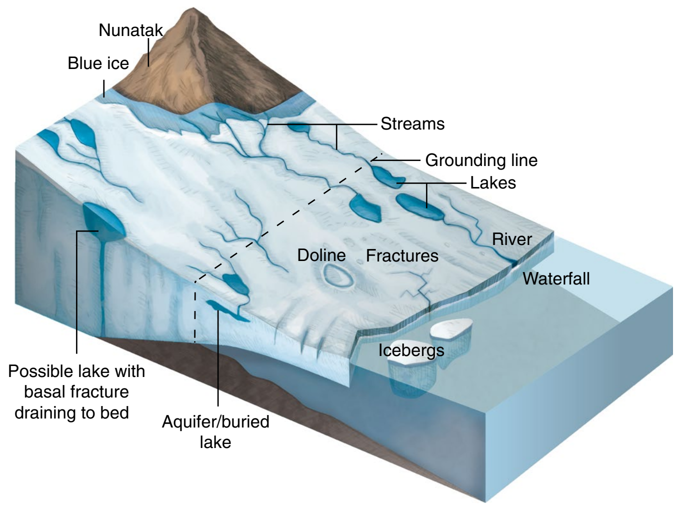

Fig. 2 | Antarctic surface hydrology. The major components of the modern Antarctic hydrologic system are shown. The possible future surface-to-bed connection is included, illustrated as a lake-bottom fracture draining meltwater to the base of the ice sheet, based on Greenland analogues. Dolines are locally uplifted, empty depressions, interpreted as evidence of surface lakes that have drained through ice shelves via ice fractures[15]. Nunataks are areas of exposed rock on the grounded ice.

In Antarctica, drainage systems often terminate where they deliver water into snow-covered areas[1,8,12,14]. Perennial firn aquifers could develop at these sites if accumulation rates are sufficiently high to insulate the downward-percolating liquid water from low wintertime surface temperatures, or if the water is routed deep enough to be thermally isolated from the surface. Perennial firn aquifers occur in Greenland[17,44–48] in locations with both moderate and high melt rates (>650 mm of water equivalent (w.e.) yr^{-1})[44] and high snow accumulation rates (~1–5 m w.e. yr^{-1})[45]. Similar high snow accumulation rates occur today on the western Antarctic Peninsula[49], as well as on the upwind flanks of coastal domes and the ice-sheet margins of West Antarctica, but surface melt rates are currently low in these regions.

Surface meltwater transport. Across broad sectors of Antarctica, meltwater transport over the surface of the ice sheet and ice shelves occurs along relatively low surface slopes through networks of streams and rivers. In some cases, water moves tens to hundreds of kilometres[14] and has persisted for decades. The Transantarctic Mountains support some of the continent's most high-latitude (~85° S) and high-elevation (~1,800 m a.s.l.) meltwater drainage systems (Fig. 1). It is currently unclear how melting in these extreme locations supports these persistent drainage systems, but it is presumably related to the abundance of low-albedo bedrock and downslope winds that emanate from the East Antarctic plateau. Streams and rivers may affect ice-sheet mass balance by moving water onto ice shelves where ponding water can contribute to ice-shelf collapse. Meltwater streams feed lakes in high-albedo snow on the Riiser-Larsen, Amery, Nivlisen and Roi Baudouin ice shelves[8,14,50]. Ice shelves receiving meltwater through this mechansim are more likey to affect ice-sheet mass balance if they are both suspectible to fracturing and buttress large upstream catchments.

Streams and rivers can also transport meltwater off ice shelves in the ocean via waterfalls[1] at the calving ice front, or through moulins, dolines and crevasses[12,19]. On the Nansen Ice Shelf[1], a waterfall fed by a surface river has persisted since at least 1974. This river and waterfall system drains a significant fraction of the meltwater formed on the ice shelf into the Ross Sea. Similar water export was observed on the Larsen B Ice Shelf before its collapse[19] (T. A. Scambos, personal communication). Simple routing calculations indicate that meltwater could be removed from other Antarctic ice shelves such as Ross, Amery, Filchner Ronne and Larsen C1. Transport of meltwater off floating ice shelves has the potential to buffer ice shelves from fracture and collapse associated with surface lakes.

Drivers of meltwater distribution

Antarctic surface meltwater distribution is driven at present by regional shifts in climate together with the influence of local-scale process and microclimates. The predominance of melting on Antarctic Peninsula ice shelves today reflects the rapid regional atmospheric warming that began in the 1950s[51]. The resulting melt intensification on ice shelves is thought to be directly responsible for multiple ice-shelf collapses over recent decades[52,53]. These collapses, together with the associated loss of buttressing, have triggered Antarctic Peninsula outlet-glacier acceleration[54]. An ice core from James Ross Island on the northeast Antarctic Peninsula indicates that surface melting rapidly increased in the late twentieth century relative to the past 1,000 years[55]. Observed warming and melt intensification across the northeastern Antarctic Peninsula are associated with a strengthening of the circumpolar westerly winds marked by the positive phase shift in the Southern Annular Mode since the 1970s[56], which in turn is considered to be the result of coincident anthropogenically induced depletion of stratospheric ozone[57]. Broader-scale climate dynamics also impact Antarctic surface melting, including oceanic–atmospheric variability in the tropical Pacific[58,59]. Striking examples of this linkage are anomalous, extensive melt events across the Ross Ice Shelf and the West Antarctic Ice Sheet that have been linked to an El Niño/Southern Oscillation (ENSO) teleconnection pattern that favours warm, marine air intrusions into West Antarctica[5,9,60]. Antarctic climate and surface melting are strongly coupled to broader climate system dynamics and anthropogenic forcing.

Local-scale processes also drive the distribution of Antarctic surface melt. Exposure of low-albedo blue ice and bedrock near ice-shelf grounding zones can enhance melting through a positive melt–albedo feedback[8,14]. On the ice sheet, blue ice areas generally produce greater meltwater volumes than the adjacent snow-covered regions. As blue ice[22] only covers 1.6% of the surface of Antarctica[61,62], the overall volume of meltwater produced by local-scale melt enhancement over blue ice areas is thought to be a small fraction of the Antarctic surface melt. Observations and modelling of meltwater production across ice-covered areas are particularly lacking in Antarctica.

Winds play an important role in surface meltwater production across Antarctica. Warming of descending katabatic winds that persistently drain from the Antarctic interior, and associated wind scouring and blue ice exposure are known to locally enhance surface melting across ice-shelf grounding zones in Dronning Maud Land, East Antarctica[8]. Analogous processes enhance melt on the Ross Ice Shelf, as well on the innermost Amery Ice Shelf[3,5]. Foehn winds play a similar role in melt generation. Although more episodic and less directionally constant than katabatics, warm, dry and clear sky conditions associated with foehn wind events enhance melting across eastern Antarctic Peninsula ice shelves[6,63,64] and the McMurdo Dry Valleys[65,66]. Local melt enhancement produced by foehn winds is linked to depletion of ice shelf firn pore space[67] and meltwater ponding on innermost Larsen C Ice Shelf[7,42,63]. As firn air depletion results in an impermeable ice surface, this process is an important precursor for meltwater-induced hydrofracture[6,68]. Foehn winds probably contributed to the collapse of the Larsen B Ice Shelf[69]. A result of the interplay of Antarctic topography and prevailing winds, wind-enhanced melting will continue to be an important component of Antarctic surface meltwater production and hydrology in coming decades.

Modes of meltwater impact

Surface meltwater on ice sheets and the adjacent floating ice shelves has the potential to significantly impact ice-sheet mass balance. We focus on three primary modes of meltwater influence on ice-sheet mass balance: (1) surface melt leading to direct surface runoff and thinning (Fig. 3a,b); (2) changing the basal thermal and hydrological state by injection of surface meltwater into the subglacial environment (Fig. 3c,d); and (3) meltwater-induced ice-shelf collapse (Fig. 3e,f), producing an acceleration of mass loss from the upstream outlet glaciers. Other influences of surface meltwater include cryohydrologic warming and enhanced ocean melting[70,71]. Cryohydrologic warming in a lake, a crevasse or a firn aquifer can change the ice rheology both on grounded ice and ice shelves through the release of latent heat[42].

The widespread and intense surface melt in Greenland today is a template for understanding surface hydrology in Antarctica in a warmer world. To date, the first mode(direct surface melt) is widespread in Greenland and on some Antarctic ice shelves[14]. The second mode, injection of surface water to the bed, is also widespread in Greenland[39,72,73] but has not yet been observed in Antarctica. The third mode, meltwater-induced ice-shelf collapse, has been implicated in the widespread collapses of northeast Antarctic Peninsula ice shelves, including Larsen A and Prince Gustav in 1995, Larsen B in 2002 and Wilkins in 2008[11,35,36,74].

Surface melt leading to direct surface runoff and thinning. In Antarctica, the first mode (Mode 1 in Fig. 3a,b), is primarily impacting ice shelves, whereas in Greenland, surface melt plays an important role in mass balance of the entire ice sheet. Before 2006, mass loss in Greenland was equally partitioned between losses from surface melt and runoff and loss due to ice dynamics[75]. Beginning in 2006, the surface melt mass loss increased, exceeding the mass loss attributed to ice dynamics[75,76]. In a recent study, up to 84% of the annual mass loss from the Greenland Ice Sheet was attributed to surface melt and runoff[76]. Surface melting and runoff have contributed to the lowering of the ice sheet margin[77] at rates of >1 m yr^{-1}. Close to the ice-sheet margin, surface meltwater is exported directly off the ice in supraglacial streams. Inland, the surface water can refreeze, be stored near the surface[44,78] or be transported to the base of the ice sheet[38,39,79]. As Antarctic melt rates increase in the future, mass loss due to surface runoff will also increase.

Injection of surface meltwater into the subglacial environment. The second mode of impact (Mode 2 in Fig. 3c,d) has not been documented in Antarctica yet, but is widespread in Greenland. In Greenland, the surface and basal hydrological systems are linked by drainage of surface lakes into fractures[79], and drainage of surface rivers into moulins[80]. Meltwater stored in the englacial hydrological system as subsurface lakes[41,43] and firn aquifers[44] may also move surface water to the ice-sheet base[47]. For example, transient storage of surface meltwater in a firn aquifer upslope of Helheim Glacier, east Greenland, flows downslope until it disappears at an extensional crevasse. Modelling suggests that this water reaches the ice-sheet bed via hydrofracture[47]. Injection of surface water to the subglacial hydrological system may increase ice mass loss through enhanced basal sliding[2] and enhanced ocean melting at calving fronts. Sudden lake drainage events can produce both localized vertical and horizontal ice displacements[38,39,81,82]. Together, the seasonal evolution of surface meltwater, its transfer to the subglacial environment and the efficiency of subglacial hydrological systems modulate the response of ice dynamics to meltwater input[83,84]. In Greenland, research has focused on both the short-term (hours to weeks)[38,39] and the seasonal response of the ice sheet to meltwater injections[85,86] as an analogue for understanding how the ice sheet will respond dynamically to increased surface melt. There is currently no evidence for coupling between Antarctic surface and basal hydrological systems. As Antarctic climate warming results in the development on grounded ice of more extensive surface lakes, aquifers and rivers, in some areas the surface and basal systems may connect. We suggest that a switch from an ice-sheet base that is isolated from surface melt to one that receives seasonal injections of surface meltwater could trigger a fundamental shift in the dynamics and mass balance of Antarctica.

Meltwater-induced ice-shelf collapse. The third mode (Mode 3 in Fig. 3e,f), is active today in Antarctica. Through-ice fractures on ice shelves may develop via two mechanisms: the downward propagation of water-filled fractures[68], referred to as hydrofracture[35], and fracturing resulting from the bending of an ice shelf as surface lakes fill and drain[32,33,74].

Hydrofracture can occur on both floating and grounded ice. The process occurs when the hydrostatic pressure at the tip of a water-filled crevasse exceeds the ambient pressure sufficiently to induce stresses at the tip of the crevasse that overcome the fracture toughness. If water fills the fracture as it grows vertically, it may fracture the full ice thickness[35,36,47,68,87,88]. Water can be supplied from a lake, stream or firn aquifer. Whether hydrofracture triggers ice-shelf collapse will depend on the fracture spacing. Closely spaced through-ice fractures are more likely to lead to an unstable ice shelf. When the fractured ice-shelf fragments have aspect ratios of horizontal length to ice thickness that are less than a critical value (~0.6)[89], iceberg capsizing can drive ice-shelf disintegration[86,90]. In contrast, widely spaced fractures will not lead to iceberg capsize and instead may provide conduits to remove the surface meltwater buffering the ice shelf from collapse[1,91].

Ponding of surface meltwater can also trigger ice-shelf collapse through ice-shelf flexing, weakening and fracturing, as lakes fill and drain[74,88]. An ice shelf deflects downwards when a surface lake fills, and hydrostatically rebounds upwards when a lake rapidly drains. This loading and unloading of surface lakes can produce flexurally induced ring and radial fractures around the lake[74,92], as observed around drained lakes on the Shackleton Ice Shelf (Fig. 1d) and the Langhovde Ice Shelf, East Antarctica[12]. A chain reaction of lake drainage events could occur if these loading-induced fractures intersect adjacent lakes. The adjacent lakes will drain into and deepen the new fracture. This chain reaction process may have triggered the drainage of over 2,000 meltwater lakes[19] in the weeks before the collapse of the Larsen B Ice Shelf[74]. Meltwater-induced flexure and fracture may also have contributed to the 2008 break-up events of the Wilkins Ice Shelf[11]. Chain-reaction lake drainages will only occur if lakes are close enough that fractures formed by one lake drainage event intersect an adjacent lake[74]. Stresses from further afield, including back-stress from land-fast sea ice[87] and larger-scale ice flow, can mute the impact of loading and unloading by preventing fracture initiation. Some surface lakes have persisted on ice shelves, such as the George VI Ice Shelf, for decades without triggering collapse[14]. Although George VI Ice Shelf (Fig. 1a) is covered with widespread, closely spaced lakes every year, its compressive flow regime[93] limits the formation of fractures — even with the persistent loading from abundant surface meltwater.

Most of our understanding of ice-shelf collapse comes from the Antarctic Peninsula. It is likely that more Antarctic ice shelves will also be impacted by hydrofracture, as warming produces more melting in tandem with sustained wind-enhanced melting, resulting in the reduced permeability of ice shelf firn and allowing the formation of melt ponds in vulnerable areas.

Role of meltwater in future mass balance

In the future, surface melting will play an increasingly important role in Antarctic Ice Sheet mass balance as the climate warms in response to GHG emissions[94,95]. The degree of influence will depend critically on melt rates, which increase nonlinearly with atmospheric temperatures — mainly as a result of the melt–albedo

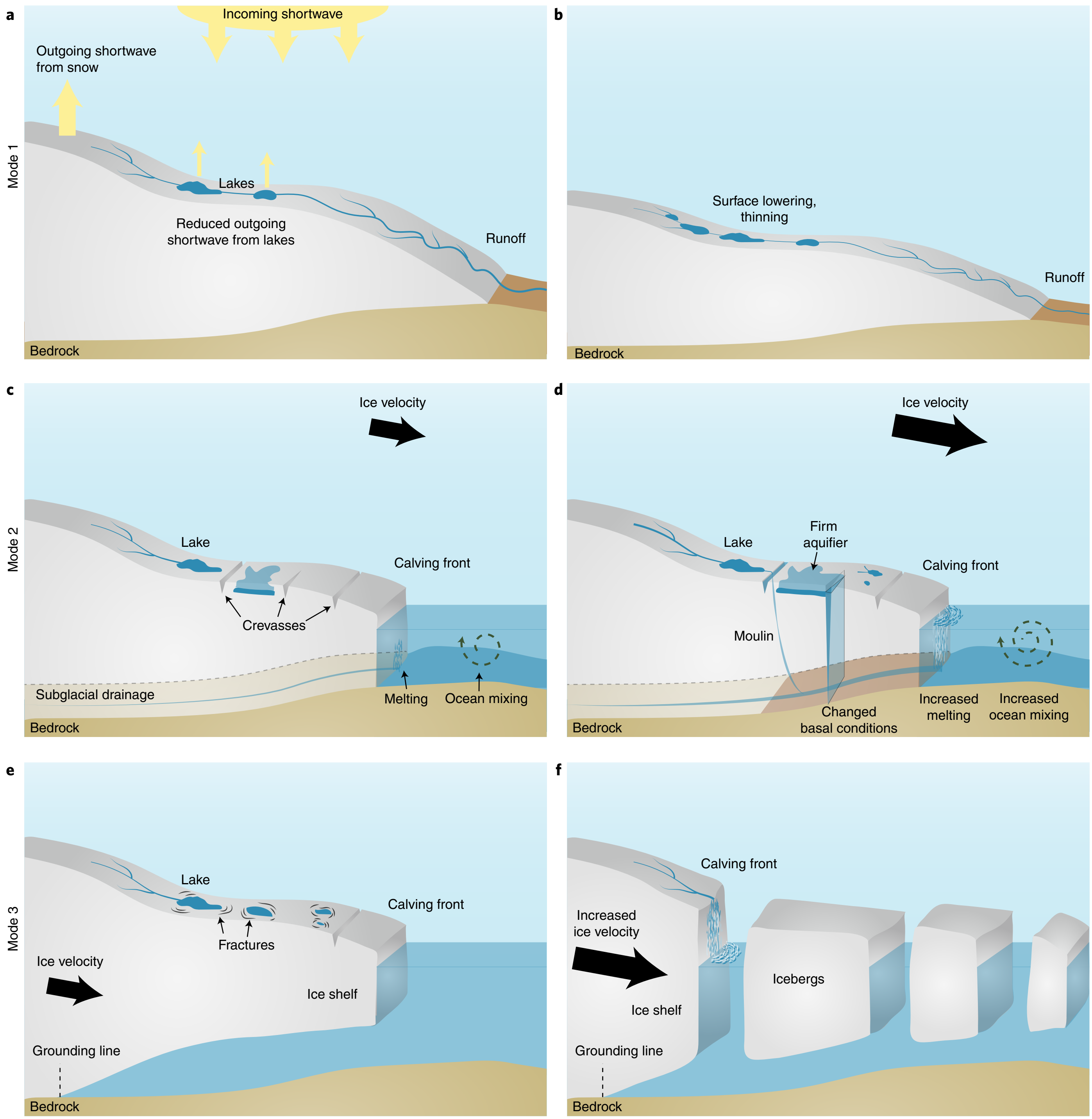

Fig. 3 | Schematic illustration of three primary modes of surface melt impact on ice-sheet mass balance. a,**b**, Mode 1. Direct surface ablation is enhanced over lake bottoms owing to the albedo feedback[30], resulting in incoming shortwave radiation reflecting less (small yellow arrow) from lakes than adjacent snow or bare ice surfaces (larger arrow). **c**,**d**, Mode 2. Connectivity between the ice surface hydrology and ice-sheet base impacts ice dynamics by modifying basal thermal and hydrologic conditions. Connections may occur through surface lakes draining into fractures, via rivers draining into moulins and via firn aquifers draining into fractures. **e**,**f**, Mode 3. Meltwater-induced ice-shelf collapse due to presence of surface lakes. Surface lakes propagate pre-existing fractures downwards by hydrofracture (light blue lake and fracture)[68,88] and load (or unload) the ice shelf, creating new fractures (dark blue lake and fractures) that drain adjacent lakes[74]. When an ice shelf collapses, mass loss will increase as the reduced buttressing force will trigger the outlet glaciers to accelerate.

positive feedback[94]. This positive feedback heightens the sensitivity of warmer regions to future temperature increases, while also enabling melt to shift from a relatively insignificant process to a potentially dominant driver of ice-shelf change over this century. Evidence for melt–temperature nonlinearity and its impacts is provided by an ice core on the northeastern Antarctic Peninsula, documenting rapid melt intensification since the mid-twentieth century coincident with numerous ice shelf collapses[55].

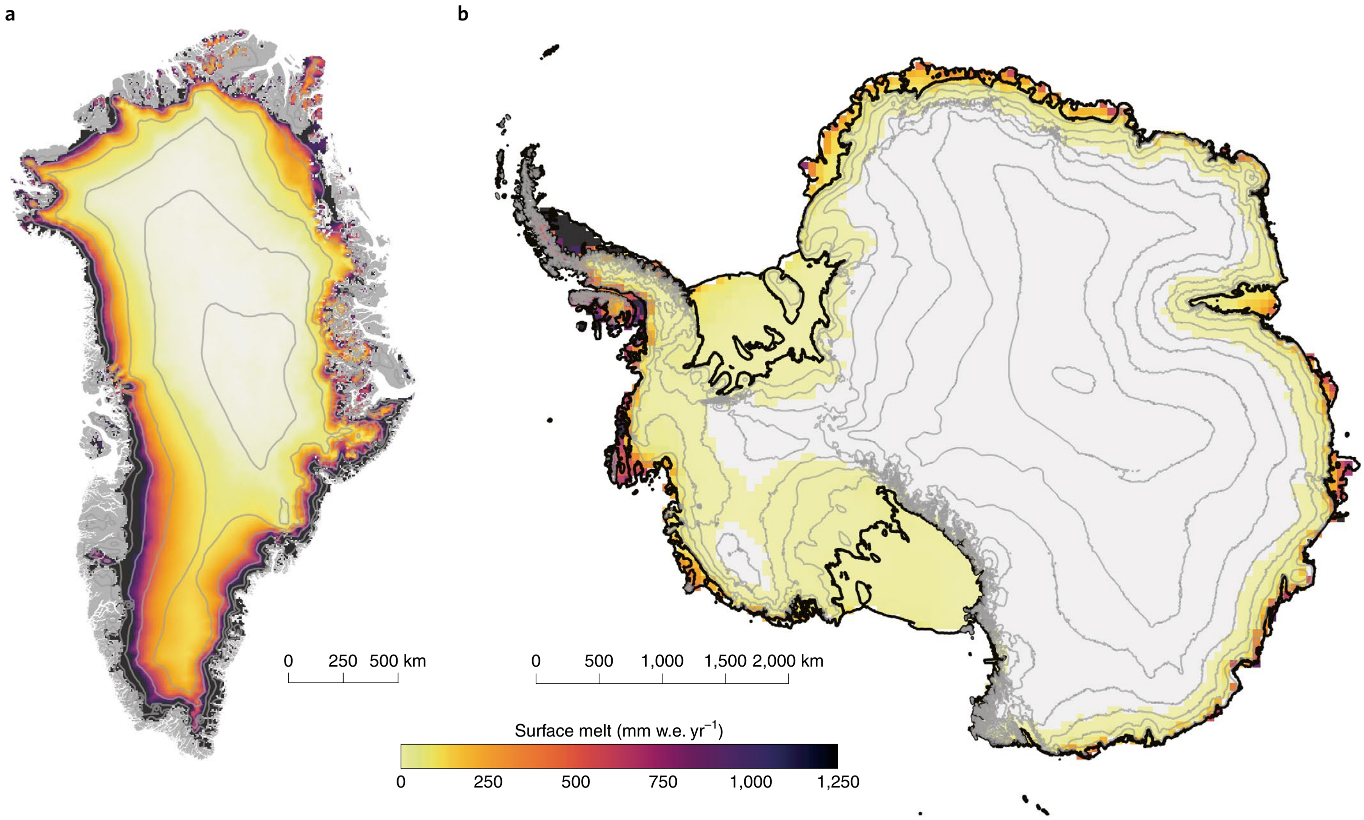

Fig. 4 | Surface meltwater production in Greenland today and Antarctica at the end of the century. a, Mean annual surface melting in Greenland as simulated over 2000–2009 in MARv3.5.2 forced by ERA-Interim[100]. **b**, Projected annual surface melting over 2091–2100 in Antarctica under RCP8.5 using an ensemble of CMIP5-based models[94]. Note that the colour scale is different to that in Fig. 1. Contours indicate surface elevation at intervals of 500 m.

Simulations of future Antarctic surface melting vary widely, with the dominant source of uncertainty in projections resulting from the uncertainty in the future evolution of GHG emissions (that is, scenario uncertainty). Additional uncertainty emerges from the biases inherent to various climate models, as well as the configuration of modelling experiments and uncertainty in the parameterization of meltwater transport, storage and influence on ice-shelf fracture. Owing to the nonlinear sensitivity of melt to temperature change, even small biases in the simulation of present-day climate can translate to large biases in the simulation of future meltwater production. Illustrating this case, models that do not reproduce melt conditions today project 200–500% more melt by 2100[95] than a subset of climate models that are able to reproduce present-day melt rates[94]. Nevertheless, even under more conservative projections[94], a near doubling of the Antarctic-wide volume of melt is simulated by 2050, irrespective of the emissions scenario selected. Beyond mid-century, there is a close coupling between CO_2 emissions and Antarctic melt. Under a high-emissions scenario (Representative Concentration Pathway (RCP) 8.5), melt on nearly all Antarctic Peninsula ice shelves — and to a lesser degree on ice shelves further south in West Antarctica — approaches or surpasses levels associated with recent Antarctic Peninsula ice-shelf collapses[94]. Other projections with more intense surface melt[95] suggest that by 2100 surface melt will trigger rapid and widespread Antarctic ice-sheet mass losses through a progression of instability mechanisms including surface melt-induced ice-shelf hydrofracture, marine ice-cliff instability and marine ice-sheet instability[89]. Here we will focus on the more conservative of these two model-based studies, albeit under a high-emissions pathway.

Figure 4 compares melt rates projected for the end of the century in Antarctica under RCP8.5 to present-day melt rates in Greenland. This provides a framework for understanding the future impact of melt in Antarctica. The region that will experience the greatest increase in surface melt will be the Antarctic Peninsula. Melt rates as high as in Greenland's lower ablation zone, where surface meltwater is connected to the bed, are projected for this region by 2100. Melt intensity is strongly dependent on elevation and latitude. If not already at risk of collapse due intensified surface melting[94], Antarctic Peninsula ice shelves will probably deplete their firn air content under a high-emissions scenario by the end of the century[6]. Lack of pore space within the firn layer of Antarctic Peninsula ice shelves will heighten their sensitivity to further melt increases by promoting meltwater pooling or runoff as opposed to percolation and refreezing[45]. A simplistic interpretation of this comparison suggests that bare ice zones, melt lakes and moulins will replace percolation zones that proliferate across much of floating and grounded ice of the Antarctic Peninsula today. This could trigger several meltwater impacts that are active in Greenland but are currently negligible in Antarctica, including meltwater runoff and the injection of meltwater to the bed. Given historical melt-rate and temperature-based thresholds for ice-shelf viability[94], the Larsen C Ice Shelf and others on the Antarctic Peninsula can be expected to collapse under this emissions scenario this century[35,53]. With high melt intensification projected and increased snowfall already observed[96], firn aquifers and subsurface lakes may develop along the Antarctic Peninsula.

The impact of surface hydrology on ice-sheet mass balance in other parts of Antarctica will grow as the extent and intensity of surface melt increases. The ponding of meltwater on ice shelves could contribute to their collapse. Whether water is exported by ice-shelf rivers will depend on surface slope, surface conditions and the ice-shelf stress state. If predictions of increased melting are accurate, by 2100 ice shelves in the Antarctic Peninsula will probably have collapsed and all remaining ice shelves including the large Ross, Filchner-Ronne and Amery ice sheets will undergo firn densification due to the increased surface melt. Atmospherically driven surface lowering due to firn compaction will be occurring in tandem with the ocean-driven basal thinning of ice shelves that is already acting on much of peripheral Antarctica[97,98]. Meltwater may collect at the grounding lines of the large ice shelves similar to the ponding and refreezing that is occurring at the grounding line of the Larsen C Ice Shelf today. The elevated surface melt on the Abbott, Getz and Shackleton ice shelves will lead to the collapse of these ice shelves unless active surface drainage can mitigate the effect of surface loading by exporting water to the ocean.

On the grounded portions of East and West Antarctica, surface lowering due to runoff and connectivity to the bed (modes 1 and 2, Fig. 3) could become significant by 2100 in certain regions. Regions where 2100 melt rates similar to those observed in Greenland today develop on grounded Antarctic ice include the Pine Island catchment and portions of Wilkes Land, East Antarctica. We expect that areas of englacial water storage — including firn aquifers and buried lakes — will expand as accumulation and precipitation increase simultaneously this century[99].

Increased snow accumulation, a result of a warming atmosphere, is likely to moderate the impact of melt. Recent coupled climate modelling indicates that owing to the enhanced moisture-holding capacity of the atmosphere and increased open-ocean evaporation, Antarctic surface mass balance may increase by 70 Gt yr^{-1} per degree of warming even as surface melt and runoff increase[99]. Evidence for ongoing warming-enhanced snowfall is preserved in ice cores. Increased snowfall could also inhibit the melt–albedo feedback, which is important for melt initiation and seasonal melt evolution on East Antarctic ice shelves[7]. Enhanced snowfall may also support the growth of the ice shelf/sheet firn layer and thus enable enhanced meltwater infiltration and refreeze as opposed to ponding[45] or promote future growth in meltwater storage in aquifers[18,45]. If the firn layer thickens, more meltwater will infiltrate and refreeze or be stored in firn aquifers[18] rather than ponding on the ice surface[45]. While increased accumulation may buffer the impact of increased surface melt on runoff and ice-shelf collapse, if increased accumulation leads to the formation of extensive firn aquifers in crevassed regions, connectivity between the surface and basal hydrologic systems may develop. Similarly, an increase in ice flux could result from meltwater injected into ice shear margins or into regions of Antarctica with cold frozen beds.

To move beyond simple projections of modern Greenland hydrology to a warmer Antarctica requires an improved understanding of surface hydrology on ice shelves and ice sheets. There are profound knowledge gaps in our understanding of the role of firn densification, the roles of hydrofracture and meltwater-loading-induced-flexure on ice-shelf fracture and calving, and how effective surface rivers are in buffering ice shelves from collapse — these must be addressed to inform our grasp of surface hydrology. Similarly, for grounded ice, we do not have a clear understanding of what happens when surface melt first reaches the base of an ice sheet. Because of melt–temperature nonlinearity and the varied local- and global-scale processes impacting melt, it is essential for climate and ice-sheet models to realistically simulate present-day Antarctic climate.

Accurate estimates of surface meltwater production today are hampered by lack of continuity in satellite datasets, and the sparse spatial and temporal in situ observations necessary to constrain the surface energy balance. New satellite campaigns (such as Landsat 8 and the Sentinel constellation) and dedicated field campaigns in melt-prone areas are beginning to address this observation void. The identification of new constraints on ice structure, the evolution and drivers of melt through time and the vulnerability of ice shelves to hydrofracture should include ice cores and geophysical mapping. Sustained and robust observations of Antarctic surface melt and hydrological processes are needed, particularly to constrain their varied drivers and impacts on ice properties and stability, to then develop and refine parameterizations of these processes in continental-scale ice-sheet models. These are critical knowledge gaps that limit our understanding of future Antarctic mass change. Addressing these uncertainties will require a sustained, coordinated, international and interdisciplinary effort.

The impact of increased surface melting on the mass balance of the Antarctic Ice Sheet will depend on the fate of the meltwater as melt on vulnerable buttressing ice shelves increases and that on the grounded ice begins to resemble the melt storage, transport and export active today in Greenland. Whether future surface melt and hydrology resembles that experienced by early Antarctic explorers, or that found in Greenland today, is tied in large part to the future emissions of GHGs. In the near future, surface melt processes will have the greatest impact on global sea level through susceptible ice shelves buttressing large catchments. When and where each mode of meltwater impact — direct thinning, injection of meltwater to the bed and hydrofracture — are activated in a wetter, warmer Antarctica will to some extent control to how much Antarctica contributes to global sea-level rise.

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Author contributions
R.E.B. conceived the idea, and all authors contributed equally to the writing.

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