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The role of channelized basal melt in ice-shelf stability: recent progress and future priorities

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Abstract

Basal channels, which form where buoyant plumes of ocean water and meltwater carve troughs upwards into ice-shelf bases, are widespread on Antarctic ice shelves. The formation of these features modulates ice-shelf basal melt by influencing the flow of buoyant plumes, and influences structural stability through concentration of strain and interactions with fractures. Because of these effects, and because basal channels can change rapidly, on timescales similar to those of ice-shelf evolution, constraining the impacts of basal channels on ice shelves is necessary for predicting future ice-shelf destabilization and retreat. We suggest that future research priorities should include constraining patterns and rates of basal channel change, determining mechanisms and detailed patterns of basal melt, and quantifying the influence that channel-related fractures have on ice-shelf stability.

Introduction

Ocean-induced weakening and retreat of floating ice shelves and ice tongues, for example at West Antarctica's Pine Island Glacier (Lhermitte and others, 2020), frequently proceeds through calving initiated from thin and weak zones such as shear margins (Alley and others, 2019). One mechanism for concentrating thinning and weakening on ice shelves is the formation of basal channels (Fig. 1), which occur where a plume of buoyant water melts a trough into the ice-shelf base. Basal channels are influenced by complex interactions between ocean evolution and ice-flow dynamics (including local creep and advection over larger length-scales), making them both indicators of change and modulators of ice-shelf stability. The widespread distribution of basal channels on floating ice shelves, evidence of rapid growth and deepening, correspondence of large channels to warm ocean water masses, and influence on ice-shelf structural stability highlight the importance of future detailed study of these features.

Basal channel characteristics and formation

Basal channels, observed in satellite imagery over ice shelves throughout Antarctica and on some floating ice tongues in Greenland, are typically ~1–3 km in width, ~50–400 m in height from the base of the ice shelf to the channel apex, and a few to many tens of kilometers in length in the approximate along-ice-flow direction, based on observations from MODIS, Landsat, ice-penetrating radar (e.g. Rignot and Steffen, 2008; Stanton and others, 2013; Alley and others, 2016) and the Reference Elevation Model of Antarctica (Alley and others, 2019; Howat and others, 2019; Chartrand and Howat, 2020). These relatively large basal channels can be observed in satellite imagery because of the hydrostatic relaxation of the overlying ice, creating surface depressions visible on the ice-shelf surface (Fig. 1). Many ice shelves may also have smaller basal channels, revealed by ice-penetrating radar, that are invisible in satellite imagery because they are narrow enough for bridging stresses to prevent easily detectable hydrostatic adjustment (e.g., Langley and others, 2014). The relatively large basal channels observed in satellite imagery are distributed widely around the Antarctic continent, but are most common on ice shelves with high basal melt rates and especially those that are directly influenced by modified Circumpolar Deep Water (Alley and others, 2016), the water mass responsible for much of the observed recent retreat of the West Antarctic Ice Sheet (e.g., Hillenbrand and others, 2017).

Basal channel formation is driven by the activity of buoyant plumes of water that persist in approximately the same location over time. Many of these plumes are initiated by the outlet of subglacial meltwater into the ice-shelf cavity (Fig. 1a). Though relatively cold, the fresh meltwater is buoyant enough to rise along the ice-shelf base, entraining ocean water that generally is well above the in situ melting temperature and melting a trough in the ice through turbulent heat transfer; many plumes eventually super-cool and lead to freeze-on as the dropping pressure along-flow raises the melting temperature and the ice-shelf base flattens, reducing entrainment (Le Brocq and others, 2013; Drews and others, 2017). The channels formed by this process, which begin at the grounding line and tend to dissipate downflow, can be referred to as subglacially sourced channels (Alley and others, 2016). At least some of these subglacially

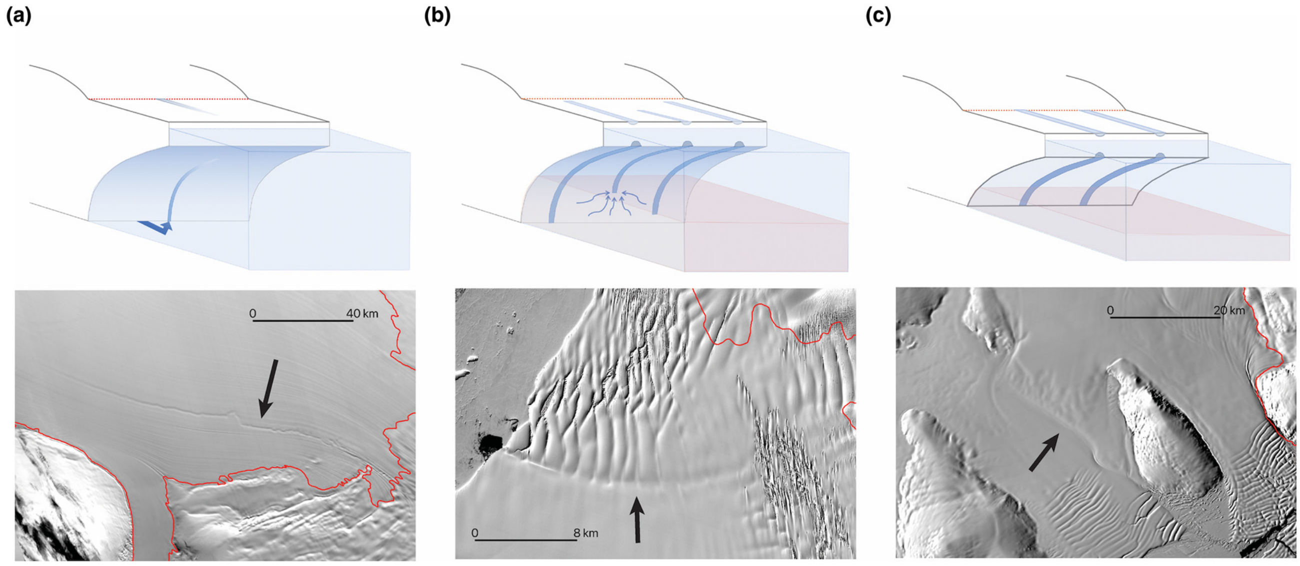

Fig. 1. Types of basal channels. (a) Subglacially sourced channel on Institute Ice Stream, Ronne Ice Shelf. Landsat-8 image from Dec. 2, 2019. (b) Ocean-sourced channel on Thwaites Eastern Ice Shelf, terminating in a persistent polynya. Landsat-8 image from January 4, 2016. (c) Grounding-line-sourced channel on Sulzberger Ice Shelf. Landsat-8 image from 19 January 2022. Channel diagrams modified from Alley and others, 2016, supplementary figure S5. Basal channel examples in satellite imagery marked with black arrows. Grounding line shown in red from the MODIS Mosaic of Antarctica 2014 (Haran and others, 2018).

sourced channels may be influenced by subglacial lake drainage events (e.g. Whiteford and others, 2022), suggesting that they experience basal melt rates that are highly temporally variable.

In contrast, the heads of many channels are detached from the grounding line, and their formation is inferred to be driven by plumes that are buoyant due to the presence of warm ocean water combined with meltwater entrained as the plume rises along the ice-shelf base (Alley and others, 2016). These ocean-sourced channels (Fig. 1b) are likely to exploit local high spots in the basal topography, which may be imparted by grounding-line irregularities (Gladish and others, 2012), suture zones (Dow and others, 2018), or by larger-scale patterns related to stretching and thinning of the ice shelf (Alley and others, 2019). They may also form spontaneously, as ocean water accelerates up an ice-thickness gradient and encounters an irregularity, which deepens as more water is channelized in a positive feedback (Sergienko, 2013). Ocean-sourced channels frequently terminate in persistent open-water polynyas at the ice edge, where the outflowing plume has enough buoyancy and heat energy to prevent the formation of fast ice (Bindschadler and others, 2011; Mankoff and others, 2012).

Grounding-line-sourced channels (Fig. 1c) fall somewhere in-between subglacially sourced and ocean-sourced channels, as they show an apparent intersection with a grounding line but without evidence of coincident subglacial outflow, which may reflect either deficiencies in subglacial hydrologic modeling or warm-ocean influence very close to relatively shallow grounding lines (initiating an ocean-sourced channel at or close to the grounding line, in thin enough ice for hydrostatic adjustment to be visible at the surface). More recent work suggests that there are no sharp boundaries between these channel categories, with many channels of hybrid origin. For example, ocean-sourced channels on Getz Ice Shelf, with a clear visible separation between the grounding line and the channel head and which terminate in persistent polynyas, are in fact likely driven by subglacial meltwater drainage and then enhanced by warm ocean water (Wei and others, 2020). Subglacially sourced channels could also appear as ocean-sourced channels if grounding-line retreat outpaces headward channel growth, particularly in areas with very thick ice where hydrostatic relaxation is limited by bridging stresses. Similarly, there is likely a continuum between basal channels and basal fractures. The hydrostatic relaxation that makes channels visible on the surface also imparts stresses that can create fractures at channel apices (Vaughan and others, 2012), which we discuss in more detail in a later section. In addition, basal fractures form high spots that buoyant plumes may exploit (Fig. 2).

Basal channel importance in ice-shelf stability

The formation of basal channels influences ice-shelf basal melt rates and patterns, an important variable controlling ice-shelf stability. Fundamentally, basal channels form due to positive feedbacks that concentrate melt in high spots in the ice-shelf base. On ice shelves with a high concentration of basal channels, shelf-average melt rates may decrease with increasing channelization, likely because the concentration of flow in buoyant plumes prevents much of the entrained warm water from reaching the ice-shelf base (Gladish and others, 2012; Millgate and others, 2013). The concentrated melting that forms basal channels is opposed by ice flow that seeks to fill the trough through ice creep (Drews, 2015; Wearing and others, 2021; Humbert and others, 2022). The fact that channels persist over long distances and many decades, and often even deepen towards the ice edge (Alley and others, 2016), suggests that basal melt in most large channels is sustained, or occurs frequently, and over the long-term equals or exceeds creep closure.

Buoyant plume flow within basal channels is directed primarily towards the ice-shelf edge, which is consistent with large-scale patterns of overturning circulation within ice-shelf cavities that directs buoyant water up the ice-shelf basal slope. This outward flow is also evidenced by the commonly observed formation of persistent polynyas where basal channels meet the ice-shelf edge (Bindschadler and others, 2011; Mankoff and others, 2012; Alley and others, 2016, 2019) and by the results of numerical modeling studies (Gladish and others, 2012; Millgate and others, 2013; Sergienko, 2013). Within basal channels, outward plume flow, concentrated on the Coriolis-favored side of the channel, may be accompanied by an adjacent opposing return flow on the non-Coriolis-favored side (Millgate and others, 2013). Flow velocity is likely to be strongly heterogeneous, with higher plume velocities near the head of the channel where the ice-shelf basal topography tends to be steeper, and on the Coriolis-favored

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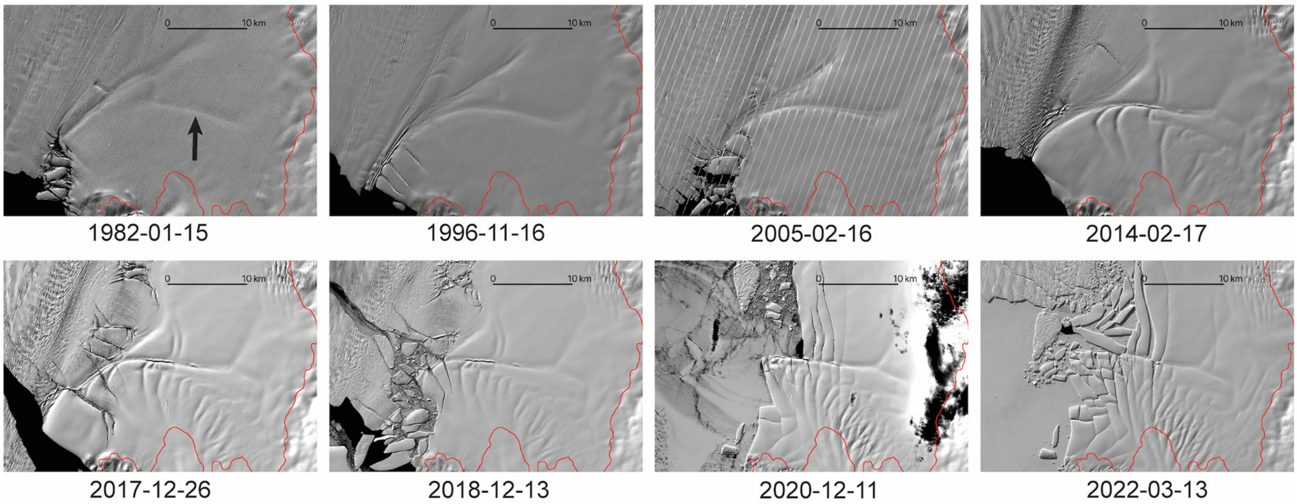

Fig. 2. An example of basal channel change on Pine Island Glacier. The arrow in the first panel indicates a basal channel, which grows first towards another channel and the ice edge, which it reaches by 1996, and then headward, which is clearly visible by 2017. Retreat occurs along the channel throughout the time series, and transverse rifts can be seen opening from the channel from 1996 onwards. These transverse rifts that initiate from the channel frequently result in calving events and ice front retreat. The grounding line shown in red is from the 2014 MODIS Mosaic of Antarctica (Haran and others, 2018). Images come from Landsat 5, 7, and 8.

side of the channel (Gladish and others, 2012; Millgate and others, 2013; Sergienko, 2013). In general, melt rates are expected to follow roughly the same pattern as velocities, with the highest melt rates near the grounding line (Rignot and Steffen, 2008; Gladish and others, 2012; Dutrieux and others, 2013; Humbert and others, 2022) where ocean forcing is greatest and the subglacial topography steepest, and on the Coriolis-favored side of the channel (Sergienko, 2013).

However, basal melt observations suggest a more complex and heterogeneous story. Measurements from autonomous underwater vehicles and radar observations have revealed terraces - relatively flat and nearly horizontal regions extending for long distances along flow, separated by steeper slopes - on the sides of some basal channels (Dutrieux and others, 2014), with calculated rates of basal melt highest on basal channel flanks, and lowest at the channel apices. Dutrieux and others (2014) found this pattern in basal channels on both Pine Island Glacier in West Antarctic and Petermann Glacier in northwest Greenland. In contrast, Stanton and others (2013), working on a different area of Pine Island Glacier, and Rignot and Steffen (2008) on a different spot on Petermann found exactly the opposite pattern: smooth channels, with the highest melt rates found at channel apices. All channels must at some point have high melt at channel apices in order to create the observed troughs. However, as the buoyant plume moving along the channel loses energy with the decrease in ice-shelf basal slope, models suggest the plume may rapidly detrain (Millgate and others, 2013), and a stratified layer near the channel apex may develop (Dutrieux and others, 2014). It is, perhaps, at this point that a smooth channel dominated by apex-melt may transition to a terraced channel dominated by flank-melt, but this hypothesis requires much more investigation.

Along with changing patterns of ice-shelf basal melt, basal channels directly impact ice-shelf stability through complex interactions with ice-shelf fracture (see Fig. 3 for a summary diagram). Vaughan and others (2012) showed that stresses associated with hydrostatic adjustment can be high enough to induce along-channel (longitudinal) basal fractures at channel apices, and this pattern has also been observed in radar transects (Dutrieux and others, 2014). In cases of many basal channels parallel to each other, swarms of surface fractures can form above channel keels as a result of the same stresses. In a pattern likely to be related to the weakening due to channel apex factures, ice shelves are often observed to develop full-thickness, along-channel rifting, and then to retreat along basal channels (e.g. Rignot and Steffen, 2008; Alley and others, 2016). An example of this behavior is demonstrated in Figure 2, which shows a time series of basal channel change on Pine Island Glacier. Rifting and retreat along the channel occurs repeatedly, but is particularly clear in the 2020 image.

Basal channels can also influence the transverse fractures that control ice-shelf calving. Dow and others (2018) observed repeated calving events on Nansen Ice Shelf that occurred along rifts that initiated and extended from the location of a basal channel. This pattern of transverse fractures (either full-thickness rifts or the surface expression of basal fractures) originating from basal channels is commonly observed around Antarctica. For example, the channel on Pine Island Glacier (Fig. 2) is both fracturing along-channel, as discussed above, and generating transverse fractures that open outwards from the channel, which are visible in every panel starting in 1996. It is not yet clear whether the association between basal channels and transverse fractures is related purely to ice dynamics or if pre-existing fractures are being widened by the plumes flowing through the channels. Basal channels form disproportionately often beneath shear margins because of advection of thinned ice from shear margins of grounded ice streams, and these ice-shelf shear-margin channels further localize thinning and weakening (Alley and others, 2019). Many large calving and retreat events initiate from these shear margins, and basal channels may play a role in weakening them and initiating these events.

Curiously, the opposite effect also seems to occur in some locations, where a propagating fracture is stopped when it reaches a basal channel. For example, the channel on the Thwaites Eastern Ice Shelf in Figure 1b appears to be arresting the propagation of rifts growing from the top of the image towards the bottom. This effect might help to stabilize an ice shelf, at least temporarily. The process may be similar to a pattern noted on the Larsen C Ice Shelf, where propagating rifts are arrested at suture zones, which contain large thicknesses of relatively soft and warm marine ice (McGrath and others, 2012). Marine ice formation in basal channels has been inferred by thermodynamic conditions (Le Brocq and others, 2013) and observed in radar transects (Whiteford and others, 2022), although it has not been observed on ice shelves with relatively warm cavities (e.g., Rignot and Steffen,

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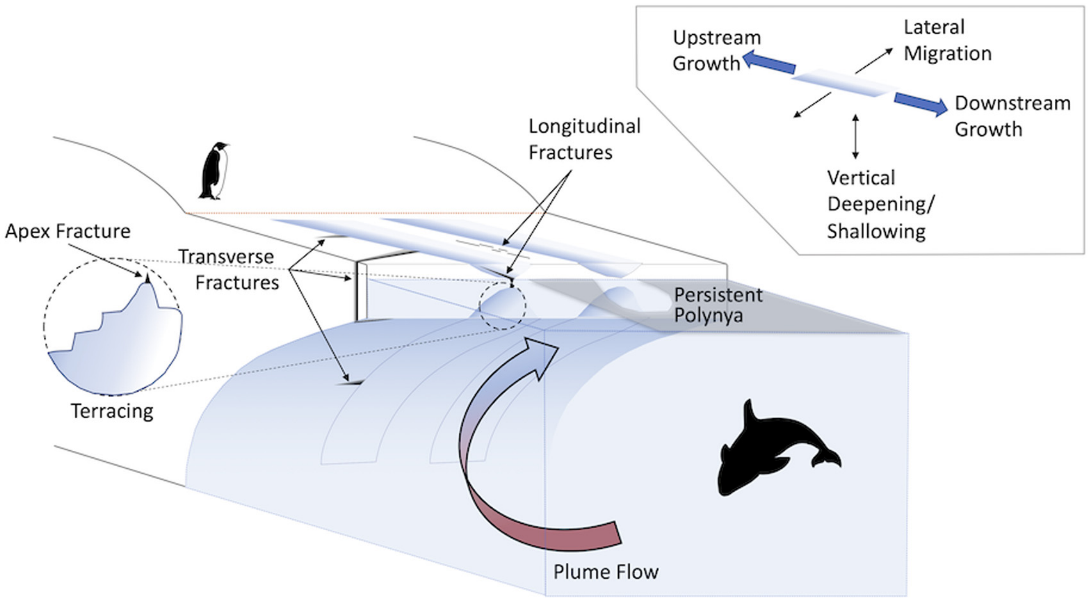

Fig. 3. Summary of suggested basal channel research priorities.

2008; Stanton and others, 2013). While the characteristics of the ice within and surrounding the channel might be responsible for arresting fracture propagation, it is also possible that the behavior could be explained by a change in ice-shelf stress state due to the presence of a basal channel focusing shear.

Along with these significant influences on ice-shelf stability, basal channels have been observed to change over time, sometimes very rapidly. A basal channel on Getz Ice Shelf grew ∼20 km upstream since Landsat observations began in the 1970s (Alley and others, 2016), with incision rates near the head of the channel of up to 22 m/year (Chartrand and Howat, 2020). The Pine Island channel in Figure 2 grew downstream to reach the ice edge from its 1986 position, and then grew headward, eventually intersecting with a basal fracture that formed from extensional stresses just downstream of the grounding line. As basal channels are most common in areas where ice-shelf basal melt rates are high and are closely associated with modified Circumpolar Deep Water intrusion in the sub-shelf cavity, it is reasonable to assume that the increase in basal channel length may be tied to increasing access of modified Circumpolar Deep Water to West Antarctic ice shelves in recent decades (e.g., Jacobs and others, 2011). Basal channels have also been observed to migrate laterally across ice shelves, independent of ice flow (Chartrand and Howat, 2020; Drews and others, 2020).

Future research priorities

Based on these observations of basal channels, their impacts, and their evolution, we suggest three priorities for future research, with components summarized in Figure 3. The first research priority we suggest is to quantify patterns and rates of basal channel change, with further consideration of how channels form and migrate. Basal channel change has been observed in all dimensions (represented in Fig. 3) and many mapped basal channels (Alley and others, 2016) have not been analyzed in any dimension over time. It is very difficult to draw conclusions about large-scale basal channel change from the few isolated studies that have been carried out. Important remaining questions include: Are most basal channels in steady-state, or is change common? Is basal channel change widespread throughout Antarctica, or concentrated in certain areas? Are changes brief or sustained in time? Many available remote sensing datasets provide valuable information to answer these questions. Long-term optical time series, such as those available from Landsat, can be used to track lateral migration and changes in channel length. High-resolution DEMs and altimetry missions constrain channel deepening and changes in cross-sectional profiles. Single profiles from ground-penetrating radar record past channel migration in the imaged layers, and repeat profiles reveal details of more recent change.

Perhaps a harder challenge is to constrain the styles and patterns of basal melt associated with basal channels. As described above, some basal channels have been observed to develop terraces (Dutrieux and others, 2014), while others are smooth (Rignot and Steffen, 2008; Stanton and others, 2013). Along-flow melt variability has been noted in calculated basal melt rates (Rignot and Steffen, 2008; Dutrieux and others, 2013) and numerical models (Gladish and others, 2012; Millgate and others, 2013; Sergienko, 2013). Across-channel melt variability has shown contradictory signals, with some sections of channels melting fastest at the apex (Stanton and others, 2013) and others on their flanks (Dutrieux and others, 2014). Persistent polynyas at the ends of basal channels give clues to the thermal forcing and temporal variability of the plumes flowing through basal channels (Bindschadler and others, 2011). Big-picture questions remain about what controls the strength, temperature, and variability of basal channel plumes, and how to reconcile the varying observations, which suggest significant spatial and/or temporal heterogeneity in basal melt patterns. While some of these questions might be answered through detailed analysis of polynya surface temperatures and sizes, most will require in situ measurements and numerical modeling. We need better constraints on basal channel geometry using ice-penetrating radar and sub-ice-shelf multibeam data, and point measurements of basal melt from phase-sensitive radar. It is also important to collect more direct measurements of plume flow in basal channels, using autonomous underwater vehicles as well as oceanographic data from instruments lowered through ice-shelf boreholes.

Finally, perhaps the most consequential basal channel research priority for understanding future ice-shelf stability and impacts on sea-level rise is to constrain the relationship between basal channels and ice-shelf fracture and calving. Fracturing has been observed to propagate both longitudinally, along basal channels,

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and transversely, away from basal channels, both of which can result in accelerated calving and ice-shelf retreat (Dow and others, 2018; Alley and others, 2019; Figure 2). Channels preferentially form in already-weak shear margins, where many calving events initiate (Alley and others, 2019). Conversely, channels may arrest the propagation of fractures, in a manner similar to suture zones filled with marine ice (McGrath and others, 2012). We need to investigate the magnitude of change to ice-shelf strength and dynamically induced stresses that is imparted by basal channel formation, and combine these results with observations of channel change to predict future ice-shelf behavior. Much of this work will be ultimately underpinned by numerical modeling, a daunting task as ice-shelf fracture is not well-represented in most numerical models. High-temporal-resolution records from optical and radar imagery will also be important to track the details of fracture propagation and calving patterns.

Basal channels are complex systems influenced by ice creep, advection, and ocean control. We have enough information already to understand that basal channels have significant impacts on ice-shelf basal melt and structural stability, and we know that they can change significantly and rapidly. Much work remains to constrain in detail the influence that basal channels will have as the world warms and ice shelves evolve in the future.

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References

Alley KE, Scambos TA, Alley RB and Holschuh N (2019) Troughs developed in ice-stream shear margins precondition ice shelves for ocean-driven breakup. *Science Advances* **2019**(5), eaax221.

Alley KE, Scambos TA, Siegfried MR and Fricker HA (2016) Impacts of warm water on Antarctic ice shelf stability through basal channel formation. *Nature Geoscience* **9**, 290–293.

Bindschadler R, Vaughan DG and Vornberger P (2011) Variability of basal melt beneath the Pine Island Glacier ice shelf, West Antarctica. *Journal of Glaciology* **57**(204), 581–595.

Chartrand AM and Howat IM (2020) Basal channel evolution on the Getz Ice Shelf, West Antarctica. *Journal of Geophysical Research/Earth Surface* **125**, e2019JF005293.

Dow CF and 8 others (2018) Basal channels drive active surface hydrology and transverse ice shelf fracture. *Science Advances* **2018**(4), eaao7212.

Drews R (2015) Evolution of ice-shelf channels in Antarctic ice shelves. *Cryosphere* **9**, 1169–1181.

Drews R and 9 others (2017) Actively evolving subglacial conduits and eskers initiate ice shelf channels at an Antarctic grounding line. *Nature Communications* **8**, 15228.

Drews R and 5 others (2020) Atmospheric and oceanographic signatures in the ice shelf channel morphology of Roi Baudouin Ice Shelf, East Antarctica, inferred from radar data. *Journal of Geophysical Research/ Earth Surface* **125**(7), e2020JF00558.

Dutrieux P and 6 others (2013) Pine Island Glacier ice shelf melt distributed at kilometre scales. *Cryosphere* **7**, 1543–1555.

Dutrieux P and 6 others (2014) Basal terraces on melting ice shelves. *Geophysical Research Letters* **41**, 5506–5513.

Gladish CV, Holland DM, Holland PR and Price SF (2012) Ice-shelf basal channels in a coupled ice/ocean model. *Journal of Glaciology* **58**(212), 1227–1244.

Haran T and 5 others (2018) MEaSUREs MODIS Mosaic of Antarctica 2013–2014 (MOA2014) Image Map, Version 1 [Grounding Line]. NASA National Snow and Ice Data Center DAAC, Boulder, CO, USA. Accessed 15 Oct 2022.

Hillenbrand CD and 14 others (2017) West Antarctic ice sheet retreat driven by Holocene warm water incursions. *Nature* **547**, 43–48.

Howat IM, Porter C, Smith BE, Noh MJ and Morin P (2019) The reference elevation model of Antarctica. *Cryosphere* **13**, 665–674.

Humbert A and 11 others (2022) On the evolution of an ice shelf melt channel at the base of the Filchner Ice Sehlf, from observations and viscoelastic modeling. *Cryosphere* **16**, 4107–4139.

Jacobs S, Jenkins A, Giulivi C and Dutrieux P (2011) Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf. *Nature Geoscience* **4**, 519–523.

Langley K and 8 others (2014) Complex network of channels beneath an Antarctic ice shelf. *Geophysical Research Letters* **41**, 1209–1215.

Le Brocq AM and 10 others (2013) Evidence from ice shelves for channelized meltwater flow beneath the Antarctic Ice Sheet. *Nature Geoscience* **6**, 945–948.

Lhermitte S and 7 others (2020) Damage accelerates ice shelf instability and mass loss in Amundsen Sea Embayment. *Proceedings of the National Academy of Sciences of the United States of America* **117**(40), 24735–24741.

Mankoff KD, Jacobs SS, Tulaczyk SM and Stammerjohn SE (2012) The role of Pine Island Glacier ice shelf basal channels in deep-water upwelling, polynyas and ocean circulation in Pine Island Bay, Antarctica. *Annals of Glaciology* **53**(60), 123–128.

McGrath D and 6 others (2012) The structure and effect of suture zones in the Larsen C Ice Shelf, Antarctica. *Journal of Geophysical Research/Earth Surface* **119**, 588–602.

Millgate T, Holland PR, Jenkins A and Johnson HL (2013) The effect of basal channels on oceanic ice-shelf melting. *Journal of Geophysical Research* **118**, 6951–6964.

Rignot E and Steffen K (2008) Channelized bottom melting and stability of floating ice shelves. *Geophysical Research Letters* **35**, L02503.

Sergienko O (2013) Basal channels on ice shelves. *Journal of Geophysical Research* **118**, 1342–1355.

Stanton TP and 8 others (2013) Channelized ice melting in the ocean boundary layer beneath Pine Island Glacier, Antarctica. *Science* **341**(6151), 1236–1239.

Vaughan DG and 8 others (2012) Subglacial melt channels and fracture in the floating part of Pine Island Glacier, Antarctica. *Journal of Geophysical Research* **117**, F03012.

Wearing MG, Stevens LA, Dutrieux P and Kingslake J (2021) Ice-shelf basal melt channels stabilized by secondary flow. *Geophysical Research Letters* **48**, e2021GL094872.

Wei W and 11 others (2020) Getz Ice Shelf melt enhanced by freshwater discharge from beneath the West Antarctic Ice Sheet. *Cryosphere* **14**, 1399–1408.

Whiteford A, Horgan HJ, Leong WJ and Forbes M (2022) Melting and refreezing in an ice shelf basal channel at the grounding line of the Kamb Ice Stream, West Antarctica. *Journal of Geophysical Research/Earth Surface* **127**, e2021JF006532.