Development of Ice-Shelf Estuaries Promotes Fractures and Calving

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Abstract

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Data Availability: Except for DigitalGlobe constellation data, all datasets used in this analysis are freely available. DigitalGlobe satellite imagery was provided by the PGC under NSF grant 1644869, and is available from the PGC upon request with eligible active research awards. Imagery-derived river widths and fracture length developed in this analysis are available at http://wonder.ldeo.columbia.edu/data/publicationData/Boghosian/Estuary/, along with MAR data used. Landsat data are available https://earthexplorer.usgs.gov, and LIMA is available at https://nimbus.cr.usgs.gov/landing/. OIB data are provided by the National Snow and Ice Data Center at https://nsidc.org/. The 1978 orthophotos are provided by the National Oceanic and Atmospheric Administration National Centers for Environmental Information at https://www.nodc.noaa.gov/archive/arc0088/0145405/1.1/data/0-data/G150AERODEM/Orthorectified/. Ice-shelf elevation data are available at https://sealevel.nasa.gov/data/dataset/?identifier=SLCP_ice_shelf_dhdt_v1_1. REMA data are available through the PGC at https://www.pgc.umn.edu/data/rema/.

Code Availability: This analysis does not depend on specific code. All results can be reproduced through the equations and procedures outlined in the Methods section of this manuscript.
As the global climate warms, increased surface meltwater production on ice shelves may trigger ice-shelf collapse and enhance global sea-level rise. The formation of surface rivers could help prevent ice-shelf collapse if they can efficiently evacuate meltwater. Here, we present observations of the evolution of a surface river into an ice-shelf estuary atop the Petermann Ice Shelf in northwest Greenland, and identify a second estuary at the nearby Ryder Ice Shelf. This surface hydrology process can foster fracturing and enhance calving. At the Petermann estuary, sea ice was observed converging at the river mouth upstream, indicating a flow reversal. Seawater persists in the estuary, after the surrounding icescape is frozen. Along the base of Petermann estuary, linear fractures were initiated at the calving front and propagated upstream along the channel. Similar fractures along estuary channels shaped past large rectilinear calving events at the Petermann and Ryder Ice Shelves. Increased surface melting in a warming world will enhance fluvial incision, promoting estuary development, longitudinal fracturing orthogonal to ice-shelf fronts, and increase rectilinear calving. Estuaries could develop in Antarctica within the next half-century, resulting in increased calving and accelerating both ice loss and global sea-level rise.

Ice shelves are increasingly losing mass due to both widespread basal melting and calving, and are also vulnerable to rapid collapse triggered by surface hydrology. Ice shelf surface hydrology can lead to rapid ice shelf collapse through the formation of surface ponds, which weaken and break the ice shelf through flexure and hydrofracture. However, recent observations of ice-shelf rivers suggest that water export off the ice shelf may limit the damage potential of ice shelf surface hydrology. The impact that rivers have on ice-shelf stability remains unresolved. A recent coupled ice-sheet-climate model of Antarctica assumes meltwater remains static, and predicts that Antarctica contributes one meter to global average sea level rise by 2100. However, satellite observations show widespread water transport onto Antarctica’s ice shelves and large volumes of water transport across Greenland. Ice-shelf rivers form in response to climate and albedo characteristics that drive meltwater production, and ocean conditions that create linear depressions in ice-shelf surface topography, where ice-shelf rivers can flow. As global temperatures rise, more ice-shelf rivers will develop, increasing the urgency to understand the impact of surface hydrology on ice-shelf stability.

The Petermann Ice Shelf in northwest Greenland (Fig. 1), one of three remaining large ice shelves in Greenland, flows along a ~25 km wide fjord. The ice-shelf surface supports a system of lakes and rivers first observed in 1978. This system may serve as an analog for the future of Antarctica’s ice shelves. Like the Nansen river in East Antarctica, the Petermann river flows to the ocean, terminating at the ice-shelf edge (Fig. 1a) which was formed by the last major calving event in 2012. Climatolgy-forced regional climate models show surface melting persists on the Petermann Ice Shelf for ~80 days each year (Extended Data Fig. 1). Rivers and lakes develop on bare ice that is exposed on the ice shelf, a region of low accumulation (Extended Data Fig. 2). The Petermann river flows along a linear depression in the center of the ice shelf, which is the surface expression of a 1–2 km-wide basal channel. Focused ocean melting initiates this channel within ~5 km of the grounding line, carving 200–400 m upward into the ice shelf base. The resulting linear depression is a persistent feature of the ice-shelf surface. The Nansen River also flows atop...
a basal channel\(^9\). Through this imprint on ice-shelf morphology, ocean processes control the location of ice-shelf rivers.

**Observations of ice-shelf estuaries**

Estuaries form near river mouths, where fresh fluvial waters and saline ocean waters mix\(^9\). Prior to this study, estuaries had not been identified on ice shelves. Using high-resolution satellite and aerial imagery, we discover the first observed ice-shelf estuary at the calving front of the Petermann Ice Shelf where the Petermann river directly connects to the ocean (Fig. 1). Four observations indicate the existence of the Petermann estuary: the presence of sea ice in the lower reach of the river (<1 km from the terminus, Fig. 1a, b); the presence of water in the lower reach of river channel after the end of the melt season (Fig. 1c, Extended Data Fig. 1); the fan-shaped convergence of sea ice at the river mouth (Fig. 1a, b); and the widening of the channel within 1 km of the terminus (Extended Data Fig. 2b, Extended Data Fig. 3). Floating ice with the same shape and texture as offshore sea ice indicates that seawater is present in the channel (Fig. 1a, b) as far as 460 m upstream from the river mouth (Fig. 1a, b). Seawater in the channel is also identified in imagery collected 26 days after the melt season (on September 12, 2014, Fig. 1c, Extended Data Fig. 1) when surface lakes are frozen and the adjacent ice-shelf surface is dry, meaning the ocean is the only source of liquid water. Seawater persisted in the channel after the melt season in September 2013–2016 (Extended Data Fig. 1). Flow reversal at the estuary is confirmed by the distinctive pattern of convergent sea ice at the estuary mouth (Fig. 1a, b) and is likely a result of tidal and/or baroclinic exchange flow\(^9\). We also find that river widths tripled in the estuary between 2010 and 2018 (Extended Data Fig. 2, Extended Data Fig. 3) while upstream (>2 km from the terminus) widths remained stable (Extended Data Fig. 3). This downstream widening is consistent with the establishment of an estuary. Once a river channel reaches sea level, it cannot incise downward any further. There is relatively little flow gradient to drive velocity, so more kinetic energy in the system is dissipated by melting channel walls. Melting and widening is also enhanced by the presence of relatively warm (>0° C)\(^{20}\) ocean water in the estuary. These observations indicate the Petermann estuary currently reaches at least 0.5 km upstream from the ice-shelf front. Ice-shelf estuaries have formed on the Ryder Ice Shelf in Greenland, evidenced in 2019 by dark water at the mouth of the channel and a continuous water surface between the river mouth and the ocean (Fig. 2c), and in 2014 by seawater in the channel after the melt season (Extended Data Fig. 4).

**Longitudinal fracture development and rectilinear calving**

After the Petermann river evolves to an estuary, new ice-shelf fractures form at the calving front and propagate upstream along the channel, parallel to ice flow (Fig. 2a, b, Extended Data Fig. 5). The fractures are located in the center of the river channel, and appear as dark linear features in satellite images (Fig. 2a, Extended Data Fig. 5) and aerial photographs (Fig. 2b, c). These features could be interpreted as the deposition of cryoconite, however, sediments are unlikely to accumulate in the channel center where water velocity is high. The ~90 m long fracture first appeared along the channel bottom at the mouth of the river in 2014, a minimum of two years after the estuary formed (Methods) (Fig. 2a). By 2017, longitudinal fractures extended ~1.6 km upstream from the ice-shelf front, within the
estuary’s reach (Fig. 2a). Aerial photographs of the fractures show a dark water color similar to through cutting rifts (Fig. 2b), indicating that the fractures propagate through the ice shelf. The Ryder Ice Shelf has similar longitudinal fractures along the bottom of its estuary (Fig. 2c). Longitudinal fractures discovered and initiated at estuary mouths are notably absent in upstream reaches of ice-shelf rivers where estuarine processes are not active.

While many calving events on the Petermann Ice Shelf formed from transverse fractures perpendicular to flow\(^{21}\), since 1978 at least two rectilinear calving events formed along a longitudinal river (Fig. 3a). An early aerial image of the Petermann ice shelf collected in 1978 shows a linear river transporting surface melt across the shelf (Fig. 3a). By 1999, calving events had fractured along the 1978 river (Fig. 3a). The river again terminated in the ocean, potentially forming an estuary. In 2008, a ~10 km long linear fracture formed along the 1999 river channel (Fig. 3a), creating another rectilinear calving event (Fig. 2a). Similar rectilinear calving occurred along a surface river and associated estuary on the Ryder Ice Shelf (Fig. 3b), where calving events typically span the full ice shelf width. Longitudinal fractures are not initiated in upstream reaches of either river. We assign the term “estuarine weakening” to the propagation of longitudinal fractures along the ice-shelf river and estuary systems producing distinctive rectilinear calving geometries (Fig. 3c). While previous work suggested ice-shelf rivers enhance transverse fractures\(^{9}\), estuaries on the Petermann and Ryder Ice Shelves appear to have contributed to the formation of longitudinal fractures and rectilinear calving events over at least the past three decades.

**Implications of estuary formation on calving**

Based on observations of the Petermann and Nansen Rivers\(^{8,9}\) we suggest ice-shelf estuaries evolve from surface rivers that incise atop basal channels given sufficient surface meltwater production. The Nansen River and the upper reaches of the Petermann river represent the river phase of this evolution. During this phase, the river’s location is fixed by pre-existing surface depressions controlled by basal channels\(^{9}\), and the river incises into the same ice each year while exporting water off the ice shelf via waterfalls\(^{8}\). There are no direct feedbacks between the ice-shelf surface hydrology and the ocean, and no channel-parallel fractures develop. Transverse fractures may be enhanced during the river phase\(^{9}\). The estuary phase begins when an ice-shelf river incises to sea level. Observations indicate that this requires consistent river incision during long melt seasons. The Nansen River, which has not become an estuary, does not form annually and only persists for 5–25 days each year\(^{8}\). In contrast, the Petermann river formed annually since 2010, and flows for 59 days each year on average (Methods). The Petermann river incised to sea level between 2010 and 2013 at a rate ranging from 1 to 5.5 cm d\(^{-1}\), overlapping the 3–10 cm d\(^{-1}\) incision range measured on glaciers and ice sheets\(^{22}\) (Methods). During the estuary phase, a direct connection to the ocean is established, leading to new processes at the ice-shelf front, including the advance of relatively warm ocean water on to the ice-shelf surface, flow reversal in the channel, and the presence of water on the ice shelf surface after the melt season. During the estuary phase, longitudinal fractures form at the front of the ice shelf and propagate upstream. We hypothesize that the evolution of an ice-shelf river to an estuary promotes fractures orthogonal to the calving front and eventual rectilinear calving events.
As opposed to ice-shelf collapse triggered by warming climate and surface melting\textsuperscript{23}, calving of tabular icebergs is understood to be controlled by ice-shelf dynamics and structure\textsuperscript{24}, independent of climatic conditions. However, the estuary-induced fractures along the Petermann and Ryder Estuaries, along with the history of rectilinear calving along rivers, indicate that surface hydrology, driven by climatic conditions, may play a role in iceberg calving. The fractures form at the ice-shelf front, downstream of the compressive arch where ice shelf stresses are otherwise isotropic\textsuperscript{25} (Fig. 3c). We suggest estuary formation may have localized stresses at the ice-shelf front through both enhanced incision and loading (Fig. 3). At the Petermann estuary, relatively warm ocean water\textsuperscript{20} advancing into the river channel may locally thin and weaken the ice through enhanced channel incision. As flow reversal limits water export, increased water storage on the shelf will lead to increased loading. Periodic loading would also increase at the ice shelf front when ocean water is present at the mouth of the estuary after the end of the melt season. We consider the possibility that the fractures resulted from stress concentrated by the basal channel\textsuperscript{26} and/or ice shelf’s progressive detachment from the fjord walls downstream\textsuperscript{27}, which would cause extensional stresses to exist transverse to the direction of flow. However, on the Nansen Ice Shelf, extensional stress transverse to the basal channel and river system, was found insufficient to initiate longitudinal fractures\textsuperscript{9}. We speculate that the development of estuaries may increase rectilinear calving and posit estuarine weakening as a climate-driven calving mode. Further studies including direct measurements and modeling of estuary evolution will provide insights into how longitudinal fractures form and influence ice shelves.

Potential estuary formation in a warming world

As the global climate warms, surface melting on Antarctica’s ice shelves will double in the next 30 years\textsuperscript{12}, and likely form more rivers atop basal channels\textsuperscript{8}. Linear topographic depressions, associated with basal channels, have been identified across Antarctica\textsuperscript{9,28}. Should sufficient surface meltwater form, we predict that these depressions would organize meltwater into rivers and set the stage for estuary development. We develop a first-order model of estuary evolution, and apply it to ice shelves where basal channels and rivers have been documented\textsuperscript{8,9,13,29}. Using a range of incision rates, we forecast how long it would take to form estuaries under current conditions i.e. the length of the Antarctic melt season remains the same (Methods). These estimates assume the ice surface is free of firn, permitting open channel flow, as is observed on the Petermann Ice Shelf. Using the current melt season duration\textsuperscript{30,31}, observations of rivers\textsuperscript{8,29}, a conservative estimate of river incision\textsuperscript{22} of 3 cm d\textsuperscript{-1}, ice-shelf elevation\textsuperscript{8,32,33}, and ice-shelf elevation change\textsuperscript{1,34} (Extended Data Figure 6), we estimate that an estuary could form in 40 years on the Pine Island Ice Shelf, and in 29 years on the Nansen Ice Shelf (Fig. 4a, Methods). While meltwater ponding drove the collapse of the Larsen B Ice Shelf\textsuperscript{3,23}, as waterfalls were observed on the ice shelf (https://www.geog.cam.ac.uk/research/projects/larseniceshelf/photos/Larsen-B-waterfall.gif, https://www.geog.cam.ac.uk/research/projects/larseniceshelf/photos/Larsen-B-waterfall-2.jpg) and surface streams terminated in rifts\textsuperscript{29} estuaries may have developed. For Larsen B, only a decade of incision would have been required for estuaries and possibly fractures to form (Fig. 4a, Methods). This estuarine weakening through rectilinear fractures could have introduced additional weaknesses in the ice shelf.
prior to its lake-drainage-triggered collapse. These predictions are sensitive to incision rate (Fig. 4a), which will vary with surface meltwater production, and also depends on the presence of firn, which modulates the efficiency of a river to drain surface melt. The greatest uncertainty in predicting estuary formation is the large range of incision rates used in our calculations due to the lack of in situ observations (Methods).

Given the projections of surface melt increase in Antarctica\(^1\), we also estimate the melt season duration required for Antarctic supraglacial rivers to evolve into estuaries in 30 years (Methods). We use our estuary evolution model constrained by measurements of ice-shelf elevation\(^3\), ice-shelf elevation change\(^1\), and a conservative incision rate\(^2\) of 3 cm d\(^{-1}\) (Methods). Again, we neglect the role of firn hydrologic processes and assume open channel flow over a firn-free, bare ice surface. As climate warms in Antarctica, low permeability surfaces will expand as they have in Greenland\(^3\), promoting surface meltwater runoff and open channel flow. In this forecast, Antarctic rivers would have to incise at the ice-shelf front for 30–45 days each season for three decades to produce estuaries (Fig. 4b). This melt-season duration is up to 1.5 times the average number of observed annual melt days on Antarctic ice shelves from 1978–2004\(^3\). If the melt season lengthens to the conditions that produced collapse of the Larsen B Ice Shelf, 45–60-days, estuaries would be widespread but restricted to the outer portions of the large ice shelves (Amery, Filcher-Ronne, western Ross). When the Antarctic melt season lengthens to the current ~80 days at the Petermann Ice Shelf, most Antarctic ice shelf rivers would incise to estuaries within three decades (Fig. 4b). Establishing an accurate chronology of the onset of estuarine weakening will benefit from direct measurements of ice-shelf rivers, as well as an understanding of the evolution of firn and other ice-shelf surface processes.

Multiple observations of ice-shelf estuaries extend our view of ice-shelf surface hydrology and stability beyond a simplified lakes-rivers framework. We suggest the role that rivers play in ice-shelf stability depends on whether the river terminates in a waterfall or evolves into an estuary. As long as water is removed off the shelf through a waterfall, rivers may mitigate surface-lake-driven ice-shelf instability. As rivers evolve to ice-shelf estuaries, new ice/ocean processes are introduced to the ice-shelf front that can concentrate stress and favor a rectilinear calving mode. We advance estuarine weakening as a new process that may enhance ice-shelf fracture and calving, linked to both atmospheric trends and patterns that drive surface melt, and to ocean melting that forms ice-shelf basal channels. As rivers and streams are found on many Antarctic ice shelves\(^7\), it is possible the formation of ice-shelf estuaries is already underway. Our first-order estimates of estuary formation in Antarctica indicate estuaries may form within the next 30 years, assuming that Antarctica’s future surface resembles that of present-day Greenland. If ice-shelf estuaries form in Antarctica, we speculate that calving may increase due to the introduction of estuarine-weakening and rectilinear calving. Estimates of estuary evolution in Antarctica would be improved by detailed analysis of ice-shelf surface processes, including firn hydrology. The discovery of the Petermann and Ryder estuary systems emphasizes the need for further investigation of how ice-shelf rivers evolve and impact ice-shelf stress, so that that a more complete set of ice-shelf surface hydrologic processes can be included in models and predictions of ice-sheet stability.
Methods

Satellite imagery

We analyzed 35 high-resolution images collected by the WorldView-1, WorldView-2, WorldView-3, GeoEye and QuickBird, satellites (collectively, the DigitalGlobe constellation) between 2010 and 2018 to track the evolution of the estuary and longitudinal fractures (Extended Data Figure 7). Except for WorldView-1, these satellites collect multi-spectral data at ~2 m spatial resolution. WorldView-1 collects panchromatic data at ~0.5 m. The Polar Geospatial Center (PGC) provided the orthorectified, projected, and top-of-atmosphere (TOA) corrected imagery.

We analyzed 49 cloud-free, pan-sharpened true-color images at 15 m resolution collected by the Landsat 8 Operational Land Imager from 2014 to 2016 to constrain the number of days the Peterman River flowed to the ice-shelf edge (Extended Data Figure 8). We use the radiometrically calibrated and orthorectified L1TP Landsat product provided by the U.S. Geological Survey. We apply a TOA correction to each image using dark object subtraction in Matlab (https://www.mathworks.com/matlabcentral/fileexchange/50636-landsat8-radiance-reflectance-brightness-temperature-and-atmospheric-correction).

We use three additional 15 m resolution panchromatic images collected by the Landsat 7 Enhanced Thematic Mapper Plus sensor and one additional panchromatic Landsat 8 image to track the rectilinear calving on the Petermann and Ryder Ice Shelves (Extended Data Figure 8). We use the radiometrically calibrated and orthorectified L1TP Landsat product provided by the U.S. Geological Survey, and do not apply a TOA correction to panchromatic images.

Aerial imagery, Digital Elevation Models (DEMs), and field photography at the Petermann Ice Shelf

We use one image from NASA’S Operation IceBridge (OIB) Digital Mapping System (DMS)39 collected in 2010 camera in our estuary analysis (Extended Data Figure 9). DMS data has a spatial resolution of 40 cm and a vertical accuracy of 10 cm40. We use the DMS-derived DEM (Extended Data Figure 9) to constrain the river’s incision rate.

We use 2 m resolution aerial imagery collected by the Agency for Data Supply and Efficiency17 (Extended Data Figure 9) in 1978 to track rivers.

We use aerial photographs collected in 2019 to interpret the longitudinal fracture along the Petermann estuary as well as interpret Ryder estuary and fractures (Extended Data Figure 9).

Climate model

We use the Modèle Atmosphérique Régionale version 3.9 (hereafter referred to as MAR) to qualitatively analyze trends in surface processes from 2010 to 2017 on the Petermann Ice Shelf. MAR is a coupled surface-atmosphere model forced with climate reanalysis data at the lateral boundaries and ocean surface and simulates the surface energy and mass budget in the upper 20 m of the ice surface using a multi-layer approach. Here we use MAR at 7.5 km spatial resolution to assess the liquid water budget.
In MAR, liquid water is present on the ice-shelf when surface melting occurs (there is enough energy to raise the snowpack temperature above 0° C) or if precipitation falls as rain. Once present, liquid water can percolate into deeper layers of the firn, refreeze, or run off the ice surface. MAR includes a simple empirical runoff delay function to account for the delayed release of meltwater as it is routed from the ice surface, accounting for accumulated meltwater over bare ice, excess meltwater that cannot be stored in firn, and surface slope^{42–44}.

We extract MAR outputs at each grid cell over the Petermann Ice Shelf. We mask model outputs using yearly ice-shelf extent masks from 2010–2017 modified from Hill et al.\textsuperscript{21} and the approximate location of the grounding line\textsuperscript{38}. We compute the fractional area of each grid cell within the boundary to weight the model output values. We spatially integrate model outputs to obtain average estimates of surface melt and snowfall across the entire shelf. We report daily values of surface melt and snow volume.

We use MAR outputs across the Petermann Ice Shelf qualitatively in this analysis. As there are few measurements of in situ melt, errors in these terms are difficult to quantify. MAR generally agrees with in situ and satellite estimates of surface mass balance (SMB), meltwater extent, and surface air temperature, with ~40% error for point measurements of SMB\textsuperscript{45}. MAR v 3.9 includes improvements relative to version 3.5.2\textsuperscript{45}.

DEM of Antarctica

We use the Reference Model of Antarctica (REMA) to constrain predictions of estuary formation in Antarctica. REMA is an ice-sheet wide DEM comprised of stereophotogrammetric DEMs created using sub-meter resolution satellite imagery collected by the DigitalGlobe constellation\textsuperscript{33} from 2007 to 2017. The final REMA mosaic is a 10-year composite representation of Antarctica’s topography that is co-registered to satellite altimetry data\textsuperscript{33}. We apply a geoid correction using the GL04C geoid\textsuperscript{46}.

We use the 100 m spatial resolution continent-wide DEM in our calculation of estuary formation in a warming world. We use the 8 m DEM with an uncertainty <0.1 m\textsuperscript{33} to calculate estuary formation under current conditions for the Pine Island Ice Shelf.

Ice-shelf elevation change

We use satellite-altimetry-derived observations of ice-shelf elevation change (\(\frac{dh}{dT}\)) to constrain predictions of estuary formation in Antarctica. The \(\frac{dh}{dT}\) record spans 1994–2012 and was synthesized from multiple platforms\textsuperscript{1}. We use the 27 km resolution gridded data product, and corresponding uncertainty. This is a coarse resolution dataset of \(\frac{dh}{dT}\), and does not capture change associated with basal channels or surface river incision.

We constrain \(\frac{dh}{dT}\) on the Larsen B Ice Shelf (excluded from the 18-year record above) with the mean thinning rate derived from satellite radar altimetry from 1992–2001\textsuperscript{34}.
Estuary identification

We identify the Petermann estuary during the melt season in DigitalGlobe imagery (Extended Data Figure 7) based on three conditions: 1) water is present in the river channel, 2) no ice obstructs the exchange of water between the river and seawater in the fjord, and 3) sea ice is present in the fjord and channel (Fig. 1). Sea ice fragments act as tracers indicating flow direction in the estuary. We also identify the estuary in post melt-season imagery (Extended Data Fig. 1). Following the end of seasonal surface melt, the only water source in the river is seawater. We apply condition (1) to images collected in September to identify the presence of seawater in the channel. While condition (3) is infrequently met during the melt season, we interpret post melt-season imagery as additional evidence that flow reversal can occur during the melt season. The Petermann estuary is also characterized by darkening water at the estuary mouth, consistent with the Beer-Lambert law, that can be seen in satellite and aerial images (Fig. 1 b, c).

We use this framework to interpret the sparse dataset of the Ryder estuary. Aerial photography collected in 2019 at the shelf edge reveals deep water at the mouth of the river channel (Fig. 2c). We also identify water in the channel after the melt season in 2014 (Extended Data Fig. 5).

Mapping Petermann estuary evolution

We track the development and evolution of the estuary since 2010 by measuring wetted widths of the Petermann estuary at regular intervals upstream from the calving front. We analyze 31 images from the DigitalGlobe constellation (Extended Data Figure 7) collected from June through August 2010–2018 that capture the Petermann Ice Shelf calving front and 3–6 km upstream from the calving front. We display all images using a bilinear interpolation and the North Pole Stereographic projection (EPSG:102018). We pan-sharpen all multispectral images prior to digitizing and display them in true color (images with four bands: red = band 4, blue = band 3, green = band 2, images with five bands: red = band 5, blue = band 2, green = band 3).

We digitize the calving front, river centerline, distance along the centerline, and river width in each image as follows. First, we trace the calving front 250 m to each side of the Petermann river. Second, we digitize the river centerline to 6 km upstream of the calving front, or to the boundary of the satellite image. Third, we calculate wetted widths along the river perpendicular to the digitized centerline. We identify the water where pixels are dark and select the water/ice edge where there is highest contrast between adjacent pixels. Within the first 75 m of the calving front, downstream of a tributary that joins the Petermann estuary ~100 m from the calving front, we measure wetted widths in 25 m increments. Starting 1 km from the calving front, we measure wetted widths at 1 km intervals. We maintain fixed scales of 1:5000, 1:2500, and 1:1000 when digitizing the calving front, the channel centerline/distance upstream and the channel widths, respectively.

We report the range in width measurements for each increment along the Petermann estuary and River. We consider the greatest source of uncertainty in our standardized width measurement procedure to be the image pixel size, which is 0.5 m for each image that was
digitized, resulting in an uncertainty in width of 1 m (0.5 m on each side of the width measurement). Other sources of uncertainty could include image geolocation and error introduced in digitization. Image geolocation is expected to be roughly uniform across each image, so would not contribute significantly to width measurement uncertainty. We expect error in the digitization procedure that is not due to the pixel size to be small. The range in widths at all locations is greater than this 1 m uncertainty, and the widening signal seen at the estuary is also greater than 1 m (Extended Data Fig. 3). In the estuarine portion of the river, widths range from 11.18 to 60.43 m (Extended Data Figure 10), greater than the 1 m uncertainty estimate. Considering all upstream portions of the river together, widths range from 12.76 to 29.28 m (Extended Data Figure 10). The smallest range in widths is 3.86 m, at 5 km upstream. The average width in the estuarine portion of the river is 32.5 m, more than 3 m greater than the widest measurement of 29.28 observed at upstream locations (Extended Data Figure 10). We conclude the widening signal associated with the estuarine portion of the river is likely due to physical processes such as meltwater production, and, critically, flow reversal.

Mapping longitudinal fracture propagation

We digitize the fracture along the bottom of the Petermann estuary in four WorldView images collected in July of 2014–2017 (Extended Data Figure 7, Extended Data Fig. 5), using a fixed scale of 1:2500. When multiple fractures are visible, we digitize each individually. We calculate the length of each fracture and the entire fracture system. We also identify fractures at the Petermann and Ryder estuary from aerial photography, which show dark linear features along the bottom of both channels (Fig. 2b, c).

The Petermann estuary time constraints

We use the Landsat 8 imagery to constrain the number of days the Petermann river incises. We identify river incision at the calving front if we identify water at the ice-shelf terminus, and continuously along the channel at least 2 km upstream. We identify water at the mouth of Petermann river in 15 images in 2014, 14 images in 2015 and 20 images in 2016. We assume the river incises between consecutive observations. Water is continuously present at the terminus for 57 days in 2014 (June 24th - August 18th), for 60 days in 2015 (June 28th - August 26th), and for 60 days in 2016 (June 11th - August 9th).

Using satellite and airborne data, we constrain the number of melt seasons required for the Petermann river to incise to sea level. The calving event on July 16th, 2012 was captured by Moderate Resolution Imaging Spectroradiometer imagery (https://earthobservatory.nasa.gov/images/78556/more-ice-breaks-off-of-petermann-glacier) and marks the first time the present-day mouth of the Petermann river was exposed to open water in the fjord as the calved iceberg drifted north. WorldView imagery reveals the rift that formed the 2012 calving event intersected the Petermann river in April 2010 (Extended Data Figure 7). We use the OIB DEM (Extended Data Figure 9) with a geoid correction to identify the elevation of the channel floor. On April 20th, 2010 the channel floor was 3.5 m above sea level. By July 30th, 2012 the iceberg drifted out into the fjord, exposing the present-day calving front to open water. We first observe seawater atop the Petermann Ice Shelf in a
WorldView-1 image collected on September 9th, 2013 (Extended Data Figure 7, Extended Data Fig. 1). We estimate that the Petermann river incised to sea level to establish an estuary in 1–4 melt seasons.

The Petermann river incision rate

On ice shelves, estuaries develop when rivers incise through underlying ice to sea level. We assume ice-shelf rivers (~10s of meters wide) are not hydrostatically compensated since they are small compared to the ice thickness (~100s of meters), and that the rest of the ice shelf is hydrostatically compensated at all locations.

We describe the elevation of the channel bottom as:

$$h_f = h_i - \frac{dh}{dT} Y - rnY$$

where $h_f$ (m) is the final channel-bottom elevation, $h_i$ (m) is the initial channel-bottom elevation, $\frac{dh}{dT}$ (m yr$^{-1}$) is ice-shelf elevation change, $Y$ (yr) is elapsed time, $r$ (m d$^{-1}$) is the channel incision rate, and $n$ (d yr$^{-1}$) is the duration of river incision each year. When $h_f = 0$ the channel bottom has reached sea level. We express the incision rate as:

$$r = \frac{1}{n} \frac{h_i}{Y - \frac{dh}{dT}}$$

We calculate $\frac{dh}{dT}$ from the thickness-change rate as:

$$\frac{dh}{dT} = \frac{\rho_w - \rho_i}{\rho_w} \frac{dH}{dT}$$

where $\frac{dH}{dT}$ is the ice-shelf thickness change rate, and $\rho_w$ and $\rho_i$ are the respective densities of seawater (1024 kg m$^{-3}$) and ice (917 kg m$^{-3}$).

We assume a constant $\frac{dH}{dT}$ and a bare ice surface. We assume the calculated incision rate, $r$, is constant over the duration of incision, $n$. We take $n$ to be 59 d yr$^{-1}$, the average annual duration of river incision from our Landsat 8 analysis. We take $\frac{dH}{dT}$ from Washam et al.$^{48}$, who measure a net $\sim 4.4 \pm 0.5$ m thickness change over 619-days from in situ radar measurements collected ~35 km upstream of the calving front, adjacent to Petermann river and coincident with the basal channel. We use Eqn. 3 to estimate $\frac{dh}{dT} = -0.27 \pm 0.03$ m yr$^{-1}$.

Given that $Y$ ranges from 1 to 4 years, we estimate $r = 1 - 5.5$ cm d$^{-1}$. This overlaps with the 3–10 cm d$^{-1}$ range measured on glaciers and ice sheets$^{22}$. The 1 cm d$^{-1}$ lower bound falls outside the measured range, but may be plausible given the flat topography of ice shelves.
We estimate the uncertainty associated with the measurements used to constrain the other terms, by considering the upper and lower bounds on each. \( n \) ranges from 57 to 60 days, \( h_i \) ranges from 3.4 to 3.6 m, and \( \Delta h / \Delta t \) ranges from -0.3 to -0.24 m yr\(^{-1}\). Taking these ranges into account we estimate \( r \) with uncertainty is 1 ± 0.15 cm d\(^{-1}\) and 5.5 ± 0.35 cm d\(^{-1}\).

**Nansen River incision rate**

We calculate the incision rate of the Nansen River using observations from Bell et al.\(^8\) and the following equation from Fountain and Walder\(^9\):

\[
i = \frac{1}{2} \left( \frac{\pi}{2n} \right)^{\frac{3}{8}} \frac{\rho_w}{\rho_i} \frac{g}{h_{iw}} \frac{19}{16} \frac{Q}{S} \frac{5}{8}
\]

Where \( n = 0.01 \) s\(^{-1}\), \( \rho_w \) and \( \rho_i \) are the respective densities of water (1000 kg m\(^{-3}\)) and ice (917 kg m\(^{-3}\)), \( g \) is the gravitational constant 9.81 m s\(^{-2}\), and \( h_{iw} = 3.35 \times 10^5 \) J kg\(^{-1}\) is the latent heat of fusion. The equation assumes the channel bottom is smooth, the channel does not widen, and all energy dissipated by water flow goes into melting. We take \( S = 0.0019 \) and the most conservative value of \( Q = 80 \) m\(^3\)s\(^{-1}\) from Bell et al.\(^8\). We calculate \( i \) is 7.2 cm d\(^{-1}\), within the range of observed river and stream incision rates\(^{22}\).

Most river discharge observations fall below 1 m\(^3\)s\(^{-1}\), and the maximum discharge rate observed from a single river/stream on glaciers and ice sheets ranges from 0.016 to 26.73 m\(^3\)s\(^{-1}\)\(^{22}\). Thus, we consider that 80 m\(^3\)s\(^{-1}\) is an overestimate of \( Q \), and that our derived incision rate of 7.2 cm d\(^{-1}\) is high for the Nansen River.

**Modelling estuary formation on ice shelves under current conditions**

We use a modified Eqn. (2) to calculate \( Y \) (yr), assuming current conditions, on the Petermann, Nansen, Pine Island and Larsen B Ice Shelves (Fig. 4a), where surface rivers\(^7\)–\(^9\),\(^16\),\(^29\) and/or basal channels\(^9\),\(^13\),\(^50\),\(^14\) have been observed. We present our results as a function of incision rate (Fig. 4a). We favor the 3 cm d\(^{-1}\) reported incision rate\(^{22}\) as it falls within the range calculated for the Petermann river. We use melt season duration, \( a \), as a proxy for \( n \), as no studies have quantified the persistence of ice shelf rivers broadly, and assume the river incises continuously. Constraints are listed in Extended Data Figure 6. We estimate uncertainty by calculating the range reported with these constraints.

Although we previously estimated that the Petermann river required between 1 and 4 years to incise to sea level, we include Petermann in these calculations for comparison. We find the Petermann estuary would have formed in 1.7 years, consistent with our observations. Considering uncertainty, this estimate ranges from 1.62 to 1.85 years.

We estimate that the Nansen River could form an estuary in 29 years. Using observations from Bell et al.\(^8\) we calculate that Nansen waterfall was observed for 18 days on average. The uncertainty in the Nansen waterfall duration is 9.4 days\(^8\). There is no uncertainty reported for the channel elevation. However, the elevation was measured with OIB’s
Airborne Topographic Mapper\textsuperscript{8}, which has a vertical accuracy of 0.1 m\textsuperscript{51}. We calculate $Y$ ranges from 17.9 to 70.9 years.

We estimate that an estuary could develop on the Pine Island Ice Shelf in 40 years. We measure $h_i$ from the 8 m REMA DEM\textsuperscript{33} with a GL04C geoid correction\textsuperscript{46}. We extract an elevation profile orthogonal to ice flow by employing a similar procedure used to measure widths along the Petermann river. We sample the DEM at 8 m intervals along the profile, and take the minimum elevation (Extended Data Figure 6). We calculate $Y$ ranges from 38.0 to 42.4 years.

We estimate that an estuary may have developed on the Larsen B Ice Shelf in 8 years. Here we calculate $h_i$ using the minimum ice-shelf thickness measurement of 179 m from Rack and Rott\textsuperscript{32} (Extended Data Figure 6) and Eqn. (3). We calculate $n$ by digitizing melt-days data from Scambos et al.\textsuperscript{31} (Extended Data Figure 6) using WebPlotDigitizer (https://automeris.io/WebPlotDigitizer), and calculate the standard error is 3.65 days. We calculate $Y$ ranges from 7.3 to 9.3 years.

**Modelling estuary formation on ice shelves in a warming world**

We use a modified Eqn. (2) to calculate $n$ (d), number of days of river incision required to form an estuary on Antarctica’s ice shelves in 30 years. We again redefine $n$ as melt-season duration. We use Pitcher and Smith’s\textsuperscript{22} lowest estimate of $r$, 3 cm d$^{-1}$. We take $h_i$ from the geoid corrected REMA DEM\textsuperscript{33,46}, downsampled to 27 km to match the resolution of the $\frac{d h}{d t}$ data\textsuperscript{1}. We apply Eqn. (5) to each grid cell.

We calculate the range in $n$ due to uncertainty in $\frac{d h}{d t}$ and $h_i$\textsuperscript{33}. For 40% of grid cells, $0 < n < 1$ d, and for 30% $1 < n < 2$ d. We also report sensitivity to $r$, which, we demonstrated earlier is significant. Taking $1 < r < 10$ cm d$^{-1}$, we find $10 < n < 20$ d in 56% of grid cells.

We present a range of scenarios for ice-shelf estuary formation given available observations. We assume rivers incise at a constant rate each day of the melt season, an oversimplification that does not account for diurnal variability in the river hydrograph\textsuperscript{43} which modulates incision rates\textsuperscript{49}. We do not account for other surface hydrologic processes, such as water storage and transport through firn or a bare ice weathering crust\textsuperscript{52,53}, which modulate the delivery of surface meltwater to rivers.
Extended Data

Post-melt-season Estuary Evidence

a) Meltwater production on the Petermann Ice Shelf

- 2010
- 2011
- 2012
- 2013
  Sept. 7, 2013
- 2014
  Sept. 12, 2014
- 2015
- 2016
  Sept. 23, 2016
- 2017

b) Seawater in the estuary channel

Extended Data Fig. 1. Ocean water atop the Petermann Ice Shelf after the melt season
a Modèle Atmosphérique Regional v. 3.9 (MAR) average daily ice surface melt averaged
across the Petermann Ice Shelf from 2010 to 2017. The red dotted lines show earliest
indication of seawater in the channel after the melt season as identified in high resolution
WorldView-1 and WorldView-2 satellite imagery (Extended Data Figure 7). b The first
evidence of water atop the ice shelf was collected by WorldView-1 in 2013 (top). Note that
break in the shadow cast by the ice-shelf terminus at the Petermann river channel confirms a direct connection between the ice shelf and the ocean. Multispectral WorldView-2 images collected in 2014 (middle) and 2016 (bottom) show water in the channel directly connected to the ocean and an absence of surface meltwater elsewhere on the ice shelf (© 2013, 2014, 2016 DigitalGlobe, Inc.).

Extended Data Fig. 2. Modelled melt and snowfall on Petermann Ice Shelf
Top: MAR simulation of daily surface melt (blue) and snowfall (gray) in averaged across the Petermann Ice Shelf from 2010 to 2017. Bottom: estuary wetted widths measured at 25 m from calving front as in Fig. 2 from 2010 to 2017. This demonstrates the lack of correlation between estuary widening and surface runoff.
Extended Data Fig. 3. Evidence for change at the mouth of the estuary

a Location of wetted width measurements at 1 km increments along the Petermann river set against panchromatic WorldView-2 image (August 30, 2018). Blue line denotes the maximum extent of sea ice found in the channel, (July 24, 2018). Purple line denotes the maximum extent of the longitudinal fracture (July 25, 2017). Red box shows the location of Fig. 2b. b The mouth of the Petermann estuary widened from 2012 (left) to 2018 (right). Left panel: 2012 with river widths shown as colored lines at 25 m increments from the ice-shelf front (QuickBird image July 19th). Right panel: 2018 image with river widths at 25m increments. The estuary is approximately three times wider in 2018. c Wetted width measurements along channel from 2010 to 2018. The channel widens at the mouth of the estuary and within 2 km from the ice-shelf front. Width measurements (points) and trendlines are colored by locations marked in Fig. 2a and Fig. 2b. (© 2012, 2018 Boghosian et al.)
DigitalGlobe, Inc.) Fracture growth and flow reversal evidence are coincident with this widening as shown in a.

Extended Data Fig. 4. Additional evidence for the Ryder Ice Shelf Estuary
(a) The Ryder estuary in a WorldView-2 image collected on August 25, 2014. Red boxes mark the location of (b) and (c), and gold star marks the approximate location of the 2019 estuary (Fig. 2c). (b) Detailed image of the downstream portion of the estuary shows water in the channel directly connected to the ocean and an absence of surface meltwater elsewhere on the ice shelf. (c) Detailed image of the upstream portion of the estuary shows water in the channel directly connected to ocean water in the rift and an absence of surface meltwater elsewhere on the ice shelf. (© 2014 DigitalGlobe, Inc.).
Extended Data Fig. 5. Detail of longitudinal fractures at the Petermann estuary

WorldView imagery along Petermann estuary from which fractures were digitized (Fig. 2a). Red boxes show location of detail views. Fractures are identified as dark linear features along the bottom of the channel. Images collected on July 14, 2014; July 17, 2015; July 15, 2016; and July 25, 2017 (© 2014, 2015, 2016, 2017 DigitalGlobe, Inc.).
Extended Data Fig. 6.
Constraints used in the estuary formation and timing calculations shown in Fig. 4a.

| Ice Shelf                | Value     | Uncertainty   | Source                          |
|--------------------------|-----------|---------------|---------------------------------|
| **Petermann Ice Shelf**  |           |               |                                 |
| River duration (n)       | 59 d yr⁻¹ | 57- 60 d yr⁻¹ | Landsat 8 imagery               |
| Elevation change rate \(\frac{dh}{dt}\) | -0.27 m yr⁻¹ | ± 0.03 m yr⁻¹ | Calculated from Washam et al.¹   |
| Initial channel elevation \(h_i\) | 3.5 m   | ± 0.1 m      | OIB DMS DEM²,³                  |
| **Nansen Ice Shelf**     |           |               |                                 |
| Waterfall duration (n)   | 18 d yr⁻¹ | ± 9.4 d yr⁻¹ | Calculated and taken from Bell et al.⁴ |
| Elevation change rate \(\frac{dh}{dt}\) | -0.018 m yr⁻¹ | ± 0.049 m yr⁻¹ | Paolo et al.⁵                  |
| Initial channel elevation \(h_i\) | 16 m   | ± 0.1 m      | Bell et al.⁴, OIB ATM⁶           |
| **Larsen B Ice Shelf**   |           |               |                                 |
| Melt season duration (a) | 55 d yr⁻¹ | ± 3.65 d yr⁻¹ | Calculated from Scambos et al.⁷ |
| Elevation change rate \(\frac{dh}{dt}\) | -0.17 m yr⁻¹ | ±0.11 m yr⁻¹ | Shepherd et al.⁸                |
| Initial channel elevation \(h_i\) | 14.86 m | NA            | Calculated from Rack and Rott⁹   |
| **Pine Island Ice Shelf**|           |               |                                 |
| Melt season duration (a) | 37 d yr⁻¹ | NA            | Trusel et al.¹⁰,¹¹               |
| Elevation change rate \(\frac{dh}{dt}\) | -0.1480 m yr⁻¹ | ± 0.062 m yr⁻¹ | Paolo et al.⁵                  |
| Initial channel elevation \(h_i\) | 50.4 m  | ± 0.1 m      | REMA                            |
Extended Data Fig. 7.
Complete list of DigitalGlobe images analyzed of the Petermann Ice Shelf (PIS) and Ryder Ice Shelf (RIS). Purpose is included with categories: river widths measured (RW), rift forming 2012 calving event (FR), estuary identification (EI), and longitudinal fractures measured (LF).

| Date     | Sensor | ID             | Ice Shelf | Purpose |
|----------|--------|----------------|-----------|---------|
| 20100605 | QB02   | 20100605212925 | PIS       | RF      |
| 20100814 | WV02   | 20100814001457 | PIS       | RW      |
| 20110815 | WV02   | 20110815211856 | PIS       | RW      |
| 20120719 | QB02   | 20120712922250 | PIS       | RF      |
| 20130623 | WV02   | 20130623001130 | PIS       | RW      |
| 20130907 | WV01   | 20130907180843 | PIS       | EI      |
| 20140617 | WV02   | 20140617213111 | PIS       | RW      |
| 20140630 | WV02   | 20140630201224 | PIS       | RW      |
| 20140714 | WV02   | 20140714195621 | PIS       | RW      |
| 20140714 | WV02   | 20140714195554 | PIS       | RW      |
| 20140716 | WV02   | 20140716015653 | PIS       | RW      |
| 20140807 | WV02   | 20140807215011 | PIS       | RW      |
| 20140816 | WV02   | 20140816225825 | PIS       | RW      |
| 20140824 | WV01   | 20140824190017 | PIS       | RW      |
| 20140825 | WV02   | 20140825190825 | RIS       | RW      |
| 20140825 | WV02   | 20140825172840 | PIS       | RW      |
| 20140912 | WV02   | 20140912180509 | PIS       | EI      |
| 20150707 | WV02   | 20150707193617 | PIS       | RW      |
| 20150710 | WV02   | 20150710174621 | PIS       | LF      |
| 20160707 | WV02   | 20160707212152 | PIS       | RW      |
| 20160709 | WV01   | 2016070923452  | PIS       | RW      |
| 20160709 | WV01   | 2016070923423  | PIS       | RW      |
| 20160710 | WV01   | 20160710014141 | PIS       | RW      |
| 20160713 | WV02   | 20160713210049 | PIS       | RW      |
| 20160713 | WV02   | 20160713174223 | PIS       | RW      |
| 20160715 | WV03   | 20160715184944 | PIS       | LF      |
| 20160717 | WV02   | 20160717215216 | PIS       | RW      |
| 20160717 | WV02   | 20160717183424 | PIS       | RW      |
| 20160729 | WV01   | 20160729213646 | PIS       | RW      |
| 20160731 | WV01   | 20160731205334 | PIS       | RW      |
| 20160923 | WV02   | 20160923200448 | PIS       | EI      |
| 20170707 | GE01   | 20170707170717 | PIS       | RW      |
| 20170714 | WV01   | 20170714011019 | PIS       | RW      |
| 20170720 | WV01   | 20170720020502 | PIS       | RW      |
| 20170725 | WV02   | 20170725222506 | PIS       | RW      |
| 20180611 | WV02   | 20180611204247 | PIS       | RW      |
| 20180724 | WV02   | 20180724192143 | PIS       | RW      |
| 20180726 | WV01   | 20180726015346 | PIS       | RW      |
| 20180831 | WV03   | 20180831214021 | PIS       | RW      |
Extended Data Fig. 8.
Complete list of Landsat 8 OLI and Landsat 7 ETM+ scenes analyzed. Purpose is included with categories: rectilinear calving (RC), and river duration (RD).
Extended Data Fig. 9.  
Complete list of aerial images and derived Digital Elevation Models (DEMs) used.

| Aerial Imagery and DEM         | Date     | Type          | Source/Credit     |
|--------------------------------|----------|---------------|-------------------|
| IODIM3_20100420_181506_10857_ORTH0.jpg | 4/20/2010 | orthophoto    | OIB               |
| IODEM3_20100420_181504_10856 DEM.tif | 4/20/2010 | DEM           | OIB               |
| g150_1978_utm20.jpg2            | 7/3/1978 | orthophoto    | Korsgaard et al.  |
| Petermann Aerial 1              | 7/15/2019| Field Photography | Roger Fishman   |
| Petermann Aerial 2              | 7/27/2019| Field Photography | Matthias Vogt   |
| Ryder Aerial 3                  | 10/13/2019| Field Photography | Josh Willis    |
| Ryder Aerial 4                  | 11/8/2019| Field Photography | Josh Willis    |

Extended Data Fig. 10.  
Range in channel wetted width measurements.

| Increment (km) | Minimum (m) | Maximum (m) | Range (m) |
|----------------|-------------|-------------|-----------|
| 0 m            | 11.38       | 60.43       | 49.05     |
| 25 m           | 11.18       | 39.99       | 28.81     |
| 50 m           | 11.33       | 38.35       | 27.03     |
| 75 m           | 11.64       | 36.82       | 25.18     |
| 1000 km        | 12.76       | 27.81       | 15.06     |
| 2000 km        | 13.44       | 25.31       | 11.87     |
| 3000 km        | 14.17       | 23.81       | 9.64      |
| 4000 km        | 18.08       | 29.28       | 11.20     |
| 5000 km        | 17.24       | 21.10       | 3.86      |
| 6000 km        | 16.69       | 28.07       | 11.37     |

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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study site and features with Greenlandic/Indigenous names, but were unable to find them; “Petermann” was used as it is consistent with the literature.

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**References**

1. Paolo FS, Fricker HA & Padman L. Volume loss from Antarctic ice shelves is accelerating. Science (80-. ), 348, 327–331 (2015).
2. Rignot E, Jacobs S, Mouginot J. & Scheuchl B. Ice-Shelf Melting Around Antarctica. Science (80-. ), 341, 266–270 (2013).
3. Banwell AF, MacAyeal DR & Sergienko OV Breakup of the Larsen B Ice Shelf triggered by chain reaction drainage of supraglacial lakes. Geophys. Res. Lett 40, 5872–5876 (2013).
4. Banwell AF & MacAyeal DR Ice-shelf fracture due to viscoelastic flexure stress induced by fill/drain cycles of supraglacial lakes. Antarct. Sci 27, 587–597 (2015).
5. MacAyeal DR, Sergienko OV & Banwell AF A model of viscoelastic ice-shelf flexure. J. Glaciol 61, 635–645 (2015).
6. Scambos T. et al. Ice shelf disintegration by plate bending and hydro-fracture: Satellite observations and model results of the 2008 Wilkins ice shelf break-ups. Earth Planet. Sci. Lett 280, 51–60 (2009).
7. Kingslake J, Ely JC, Das I. & Bell RE Widespread movement of meltwater onto and across Antarctic ice shelves. Nature 544, 349 (2017). [PubMed: 28425995]
8. Bell RE et al. Antarctic ice shelf potentially stabilized by export of meltwater in surface river. Nature 544, 344–348 (2017). [PubMed: 28426005]
9. Dow CF et al. Basal channels drive active surface hydrology and transverse ice shelf fracture. Sci. Adv 4, (2018).
10. DeConto RM & Pollard D. Contribution of Antarctica to past and future sea-level rise. Nature 531, 591–597 (2016). [PubMed: 27029274]
11. Smith LC et al. Efficient meltwater drainage through supraglacial streams and rivers on the southwest Greenland ice sheet. Proc. Natl. Acad. Sci 112, 1001–1006 (2015). [PubMed: 25583477]
12. Trusel LD et al. Divergent trajectories of Antarctic surface melt under two twenty-first-century climate scenarios. Nat. Geosci 8, 927 (2015).
13. Dutrieux P. et al. Basal terraces on melting ice shelves. Geophys. Res. Lett 41, 5506–5513 (2014).
14. Rignot E. & Steffen K. Channelized bottom melting and stability of floating ice shelves. Geophys. Res. Lett 35, n/a−n/a (2008).
15. Hill EA, Carr JR & Stokes CR A Review of Recent Changes in Major Marine-Terminating Outlet Glaciers in Northern Greenland. Front. Earth Sci 4, (2017).
16. Macdonald GI, Banwell AF & MacAyeal DR Seasonal evolution of supraglacial lakes on a floating ice tongue, Petermann Glacier, Greenland. Ann. Glaciol 59, 56–65 (2018).
17. Korsgaard NJ et al. Digital elevation model and orthophotographs of Greenland based on aerial photographs from 1978–1987. Sci. Data 3, 160032 (2016).
18. Münchow A, Padman L. & Fricker HA Interannual changes of the floating ice shelf of Petermann Glacier, North Greenland, from 2000 to 2012. J. Glaciol 60, 489–499 (2014).
19. Holland PG et al. Estuarine hydrology. Encycl. Hydrol. Water Resour 244–248 (1998).
20. Johnson HL, Münchow A, Falkner KK & Melling H. Ocean circulation and properties in Petermann Fjord, Greenland. J. Geophys. Res. Ocean 116, (2011).
21. Hill EA, Carr JR, Stokes CR & Gudmundsson GH Dynamic changes in outlet glaciers in northern Greenland from 1948 to 2015. Cryosph. Discuss 2018, 1–39 (2018).
22. Pitcher LH & Smith LC Supraglacial Streams and Rivers. Annu. Rev. Earth Planet. Sci 47, 421–452 (2019).
23. Scambos TA, Hulbe C. & Fahnestock M. Climate-Induced Ice Shelf Disintegration in the Antarctic Peninsula. in Antarctic Peninsula Climate Variability: Historical and Paleoenvironmental Perspectives 79–92 (American Geophysical Union, 2003). doi:10.1029/AR079p0079.

24. Lazzara MA, Jezek KC, Scambos TA, MacAyeal DR & van der Veen CJ On the recent calving of icebergs from the Ross Ice Shelf. Polar Geogr. 23, 201–212 (1999).

25. Doake CSM, Corr HFJ, Rott H, Skvarca P. & Young NW Breakup and conditions for stability of the northern Larsen Ice Shelf, Antarctica. Nature 391, 778–780 (1998).

26. Bassin JN & Ma Y. Evolution of basal crevasses links ice shelf stability to ocean forcing. Earth Planet. Sci. Lett 409, 203–211 (2015).

27. Hill EA, Gudmundsson GH, Carr JR & Stokes CR Velocity response of Petermann Glacier, northwest Greenland, to past and future calving events. Cryosph. 12, 3907–3921 (2018).

28. Alley KE, Scambos TA, Siegfried MR & Fricker HA Impacts of warm water on Antarctic ice shelf stability through basal channel formation. Nat. Geosci 9, 290–293 (2016).

29. Glasser NF & Scambos TA A structural glaciological analysis of the 2002 Larsen B ice-shelf collapse. J. Glaciol 54, 3–16 (2008).

30. Trusel LD, Frey KE, Das SB, Munneke PK & van den Broeke MR Satellite-based estimates of Antarctic surface meltwater fluxes. Geophys. Res. Lett 40, 6148–6153 (2013).

31. Scambos TA, Hulbe C, Fahnestock M. & Bohlander J. The link between climate warming and break-up of ice shelves in the Antarctic Peninsula. J. Glaciol 46, 516–530 (2000).

32. Rack W. & Rott H. Pattern of retreat and disintegration of the Larsen B ice shelf, Antarctic Peninsula. Ann. Glaciol 39, 505–510 (2004).

33. Howat IM, Porter C, Smith BE, Noh MJ & Morin P. The Reference Elevation Model of Antarctica. Cryosph. 13, 665–674 (2019).

34. Shepherd A, Wingham D, Payne T. & Skvarca P. Larsen Ice Shelf Has Progressively Thinned. Science (80-. ). 302, 856 (2003).

35. MacFerrin M. et al. Rapid expansion of Greenland’s low-permeability ice slabs. Nature 573, 403–407 (2019). [PubMed: 31534244]

36. Liu H, Wang L. & Jezek KC Spatiotemporal variations of snowmelt in Antarctica derived from satellite scanning multichannel microwave radiometer and Special Sensor Microwave Imager data (1978–2004). J. Geophys. Res. Earth Surf 111, (2006).

37. Bjørk AA, Kruse LM & Michaelsen PB Brief communication: Getting Greenland’s glaciers right – a new data set of all official Greenlandic glacier names. Cryosph. 9, 2215–2218 (2015).

38. Forster RR et al. Extensive liquid meltwater storage in firm within the Greenland ice sheet. Nat. Geosci 7, 95 (2013).

39. Dominguez R. IceBridge DMS L1B Geolocated and Orthorectified Images, Version 1. (2019) doi:10.5067/OZ6VNOPMPRJ0.

40. Arvesen JC & Dotson RC Photogrammetric Processing of IceBridge DMS Imagery into High-Resolution Digital Surface Models (DEM and Visible Overlay). in AGU Fall Meeting Abstracts vol. 2014 C21D-03 (2014).

41. Dee D. et al. The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. Q. J. R. Meteorol. Soc 137, 553–597 (2011).

42. Lefebre F, Gallée H, van Ypersele J-P & Greuell W. Modeling of snow and ice melt at ETH Camp (West Greenland): A study of surface albedo. J. Geophys. Res. Atmos 108, (2003).

43. Smith LC et al. Direct measurements of meltwater runoff on the Greenland ice sheet surface. Proc. Natl. Acad. Sci 114, E10622–E10631 (2017).

44. Zuo Z. & Oerlemans J. Modelling albedo and specific balance of the Greenland ice sheet: calculations for the Søndre Strømfjord transect. J. Glaciol 42, 305–317 (1996).

45. Fettweis X. et al. Reconstructions of the 1900–2015 Greenland ice sheet surface mass balance using the regional climate MAR model. Cryosph. 11, 1015–1033 (2017).

46. Förste C. et al. The GeoForschungsZentrum Potsdam/Groupe de Recherche de Géodésie Spatiale satellite-only and combined gravity field models: EIGEN-GL04S1 and EIGEN-GL04C. J. Geod 82, 331–346 (2008).
47. Morlighem M. et al. BedMachine v3: Complete Bed Topography and Ocean Bathymetry Mapping of Greenland From Multibeam Echo Sounding Combined With Mass Conservation. Geophys. Res. Lett 44, 11,11–51,61 (2017).

48. Washam P, Nicholls KW, Münchow A. & Padman L. Summer surface melt thins Petermann Gletscher Ice Shelf by enhancing channelized basal melt. J. Glaciol 65, 662–674 (2019).

49. Fountain AG & Walder JS Water flow through temperate glaciers. Rev. Geophys 36, 299–328 (1998).

50. Vaughan DG et al. Subglacial melt channels and fracture in the floating part of Pine Island Glacier, Antarctica. J. Geophys. Res. Earth Surf 117, (2012).

51. Martin CF et al. Airborne Topographic Mapper Calibration Procedures and Accuracy Assessment. (2012).

52. Irvine-Fynn TDL, Hodson AJ, Moorman BJ, Vatne G. & Hubbard AL POLYTHERMAL GLACIER HYDROLOGY: A REVIEW. Rev. Geophys 49, (2011).

53. Cooper MG et al. Meltwater storage in low-density near-surface bare ice in the Greenland ice sheet ablation zone. Cryosph. 12, 955–970 (2018).
Figure 1. Evidence for the Petermann river estuary.

a) Suspended ice in channel

b) Convergent sea ice

c) Water in channel post melt season

Figure 1a shows suspended sea ice in the lower reach of the Petermann river, and convergent sea ice at the mouth of the Petermann estuary in a WorldView-2 image collected July 24, 2018. The red box denotes the extent of Fig. 1b and 1c. Inset shows a Landsat 8 image of the Petermann Ice Shelf collected on July 11, 2016 with a map of Greenland in the upper right and the location of the Petermann Ice Shelf marked with a red star (Courtesy of the U.S. Geological Survey). Blue line denotes the Petermann river extent. Black line approximates the 2008 grounding line. Figure 1b shows a detail of the image shown in Fig. 1a. The convergence of sea ice at the
mouth of the estuary and suspended sea ice in the channel indicate a flow reversal. Ocean water atop the ice shelf after the end of the melt season, on September 12, 2014. (© 2014, 2018 DigitalGlobe, Inc.)
Figure 2. Development of longitudinal fracture along Petermann and Ryder Ice Shelf rivers.
a From left to right, the growth of the longitudinal fracture (gold line) in the Petermann estuary from 2014 to 2017. Images collected on July 14, 2014; July 17 2015; July 15 2016; and July 25, 2017 (WorldView). Undigitized versions of these figures are included in Extended Data Fig. 5. b Aerial images of the fracture at the bottom of the Petermann river channel. Top collected by Matthias Vogt on July 27, 2019, bottom collected by Roger Fishman on July 15, 2019. Red box on Fig. 2a shows the approximate locations of b (© 2014, 2015, 2016, 2017 DigitalGlobe, Inc.). c Aerial images of the river, estuary and fractures on the Ryder Ice Shelf (location map on upper left). Left: an incised river channel with dark water at the ice-shelf front indicates incision to sea level and the presence of an estuary at the river mouth. Dark line initiated at the ice shelf front indicates a longitudinal fracture along the river. Right: aerial view of fracturing at the bottom of the river on the
Ryder Ice Shelf. Images collected by Josh Willis on November 8, 2019 and October 13, 2019.
a) Petermann rivers and rectilinear calving 1978 - 2008

In 1978 a long straight river is present on the Petermann Ice Shelf. Future ice edges (1999 and 2008) and estuaries (1999) are annotated (image from July 3, 1978). Middle: in 1999 the ice shelf had calved along the upper portion of the 1978 river, with the lower portion reaching the ocean in a possible estuary (red star). (July 7, 1999 panchromatic Landsat 7 image) 2008 ice edge annotated in red. Right: image from 2008 shows the calving occurred along the 1999 river also visible in 1978. The iceberg produced by the longitudinal fracture coincident with the river is present (July 13, 2008 panchromatic Landsat 7 image).

b) Ryder rivers and rectilinear calving 2010 - 2014

In 2010 a long straight river is present. Middle: in 2014 the ice shelf had calved along the upper portion of the 2010 river, with the lower portion reaching the ocean in a possible estuary (red star). (July 17, 2014 panchromatic Landsat 7 image) 2014 ice edge annotated in red.

c) Estuarine weakening

Calving controlled by compressive arch stress field
Calving controlled by estuarine weakening

Figure 3. Rectilinear calving and estuarine weakening at the Petermann and Ryder Ice Shelves.

a) Left: in 1978 a long straight river is present on the Petermann Ice Shelf. Future ice edges (1999 and 2008) and estuaries (1999) are annotated (image from July 3, 1978). Middle: in 1999 the ice shelf had calved along the upper portion of the 1978 river, with the lower portion reaching the ocean in a possible estuary (red star). (July 7, 1999 panchromatic Landsat 7 image) 2008 ice edge annotated in red. Right: image from 2008 shows the calving occurred along the 1999 river also visible in 1978. The iceberg produced by the longitudinal fracture coincident with the river is present (July 13, 2008 panchromatic Landsat 7 image).
b Left: in 2010 an ice-shelf terminating river is present on the east side of the Ryder Ice Shelf (location map in upper left). The calving front morphology is straight along the width of the shelf. Future 2014 ice edge is annotated (July 8, 2010 panchromatic Landsat 7 image). Right: in 2014 the ice shelf had calved along the upper portion of the 2010 river (August 1, 2014 panchromatic Landsat 7 image). c Schematic of estuarine weakening process with shaded compressive arch. Longitudinal fractures are initiated at the estuary mouth, downstream of the compressive arch (gray shaded region). Landsat images courtesy of the U.S. Geological Survey.
Figure 4. Estuary formation in Antarctica.

a) Predictions of time (years) until an estuary forms on ice shelves as a function of incision rate. Estimates are provided for Nansen and Pine Island Ice Shelves, as well as on the Petermann and Larsen B Ice Shelves. Horizontal dashed line marks 30 years from present, 2050, when Antarctic surface melt is expected to double. Vertical dashed line shows the conservative estimate of incision rate of 3 cm d$^{-1}$ chosen to report estuary formation predictions and used in subsequent calculations (Methods).

b) Length of melt season necessary to produce estuaries on Antarctic ice shelves in 30 years (by 2050). Basemap from the Landsat Image Mosaic of Antarctica (LIMA).