Surface outburst of a subglacial flood from the Greenland Ice Sheet

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Article

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Abstract

As Earth’s climate warms, surface melting of the Greenland Ice Sheet is projected to intensify, contributing to rising sea levels1–4. Observations5–7 and theory8–10 indicate that meltwater generated at the surface of an ice sheet can drain to its bed via crevasses and moulins, where it flows relatively unhindered to the coast. This understanding of the movement of water within, and beneath, ice sheets underpins theoretical models which are used to make projections of ice sheet change11. In this study, we show the first evidence of a disruptive drainage pathway in Greenland, whereby a subglacial flood – triggered by a draining subglacial lake – breaks through the ice sheet surface. This unprecedented outburst of water causes fracturing of the ice sheet, and the formation of 25-metre-high ice blocks. These observations reveal a complex, bidirectional coupling between the surface and basal hydrological systems of an ice sheet, which was previously unknown in Greenland. Analysis of over 30 years of satellite imagery confirms that the subglacial lake has drained at least once previously. However, on that occasion the floodwater failed to breach the ice surface. The two contrasting drainage regimes, coupled with the increased rates of ice melting and thinning that have occurred over the past three decades years, suggest that Arctic climate warming may have facilitated a new, disruptive mode of hydrological drainage on the ice sheet. As such, our observations reveal an emerging and poorly understood phenomenon, which is not currently captured in physical ice sheet models.
The Greenland Ice Sheet has been losing ice at an average rate of $\sim$150 billion tonnes per year since 1992, contributing $\sim$11 mm to global sea level rise. Approximately one half of this ice mass loss has been attributed to surface mass balance (SMB) processes, driven primarily by enhanced melting and run-off from the ice sheet surface. As Arctic warming continues to amplify throughout the 21st century, both the intensity and areal extent of Greenland surface melting and run-off are projected to increase, leading to even greater ice mass loss. Notably, the past decade has seen two widespread summertime melt episodes across the Greenland Ice Sheet, in 2012 and 2019, and concomitant extreme losses in ice mass. The increased frequency of events such as these is likely to drive further positive feedback mechanisms related to changes in bare ice exposure and the capacity of firn to accommodate meltwater refreezing, which may further accelerate the Greenland Ice Sheet’s contribution to sea level rise.

Understanding the passage of meltwater from its origin on the ice sheet to the ocean is critical for understanding the Greenland Ice Sheet’s future mass balance, sea-level rise, and indeed the fate of the wider Arctic climate and ecological system. It is well established that surface meltwater penetrates to the bed of the Greenland Ice Sheet via moulins and crevasses. Observational studies, mainly in south and west Greenland, have shown that the subglacial hydrological system can rapidly evolve in response to seasonal water input, in turn modulating ice dynamics. These studies demonstrate that temporal variability in water flow through the subglacial system is a key control on the dynamic response of the ice. As such, it is critical to determine both the mode (continuous versus episodic) and pathway (whether meltwater drains across the surface, within or beneath the ice sheet) of drainage, together with the extent to which meltwater is stored (englacially or subglacially) whilst in transit. These factors affect the capacity of meltwater to impact a broad range of glaciological and climatological processes, including ice dynamics, thermodynamics, ice-ocean interactions, fjord circulation, primary productivity, and rates of sediment and nutrient transfer to the ocean.

Although subglacial lakes were first mapped in Antarctica and Iceland over 50 years ago, they have only been identified beneath the Greenland Ice Sheet in the past decade. Recently, dynamically active Greenlandic lakes have been discovered, which, unlike their Antarctic counterparts, are primarily fed by seasonal inputs of surface meltwater. Active subglacial lakes have wider importance because they provide a mechanism to force large volumes of water and sediment through the subglacial hydrological system when they drain. In turn, this has the potential to alter the morphology of the subglacial drainage system, and thus impacting both the local dynamics and the characteristics of the overlying ice sheet, together with

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its downstream behaviour\textsuperscript{49}. For example, following the 2015 drainage of a subglacial lake in southwest Greenland, a $\sim 25\%$ reduction in ice flow speed was observed\textsuperscript{36}. Given projected increases in Arctic atmospheric temperatures, ice melting and run-off during the 21\textsuperscript{st} century\textsuperscript{41,42}, subglacial lake drainage events may be expected to increase in extent and frequency\textsuperscript{32,43}. However, the impact of such extreme forcing upon the Greenland Ice Sheet remains highly uncertain, due to a paucity of observations.

Brikkerne Glacier (81.5°N, 44.48°W) is a marine-terminating glacier draining ice from one of the most northerly sections of the Greenland Ice Sheet into Victoria Fjord (average depth $\sim 250$ m\textsuperscript{44}). The glacier has three tidewater outlets, with the main (northernmost) terminus measuring $\sim 4$ km wide, and maintaining a small floating ice tongue\textsuperscript{45}. Between 1968 and 1978, the main glacier outlet advanced by 9 km, before retreating at an average rate of 76 m a\textsuperscript{−1} between 1978 and 2015\textsuperscript{46}. The glacier exhibits a pronounced seasonal cycle with velocities typically increasing from June, and reaching peak values in late July/August at about 2 times the annual average (Supplementary Material Figure 1). Air temperatures at the upper part of this glacier have progressively increased over the past half-century, with decadal average air temperatures rising from -14.6°C in the 1960s to -13.2°C in the 2010s\textsuperscript{22} (Supplementary Material Figure 2a-c). As a result, the percentage of days per year where surface melt exceeds 5 mm w.e. has almost doubled, increasing from 8\% to 14\% between the 1960s and 2010s\textsuperscript{22}.

In this study, we use 2 m resolution timestamped ArcticDEM (http://arcticdem.org) Digital Surface Models (DSMs)\textsuperscript{47}, Landsat optical and Sentinel-1 radar imagery, and satellite altimetry to monitor the evolution of the ice sheet surface across the Brikkerne Glacier catchment between 2012 and 2019. During this 7-year period, the majority of the glacier surface remained relatively stable. However, during a 10-day interval in the late summer (August) of 2014, a localised region of the ice surface $\sim 25$ km inland from the margin, dropped in elevation by up to 85 m, forming a $\sim 2$ km\textsuperscript{2} collapse basin (Figure 1). The stresses exerted on the surrounding ice by this rapid, localised subsidence of the surface caused structural failure, leading to the formation of concentric crevassing around the rim of the collapse basin (Figure 1). Prior to the collapse, the basin footprint had been rising at an average rate of 46 cm a\textsuperscript{−1} between 2012 and 2013, with the outer edge of the basin domed by $\sim 10$-15 m above the surrounding ice surface (Figure 2). We interpret this dynamic feature to be the surface signature of a subglacial lake filling, then rapidly draining, similar to events that have been previously observed in Greenland\textsuperscript{32–35}, Antarctica\textsuperscript{48} and Iceland\textsuperscript{49,50}.

Assuming the volume of the feature was equivalent to the volume of water lost during the subglacial lake drainage event, the outburst flood had a total volume of $9 \times 10^7$ m$^3$. This equates to a mean rate of water discharge of 101 m$^3$ s$^{-1}$ during the 10-day period between satellite acquisitions (22\textsuperscript{nd} July - 1\textsuperscript{st} August 2014); albeit the drainage duration may have been much
shorter, and the peak discharge higher. Nevertheless, this mean discharge rate is still approximately 2 orders of magnitude
greater than that of an Antarctic subglacial lake of the same volume\textsuperscript{43}. This newly identified active subglacial lake represents
the largest such event recorded beneath the mainland Greenland Ice Sheet, albeit smaller than the $4 \times 10^8$ m$^3$ subglacial lake
drainage under the neighbouring Flade Isblink Ice Cap\textsuperscript{35}. What is remarkable, and unprecedented for Greenland, is the observed
behaviour of the ice sheet downstream of the subglacial lake.

As the subglacial lake drained suddenly, a $\sim 1$ km wide rupture with crevasses to a depth of at least 40 m and ice blocks up to
25 m in height appeared in the ice surface approximately 1 km downstream of the collapse basin (Figure 1f & 2). Immediately
downslope of these ice blocks, a $\sim 6$ km$^2$ region of the ice surface became scoured clean. Together, these observations indicate
that a substantial volume of water had flooded across the ice surface (Figure 1). Similar to subglacial lake jökulhlaups in
Iceland characterised by extremely rapid linear rises in lake discharge, we suggest that a turbulent sheet flood, produced by the
subglacial lake drainage, propagated to the surface via englacial routeways and hydrofracturing due to basal water pressures
greatly in excess of ice overburden pressure\textsuperscript{51–54}. Upstream of the ice blocks there is additional disturbance of the ice surface,
with a newly formed $\sim 1.6$ km$^2$ fan-shaped feature bounded by two raised linear ridges extending $\sim 800$ m in length and up to 5
m in height (Figures 1 & 2). We propose that some water was also forced up through a concentric ring fracture at the rim of
the collapse basin (Figure 1), and this outburst of water produced a slushflow fan\textsuperscript{55}. Having breached the surface and flooded
across the ice, outburst water re-entered the englacial (and presumably subglacial) system through moulins located several
kilometres downstream (Supplementary Material Figure 3b-c), where it would have been routed to the glacier’s calving front.

This is the first time that such a phenomenon has been observed on the Greenland Ice Sheet, and demonstrates a previously
unknown level of complexity and interconnectedness between its surface and basal hydrological systems. In particular, contrary
to current understanding of the ice sheet’s hydrological system, it provides evidence that water flow is not always unidirectional
from the ice sheet surface to its base, but instead can travel from the surface to the bed, and back again, over short spatial and
temporal scales. Although this type of behaviour has previously been observed on much smaller, geothermally-active, Icelandic
ice caps\textsuperscript{53, 54}, it has not, until now, been resolved as a mechanism affecting the larger ice masses of Greenland or Antarctica.

In addition to the formation of the collapse basin and the downstream fracturing of the ice surface, several other unusual
events occurred during the same 10-day period. In the vicinity of the collapse basin, a supraglacial lake adjacent to the nunatak,
which had been growing annually in size since 2004 (Figure 3a-c), abruptly drained. At the same time, several changes were
observed further downstream and at the glacier terminus, namely (1) a large calving event (the 7th largest event recorded in the
past 32 years) occurred at the main glacier terminus, leading to a 500-600 m retreat of the glacier’s calving front (Figure 3e-g), (2) an ice-marginal lake broke through its lateral moraine dam and emptied in its entirety (Supplementary Material Figure 3c), and (3) two downstream supraglacial lakes on the main glacier drained completely (Supplementary Material Figure 3a). Given the destructive nature of the outburst flood, it is likely that at least some of these events may have been connected, although the 10-day temporal sampling of the optical satellite imagery makes it impossible to determine the chronology of these events precisely.

As the subglacial lake is likely to have been filled by summer supraglacial meltwater input, it is probable that the lake had been gradually filling for some time. As the lake filled, subglacial water pressure would have increased, and we hypothesise that in 2014 the pressure was sufficient to break the seal on the lake, thus initiating the subglacial sheet flood. Indeed, subglacial outburst floods in Iceland which breach the ice surface are typically triggered by a rapid input of meltwater, such as a volcanic eruption rapidly melting the ice. Here, the coincident drainage of the large adjacent supraglacial lake (Figure 3a-c) would have provided an additional rapid injection of water into the system causing a rapid linearly rising discharge event, irrespective of whether it triggered, or was triggered by, the subglacial lake drainage itself. It is also notable that the drainage event occurred at the same time as the largest rainfall event that year (based upon RACMO2.3p2 Regional Climate Model simulations; Supplementary Material Figure 2d-f), thereby adding a further source of water to the flood.

In the years following the drainage event, the ice surface of the collapse basin began to rise rapidly (average rate of 12 m a\(^{-1}\) between 2016-2017; Figure 2), indicating refilling of the subglacial lake, most likely due to recharge by surface meltwater. Between 2017 and 2019, the floor of the collapse basin subsided again by \(\sim 10\) m (Figure 2), suggesting continued dynamic behaviour of the underlying lake. To place these observations within a longer-term context, we therefore analysed Landsat imagery from the past 36 years to look for evidence of past similar drainage events. This analysis revealed that the distinctive oval-shaped surface feature above the subglacial lake has existed since at least 1985, and persists to the present day (24\(^{th}\) May 2021). To identify past lake drainage, we inspected consecutive Landsat images for evidence of a simultaneous (1) change from doming to a depression in the surface, and (2) formation of tension fractures around the rim of the basin. Using these criteria, we identified a single drainage event prior to 2014, which occurred between 21\(^{st}\) June 1990 and 1\(^{st}\) August 1990 (Supplementary Material Figure 3d-g). On this occasion however, and in contrast to the behaviour recorded during the 2014 event, no downstream surface fracturing and outburst of water occurred, suggesting that the flow of water from the lake outburst flood to the ocean occurred entirely at the ice sheet base.
We hypothesise that the contrasting response of the ice sheet to the 1990 and 2014 outburst floods is attributable to the extensive thinning of the ice sheet that has occurred during the intervening period. Specifically, that recent thinning of ice in this region may have facilitated the breach of the subglacial flood to the surface in 2014. Notably, in the decade prior to the 2014 outburst event, the Greenland Ice Sheet experienced exceptionally high and sustained rates of mass loss\textsuperscript{12}, and both model simulations\textsuperscript{22} and satellite altimeter observations indicate that the ice thinned by $\sim$13 m (or 5\% of the average local ice thickness\textsuperscript{44}) between 1990 and 2014 (Figure 3d). If correct, this hypothesis suggests the emergence of highly dynamic and bidirectional hydrological connections between the surface and the bed of an ice sheet, which challenges the classical model of unidirectional ice sheet meltwater flow. Furthermore, such connections may be expected to become more common in the future, as the ice sheet thins and surface melt intensifies under a warming climate. At present, however, neither the theory nor the implications of such a phenomenon are currently understood, nor is this process included in current physical models.

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Author contributions statement

JSB, AAL, MM, SJL and AJS, devised the project. JSB and MM wrote the manuscript, with input and interpretation of the science from all authors. AS processed and provided Sentinel-1 SAR imagery. BN and MRvdB provided RACMO2.3p2 forcing data. AAL calculated ice surface thinning using RACMO2.3p2 and modelled subglacial routing. TS processed and provided CryoSat-2 altimetry data. LSS and SBS processed and provided ICESat altimetry data. LIM delineated supraglacial lake and terminus margins. JM provided ice velocity data. LT processed and provided ICESat-2 elevation data.

Competing interests

The authors declare no competing financial interests.
Figure 1. a True colour composite Landsat 8 scene acquired on 22nd July 2014 before the subglacial outburst flood (SL1 indicates the location of supraglacial lake 1 referred to in the text) b Three-dimensional shaded relief of the collapse basin mapped using 2 m resolution ArcticDEM data acquired on 9th July 2012 c Three-dimensional shaded relief of downstream region (as shown in panel a) on 9th July 2012. Arrow shows direction of ice flow. d True colour composite Landsat 8 scene capturing the subglacial lake drainage and surface outburst on 1st August 2014 e Three-dimensional shaded relief of the collapse basin acquired on 28th April 2015, after the subglacial lake drained f Three-dimensional shaded relief of the same downstream region (as shown in panel d) on 28th April 2015, showing uplifted ice blocks (up to 25 m high) and raised ridges. Direction of ice flow is same as panel c
Figure 2. Elevation profiles through time. a Repeat elevation profiles A-A (location shown in panel c) from co-registered ArcticDEM following ICESat-2 track 1130. The profiles show a domed surface towards the northern rim of the basin between 2012 and 2014. By 2015, the basin floor has dropped, due to the sudden drainage of the subglacial lake in 2014 (Figure 1; Supplementary Material Figure 3h-k). In 2017, the basin floor rises before subsiding again by summer 2019 (ICESat-2 dashed line). b Repeat elevation profile B-B (location shown in panel c) along ICESat-2 track 1032 show crevassing and uplifted ice blocks from the surface outburst of water at 3600 m along the transect. c Surface elevation change between 9th April 2013 and 28th April 2015, due to subglacial lake drainage. The maximum displacement is an ∼85 m decrease in surface elevation, near to the headwall. Subsidence also occurs near the headwall due to the drainage of a supraglacial lake. Uplifted ice blocks 1 km downstream measure up to 25 m in height. d Sentinel-1 SAR backscatter image post collapse (22nd January 2015), exhibiting a fan-shaped feature beyond the basin and high backscatter caused by subglacial water breaking the ice surface.
**Figure 3.**

- **a** Change in area of the supraglacial lake at the base of the nunatak between 1998 and 2020. Red bars indicate the periods when the subglacial lake drained in 1990 and 2014.
- **b** Nunatak supraglacial lake (outlined in red) before the basin collapsed on 22nd July 2014 as indicated by Landsat 8.
- **c** Drainage of supraglacial lake at base of nunatak on 1st August 2014, coinciding with subglacial lake drainage.
- **d** Change in ice elevation at the location of the collapse basin according to RACMO2.3p225 (solid grey line), CryoSat-2 (navy line), and ICESat elevation change (dh) about 30 km from the collapse basin (black points).
- **e** Change in terminus of the main northern outlet relative to previous observation, measured using GEEDiT and MaQiT tools40, negative values indicate glacier retreat, positive values indicate glacier advance.
- **f** Northern outlet of the glacier before drainage event on 22nd July 2014 and **g** after drainage event showing ~550 m retreat at the terminus.
Methods

ICESat-2

Advanced Topographic Laser Altimeter System (ATLAS) Ice, Cloud and land Elevation Satellite-2 (ICESat-2) Land Ice Along-Track Height Product (ATL06) data were obtained from the National Snow and Ice Data Center (NSIDC) for the period (2019-2020). Four tracks (49, 103, 545 and 1130) covered the study site. Points scattered by cloud, blown snow or aerosols, or flagged as low-quality were discarded prior to analysis.

ArcticDEM

ArcticDEM 2 m spatial resolution Digital Surface Models (DSMs) were generated by applying the Surface Extraction with TIN-based Search-space Minimization (SETSM) algorithm to stereoscopic WorldView and GeoEye satellite imagery by the ArcticDEM Team. We coregister all the ArcticDEM stripfiles (2012-2017) in the study area with seasonally relevant (March-May) ICESat-2 ATL06 data. Artefacts in the ArcticDEM and mask dynamic surfaces e.g. crevassing are manually filtered before performing a least-squares planar fit to the residuals to calculate the vertical offset:

\[ \Delta z = a + bx + cy \]  

where \( x \) and \( y \) are the residuals in the range and azimuth directions. The \( a \), \( b \) and \( c \) parameters are estimated using the intercept, \( x \) coefficient and \( y \) coefficient, respectively. We then remove the plane from the \( z \) component (elevation) of each DSM.

A total of 1352 ICESat-2 points were used for co-registering the 14 DSMs in the study area.

Subglacial lake volume

The area of the collapse basin is calculated by differencing the pre-collapse and post-collapse ArcticDEM DSMs from 2014 and 2015. We define the depression as those pixels where the average elevation changes between these dates were greater than the 1σ elevation variability. Subglacial lake volume is then calculated by multiplying the area by the mean depth.

Sentinel-1 SAR

We use GMTSAR (https://topex.ucsd.edu/gmtsar/) to align and geocode Sentinel-1 Interferometric Wide swath mode Single-Look Complex Synthetic Aperture Radar (SAR) data (scihub.copernicus.eu) to create 15 m pixel backscatter images. Radar speckle is minimised during post-processing using a 3D block-matching filter, implemented in MATLAB (http://www.cs.tut.fi/ foi/GCF-BM3D/).
We compute height evolution time series at 60-day epochs (Figure 3d) from CryoSat-2 radar altimeter observations acquired between October 2010 and October 2020. We use measurements of ice sheet elevation acquired by CryoSat-2 operating in Synthetic Aperture Radar Interferometric (SARIn) mode, provided in the baseline-D level 2i product, and corrected for echo-deviations from the on-board tracking gate, off-nadir ranging due to slope, dry and wet atmosphere, ionosphere and solid earth tide (ESA, 2012). Using a model fit method\textsuperscript{10,11}, we generate time series of ice sheet surface height change on a 5 x 5 km grid, and model the elevation ($z$) as a function of topography ($x,y$), satellite heading ($h$) and time ($t$):

$$z(x,y,t,h) = \bar{z} + a_0x + a_1y + a_2x^2 + a_3y^2 + a_4xy + a_5h + a_6t$$ (2)

We solve for model coefficients using an iterative least-squares fit to minimise the impact of outliers, and discard any unrealistic estimates from poorly constrained solutions using a set of statistical thresholds which include: a minimum of 70 data points, a minimum time series length of 2 years, a maximum root mean square difference of 12 m, a maximum elevation rate magnitude of 10 m a\textsuperscript{-1}, and a maximum surface slope of 5°.

We account for temporal variations in range due to changes in radar echo shape using an empirical correction based upon correlated changes in elevation and backscattered power\textsuperscript{12}. Using a linear fit, we compute the gradient in elevation as a function of power in order to determine a height correction:

$$z_{\text{corrected}} = dz - (dp \frac{dz}{dp})$$ (3)

which we apply to time series of height change in each grid cell. We compute time series of height evolution by averaging the gridded and corrected elevation anomalies within 60-day intervals for the northern Greenland between 500 and 800 m a.s.l according to ArcticDEM\textsuperscript{2}.

**ICESat**

NASA's Ice, Clouds, and Land Elevation Satellite (ICESat) was launched in January 2003 into a polar orbit, carrying the Geoscience Laser Altimeter System (GLAS)\textsuperscript{13}. With a satellite inclination of 94°and a laser instrument, ICESat allowed for precise observations of ice sheet surface elevation change far enough north to cover the area of Brikkerne Glacier. The ICESat mission lasted until 2009, but due to initial challenges with the GLAS instrument, it operated on campaign basis three times a
Here, we use release 34 GLAS/ICESat Level-2 Global Antarctic and Greenland Ice Sheet Altimetry Data (GLAH12)\textsuperscript{14} processed with the plane-fitting method\textsuperscript{15} to estimate and subtract the local topography from the elevation data, to obtain an estimate of the temporal evolution of the ice surface (see Figure 3d). The GLAH12 data have been pre-processed to remove the intercampaign bias following\textsuperscript{16} and the saturation biases as provided in GLAH12.

**RACMO**

In order to calculate ice thickness change as a result of surface mass balance processes, we calculate cumulative SMB anomalies using daily surface mass balance (SMB) from the 1 km Regional Atmospheric Climate Model RACMO2.3p\textsuperscript{2}\textsuperscript{17} to give a mass change, which is then converted to height, assuming that the change occurs at the density of ice (917 kg m\textsuperscript{3}).

**Nunatak supraglacial lake area**

The supraglacial lake beneath the nunatak was manually delineated using cloud-free Landsat and Sentinel-2 imagery for the period 1988-2020. Maximum lake area was calculated for each available image.

**Calving front change**

Terminus positions of the 3 main lobes of Brikkerne Glacier were manually digitised from all available Landsat and Sentinel-2 optical imagery between 2002-2020, using the Google Earth Digitisation Tool (GEEDiT)\textsuperscript{18}. Images obscured by cloud and/or melange were excluded from the dataset. Changes in the calving front were analysed using the centreline method in Margin change Quantification Tool (MaQiT)\textsuperscript{18}.

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Supplementary Material

Supplementary Methods

RACMO

We use daily 2 m temperature, precipitation, melt and runoff from the Regional Atmospheric Climate Model RACMO2.3p2 at 5.5 km horizontal resolution (1990-2020)\(^1\). The model combines the dynamical core of the High-Resolution Limited Area Model (HIRLAM) and the physics of the European Centre for Medium-Range Weather Forecasts-Integrated Forecast (ECMWF-IFS cycle CY33r1). RACMO2.3p2 is forced by the latest ERA5 reanalyses (1990-2020) on a 3-hourly basis within a 24 grid-cell wide relaxation zone at the 40 vertical atmospheric levels. The model also includes a 40-layer snow module that simulates melt, runoff, water percolation, retention and refreezing in firn. Snow layers are initialised in September 1957 using vertical temperature and density profiles from the Institute for Marine and Atmospheric research Utrecht-Firn Densification Model (IMAU-FDM). The model accounts for dry snow densification, drifting snow erosion and sublimation, and explicitly simulates snow albedo. Bare ice albedo is prescribed from a down-sampled version of the 500 m MODIS albedo 16-day product (MCD43A3) as the 5% lowest surface albedo records for the period 2000-2015, clipped between 0.30 for dark bare ice and 0.55 for bright ice beneath perennial firn. For additional details and relevant references, we refer to Noël et al.\(^1,2\).

Ice velocity

Ice surface flow velocity timeseries was generated using optical and synthetic aperture radar (SAR) sensors between 1988 and 2020. Ice displacements in Landsat-8 and Sentinel-2 are tracked using the persistence of surface features between two image pairs\(^3,4\). For the SAR missions (Sentinel-1A/B, ENVISAT, RADARSAT-2, ALOS and ERS-1/2) offset displacements caused by motion of the ice are tracked and processed following Mougino et al.\(^5\). We calculated the median ice velocity at 81.81°N, 45.34°W, a location close to the terminus of the glacier.

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Figure 1. a Velocity timeseries between 1988 and 2020 using various sensors. The horizontal extent of each line represents the period between image pairs. b Velocity timeseries between 2012 and 2020 showing seasonal trends. Red bars indicate the period when the basin collapsed in 1990 (22$^{nd}$ June - 1$^{st}$ August) and 2014 (22$^{nd}$ July - 1$^{st}$ August).
Figure 2. External forcings derived from RACMO2.3p2 at 81.70°N, 43.97°W between 1988-2020. 

- **a**: 7-day rolling average 2 m temperature between 1988-2020.
- **b**: Daily 2 m temperature for 1990.
- **c**: Daily 2 m temperature for 2014.
- **d**: Daily total snowfall (blue) and rainfall (orange) between 1988-2020.
- **e**: Daily total snowfall and rainfall for 1990.
- **f**: Daily total snowfall and rainfall for 2014.
- **g**: Daily total runoff (light blue) and melt (purple) between 1988-2020.
- **h**: Daily total runoff and melt for 1990 (Noël et al., 2018).
- **i**: Daily total runoff and melt for 2014.
Figure 3. True colour Landsat 5 and 8 composites show coincident events at Brikkerne Glacier following two subglacial lake drainages.

a. Landsat scene showing study area after the 2014 subglacial lake drainage event on 1st August 2014, with subglacial routing I in dark blue.

b. Before the 1990 subglacial lake drainage event on 16th June 1990, the oval feature has wind-scoured bare ice with snow surrounding it suggesting it is higher than the surrounding topography and therefore domed. Supraglacial lake (SL1) is filled.

c. After the 1990 drainage event on 1st August 1990, showing tension fractures caused by downwards motion of ice. The nunatak supraglacial lake has drained.

d. Sedimented meltwater is present in the deepest part of the collapse basin on 3rd August 1990.

f. Following a snowfall event, shadowing on the southwest side of the collapse basin indicates that the feature has subsided.

b. Before the 2014 drainage event on 28th June 2014, some surface meltwater is evident around the rim of the basin and beyond the feature.

g. Landsat scene acquired on 7th July 2014 showing the supraglacial lake beneath the nunatak has an ice lid.

h. Shadowing on the southwest side of the collapse basin indicates that the surface feature is still collapsed on 15th August 2014. A fan-like feature with raised ridges occurs between the basin and uplifted ice blocks caused by subglacial outburst of a subglacial lake which leaves behind an outwash plain downstream where the ice is cleaner. Supraglacial lake (SL1) has now drained.

i. Shadowing again is present on the southwest side of the collapse basin, and the fan-like feature is prominent.