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Brief Communication: Lateral Surface Meltwater Export from Bach Ice Shelf Resumes After 9-Year Hiatus

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Abstract

Lateral surface meltwater export from Antarctic ice shelves is a rarely observed phenomenon. Here, we present remotely sensed evidence for its re-initiation on Bach Ice Shelf following a nine-year hiatus. Using regional climate model outputs alongside these observations, we assess the potential drivers of this change and evaluate its implications for the future stability of Bach Ice Shelf.

1.0 Introduction

Antarctic ice shelves are critical regulators of Antarctic Ice Sheet mass balance, providing buttressing that restrains upstream ice flow and limits global mean sea-level rise (Fürst et al., 2016). Their stability is governed by a range of processes, including warming air temperatures and enhanced surface melt. At present, surface meltwater poses an instability risk by promoting hydrofracture-driven collapse (Banwell et al., 2013; Lai et al., 2020). Under future warming, it may also contribute to a negative surface mass balance (SMB) through enhanced surface runoff (Gilbert and Kittel, 2021; Kittel et al., 2021). Here, we investigate the return of lateral surface meltwater export from Bach Ice Shelf (on the western Antarctic Peninsula (AP)) following a 9-year hiatus; a phenomenon that is rarely observed under present-day conditions in Antarctica.

The AP experienced a pronounced increase in 2 m air temperatures (hereafter T_{2m}) during the second half of the 20th century, with records from Vernadsky Station (formerly Faraday Station until 1996) on the western AP indicating a warming rate of approximately 0.56 °C per decade between 1951 and 2000 (Turner et al., 2005). However, more recently, natural internal variability of the regional atmospheric circulation led to a partial cooling of the AP between 1999 and 2014 (Turner et al., 2016). Since 2015, warming across the AP has resumed (Carrasco et al., 2021), with expected implications for summer surface meltwater production.

The late-20th-century warming observed across the AP coincides with - and slightly precedes - several major ice-shelf collapse events. Between the 1950s and 2008/09, total ice-shelf area across the AP decreased by more than 28,000 km², largely due to partial or complete disintegration affecting seven of the region's twelve ice shelves (Cook et al., 2010). Further, for four of these ice shelves, meltwater-driven fracture (hydrofracture) was implicated as a potential collapse mechanism. For the Larsen A and Larsen B ice shelves, located on the

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eastern AP, meltwater ponding and associated fracturing was implicated in their rapid disintegration through hydrofracture (e.g. Banwell et al., 2013; Scambos et al., 2000). In contrast, at the Wordie and Wilkins ice shelves on the western AP, surface and /or subsurface meltwater likely promoted the propagation of shallow surface crevasses into full-depth rifts, as meltwater infilled crevassed areas (Doake et al., 1991; Scambos et al., 2009).

Given the evidence for meltwater-driven ice-shelf instability across the AP, renewed regional warming (T_{2m}) since 2015, and projections of a non-linear increase in surface melt under future warming (Gilbert and Kittel, 2021; Trusel et al., 2015), identifying recent changes in ice-shelf surface meltwater regimes is essential. Two phenomena are of particular interest: (i) meltwater-driven hydrofracture events and (ii) lateral surface meltwater export, either off the ice-shelf edge or through rift systems. Whilst ice-shelf hydrofracture is increasingly investigated through field-based (Banwell et al., 2024) and remotely-sensed observations (Dunmire et al., 2020; Sommer et al., 2024.; Trusel et al., 2022), evidence for lateral surface meltwater export remains scarce (Bell et al., 2017).

Here, we present evidence for the re-initiation of lateral surface meltwater export from the Bach Ice Shelf after a 9-year hiatus. Using a combination of optical remote sensing and regional climate model outputs, we document the return of this phenomenon and examine the conditions that enabled it. We map cumulative summer (November-March) surface meltwater areas across the ice shelf using a multi-band thresholding approach applied to Landsat 7, 8 and 9 records (2012–2025). To support these observations, we use a 43-year (1980-2023) climatology comprising cumulative annual (April–March) gridded snowmelt and SMB products from the Regional Atmospheric Climate Model (RACMO2 (Noël et al., 2023)). From these, we derive the melt-to-SMB ratio as an indicator of surface ponding or runoff potential (a conservative approach *adapted from* Donat-Magnin et al. (2021), van Wessem et al. (2023) and Pfeffer et al. (1991)). These data are then complemented by mean annual (April-March) T_{2m} data from ERA5 reanalysis for 1980-2025 (Hersbach et al., 2020), as the authors did not have access to downscaled RACMO2 T_{2m} data at the time of writing.

2. Methods

2.1 Maximum Summer Surface Meltwater Extents

Maximum ice-shelf surface meltwater (i.e., water in lakes and streams) extents for each austral summer (November–March) in the Landsat 8 and 9 record were mapped using an adapted version of the multi-band thresholding approach (Moussavi et al., 2020). All available Landsat 8 and 9 Top-of-Atmosphere, Tier-2, Collection-2 images were classified using the thresholds presented in Tuckett et al. (2025). To ensure data quality, each water mask was manually cleaned by a subject expert. The cleaned masks for each melt season were then stacked to produce a maximum surface meltwater extent for that summer.

In addition to the Landsat 8/9 summer products, a corresponding surface meltwater extent was generated for the 2012/13 austral summer using Landsat 7 data alone. This season was

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selected because it provides insight into the extent of surface ponding and run-off immediately prior to the onset of the observed nine-year hiatus in lateral surface meltwater export. Consistent image-selection criteria, multi-band thresholds, and manual masking procedures were applied, following the same approach used for Landsat 8 and 9. For each austral summer investigated, we visually examined the maximum ice-shelf surface meltwater extents, paying particular attention to years in which surface meltwater features intersect with rifts and/or the calving margin, as an indicator of surface meltwater runoff.

2.2 Rift Extents

Bach Ice Shelf's dominant, but still nascent, rift system (see Figure 1) was manually digitised for each year in which summer surface meltwater extents were produced (2012/13–2024/25). Image selection for rift digitisation focused on identifying the least cloudy scene available from as late in the melt season as possible, to capture maximum rift extent. The final images used (comprising a mix of Landsat 7, 8, and 9 Top-of-Atmosphere, Tier-2, Collection-2 scenes) are given in Table S1. Rifts were digitised at a scale of 1:50,000 using only the red–green–blue (RGB) band combination.

2.3 Modelled Melt and Surface Mass Balance

To quantify snowmelt and SMB over Bach Ice Shelf, we used the Regional Atmospheric Climate Model (RACMO2.3p2), forced by ERA5 reanalysis, with daily 27 km × 27 km outputs statistically downscaled to 2 km × 2 km resolution (Noël et al., 2023). We applied an ice-shelf mask (Gerrish et al., 2024) to extract values over Bach Ice Shelf and calculated cumulative snowmelt and SMB for each melt year, defined as April to March of the following year. By defining the year as April to March we were able to capture the SMB and snowmelt conditions preceding and spanning each full melt season, allowing us to consider the winter evolution of the snow/firn layer.

2.4 Melt to Surface Mass Balance Ratio (Melt-to-SMB)

Melt-to-SMB ratios were derived from statistically downscaled (2 km) RACMO2.3p2 snowmelt and SMB fields (Noël et al., 2023). While previous studies report melt-over-accumulation (MOA) ratios (Donat-Magnin et al., 2021; Melchior Van Wessem et al., 2023; Pfeffer et al., 1991), commonly computed as liquid input (snowmelt + rainfall) relative to solid input (snowfall, sometimes adjusted for sublimation; Esch et al., 2025), we use melt alone in the numerator and SMB in the denominator for practical and conceptual reasons. Practically, we opted to use the highest resolution dataset available as it likely better represents processes across Bach Ice Shelf, even though separate rainfall and accumulation fields were not available. Conceptually, SMB integrates the key processes that regulate firn air content, namely solid and liquid precipitation, sublimation/evaporation, wind-driven snow redistribution, and runoff (Lenaerts et al., 2019). Using a coarser resolution version of RACMO at 11 km with a wider availability of SMB-relevant variables (van Dalum et al., 2024) indicates rainfall is generally very small on Bach ice Shelf and including rain in the numerator and/or denominator would shift ratios only slightly, and the main conclusions of our study would be unaffected.

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2.5 Modelled 2 m Air Temperatures (T_{2m})

We used the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5 (Hersbach et al., 2020)) to quantify mean annual 2 m air temperature (T_{2m}) over Bach Ice Shelf. ERA5 provides hourly atmospheric reanalysis at 0.25° × 0.25° grid spacing. Using an ice-shelf mask from Gerrish et al. (2024) we extracted T_{2m} values over Bach Ice Shelf and computed daily ice-shelf-averaged temperatures. Annual mean T_{2m} was then calculated for each melt year (1980-2025), defined as April to March of the following year. By defining the year as April-March, our T_{2m} data were consistent with our modelled snowmelt and SMB data (Section 2.3).

3. Results and Discussion

Our results show renewed surface meltwater runoff from the calving margin beginning in the 2022/23 melt season, following nearly a decade of inactivity. During the hiatus, cumulative summer surface meltwater areas across the ice shelf did not exceed 90 km² and surface meltwater was typically clustered within Williams Inlet near the ice-shelf grounding line (Figs. 1, 2). The 2019/20 melt season was an exception, with lateral surface meltwater transport across the ice-shelf surface but no clear evidence of surface meltwater export, and a cumulative melt area of 236 km². The hiatus ended in 2022/23, when surface meltwater was not only extensive (329 km²), but was exported via two main pathways: (i) over the ice-shelf edge and (ii) into a nascent rift system (Fig. 1).

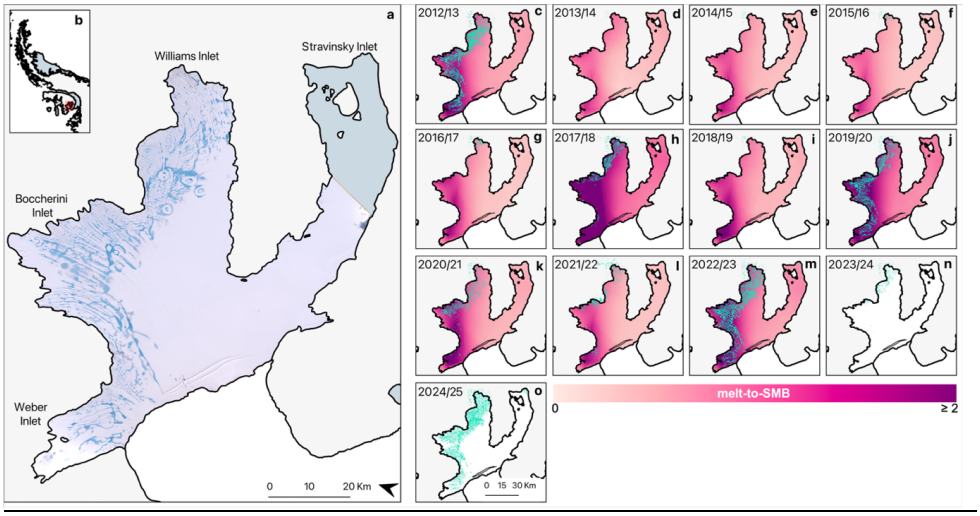

Figure 1: Surface meltwater extent and melt-to-SMB ratio for the austral summers of 2012/13 to 2024/25. *a) Sentinel-2 image of Bach Ice Shelf on 08/02/2022, (b) places Bach Ice Shelf in the context of the Antarctic Peninsula. (c - o) Cumulative surface meltwater extent (teal) and rift extent (black polylines) for each austral summer (November–March), overlain on the mean annual melt-to-SMB ratio derived from RACMO2.3p2 (Noël et al., 2023) (April preceding to March ending each melt season). Darker pinks show high melt-to-SMB values, while lighter pinks represent relatively lower melt-to-SMB values. Shapefile data from the SCAR Antarctic Digital Database, 2024 (Gerrish et al., 2024). Note for 2023/34 onwards melt-to-SMB values were unavailable.*

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Evaluating cumulative summer surface meltwater extent in the context of mean ice-shelf integrated snowmelt and SMB reveals that the first four years of the nine-year hiatus (2013/14–2016/17) correspond to periods when SMB markedly exceeded snowmelt (Fig. 2a). As a consequence, average melt-to-SMB values fell below the thresholds previously used to indicate surface ponding and run-off potential; 0.7 (Melchior Van Wessem et al., 2023; Pfeffer et al., 1991) and 0.85 (Donat-Magnin et al., 2021) (Fig. 2b). In contrast, from 2017/18 onwards the difference between snowmelt and SMB was reduced, and for two years (2017/18 and 2019/20) average snowmelt exceeded average SMB. As a result, melt-to-SMB values exceeded 0.7 in all but one year from 2017/18 onward, consequently meeting the lower of the previously established thresholds for ponding and runoff, and ranging between 0.75 and 1.35 (Fig. 2). This relatively sustained period of elevated melt-to-SMB values likely preconditioned the ice shelf for widespread ponding events (e.g. the austral summers of 2019/20, 2022/23, and 2024/25) and for the occurrence of lateral surface meltwater export, observed in 2022/23 and 2024/25 (Fig. 1).

From 1981 to 2025, mean annual T_{2m} (April - March) was marked by large year-to-year variability, but a linear regression over the period indicates a trend of +0.06°C yr^{-1} ($p < 0.001$). Temperatures were lowest in 1980/81 (–14.4°C) and highest in 2022/23 (–8.4°C) (Fig. 2), with a 45-year annual mean of –11.1 ± 1.4°C. This overall warming trend is episodic. Temperatures were remarkably stable between 2001/02 and 2005/06 (–10.7 ± 0.2 °C), followed by a slight but consistent decline from –10.6 °C in 2003/04 to –11.8 °C in 2006/07. Following this, T_{2m} rebounded and warming became particularly pronounced in 2019/20, culminating in record high temperatures in 2022/23 (-8.36°C).

Overall, our findings indicate that lateral surface meltwater export resumed on Bach Ice Shelf in 2022/23, ending a nine-year hiatus beginning in 2013/14. The onset of this hiatus was likely driven by a four-year interval during which SMB values were high relative to snowmelt (i.e., low melt-to-SMB ratios). During this period, firn-air content on the ice shelf likely increased, enabling meltwater to percolate into and refill pore space rather than forming surface ponds or driving lateral export (Kuipers Munneke et al., 2014). Although several subsequent years exhibited high melt-to-SMB ratios (e.g. 2017/18), extensive surface ponding did not reappear until 2019/20, and lateral surface meltwater export did not resume until 2022/23. This lag in surface meltwater expression likely reflects a delayed system response, with the ice shelf buffered by the firn-air reservoir generated during the preceding high-accumulation years.

Previous studies have demonstrated clear links between T_{2m} and both accumulation and melt on ice shelves, with surface melt increasing exponentially as T_{2m} rises and accumulation responding more linearly (Gilbert and Kittel, 2021; Trusel et al., 2015). Here, our T_{2m} record up to 2022/23 indicates that this melt season exhibits both the highest T_{2m} (–8.36 °C) and the greatest maximum surface meltwater extent on the ice shelf (329 km²). Notably, this same year also marks the return of lateral surface meltwater export. While T_{2m} remained relatively

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consistent across the ice shelf between 2001/02 and 2005/06, we identify a significant long-term warming trend of +0.06 °C yr^{-1} ($p < 0.001$) over the 45-year climatology.

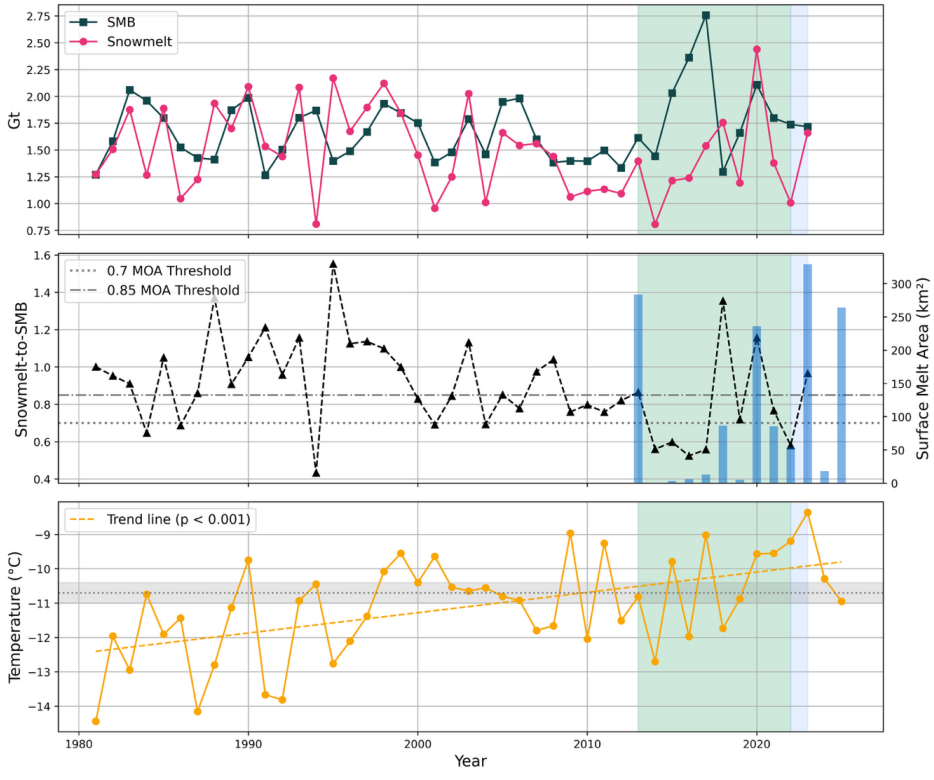

Figure 2: Time series of mean annual (April-Mar) Surface Mass Balance, melt-to-SMB ratios, and 2m air temperatures. *(a) Surface Mass Balance and Snowmelt from RACMO2.3p2 (1980-2023) (2km x 2km) (Noël et al., 2023), (b) melt-to-SMB ratio, derived from RACMO2.3p2 (1980-2023) (2km x 2km) (Noël et al., 2023), and (c) 2m air temperatures from ERA5 (1980-2025) (Hersbach et al., 2020). Total annual maximum surface meltwater area is also plotted on (b) for the period of 2012/13 – 2024/25, as derived from Landsat 7, 8 and 9 optical imagery. The green shaded regions denote the 9-year hiatus in surface meltwater export, and the blue shaded region marks the subsequent reactivation of lateral surface meltwater export from the ice shelf. For all panels, x-axis tick marks denote April-March melt seasons for RACMO2.3p2 and ERA5 data (e.g. 1981 = Apr 1980-Mar 1981), and November-March seasons for total annual maximum lake areas. Additional grey dashed and dotted lines in (b) denote two published MOA thresholds: 0.7 (Melchior Van Wessem et al., 2023; Pfeffer et al., 1991) and 0.85 (Donat-Magnin et al., 2021). The dashed and shaded line in (c) marks the T_{2m} threshold of –10.7 ± 0.3 °C, as calculated by (Melchior Van Wessem et al., 2023).*

Given projected warming on the Antarctic Peninsula under a range of 21st-century climate scenarios, it is increasingly pertinent to consider how Bach's surface meltwater network will respond. In this context, our cumulative surface meltwater extents (Fig. 1) partially intersect

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regions that are both vulnerable to hydrofracture and provide active buttressing, as identified by Lai et al. (2020). Continued surface melting may therefore drive hydrofracture in these regions and promote both ice-shelf weakening and broader ice-sheet instability.

4. Concluding Remarks

Ultimately, whether lateral surface meltwater export continues on Bach Ice Shelf depends on the balance between snowmelt and accumulation, and therefore on future variations in T_{2m}. The end of the nine-year hiatus in lateral surface meltwater export may indicate a transition toward climatic conditions in which SMB no longer provides an effective buffer against surface melt (Veldhuijsen et al., 1983). Moreover, while annual mean temperatures on the ice shelf currently ensure that snowfall dominates the precipitation regime, further increases in T_{2m} could lead to more frequent rain-on-snow events (Vignon et al., 2021). These events may promote additional firn saturation and intensify surface meltwater expression, reinforcing the positive melt–albedo feedback.

The consequences of increased ponding and/or lateral surface meltwater export on Bach Ice Shelf are several-fold: meltwater ponds promote ice-shelf flexure and fracture and may drive ice-shelf collapse in extreme cases. Further, a continuation of the observed lateral surface meltwater export (i) off the ice-shelf edge, and (ii) into the nascent rift system has the potential to drive ice-shelf thinning and promote ice-shelf calving events respectively. Given the anticipated climate warming across Antarctica, the reactivation of lateral surface meltwater export on Bach Ice Shelf may signal a shift toward conditions in which the buffering of meltwater by accumulated snow is progressively overwhelmed, increasing the likelihood of sustained meltwater export and reduced ice-shelf stability.

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Data Availability

All data processing scripts as well as maximum summer surface meltwater extents and rift extents will be made publicly available upon final publication via Github. ERA5 reanalysis is publicly available through the Climate Data Store (https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview). Statistically downscaled RACMO2.3p2 products are freely available upon request to Brice Noël (bnoel@uliege.be). The Bach Ice Shelf shapefile can be accessed at: https://doi.org/10.5285/4ecd795d-e038-412f-b430-251b33fc880e (Gerrish et al., 2024).

Author Contributons

RLD, MLM, and LT conceptualised the study, conducted formal analysis. RLD lead original draft preparation, supported by MLM. RLD conducted data visualisation. All authors contributed to data curation and reviewed and edited the manuscript.

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