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Key Points:

- The recent deceleration, thickening and advance of Greenland's largest outlet glacier, Jakobshavn Isbræ, was short-lived (2016–2018)
- The onset of re-acceleration preceded oceanic warming and was likely facilitated by a thinning-induced reduction in effective pressure
- Over winter 2020/21, sustained calving and elevated speeds were likely driven by a reduction in rigid mélange extent in the Ilulissat Icefjord

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

H. J. Picton,
hannah.picton@ed.ac.uk

Citation:

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A Reassessment of the Role of Atmospheric and Oceanic Forcing on Ice Dynamics at Jakobshavn Isbræ (*Sermeq Kujalleq*), Ilulissat Icefjord

H. J. Picton[1], P. W. Nienow[1], D. A. Slater[1], and T. R. Chudley[2]

[1]School of Geosciences, University of Edinburgh, Edinburgh, UK, [2]Department of Geography, Durham University, Durham, UK

Abstract Jakobshavn Isbræ (*Sermeq Kujalleq*) has been the largest single contributor to mass loss from the Greenland Ice Sheet over the past three decades. Previous research emphasizes the dominant role of oceanic forcing, with the recent advance, deceleration and thickening of Jakobshavn attributed to reduced ocean temperatures. Here, we use satellite imagery and remotely sensed data sets of ice surface velocity, ice surface elevation and ice discharge to extend observations of ice dynamics at Jakobshavn Isbræ between 2018 and 2023. We then use in situ oceanic and meteorological data, in combination with modeled estimates of surface runoff, to explore the potential role of climatic forcing over this 5-year period. Our results show that Jakobshavn began to re-accelerate in 2018, with mean annual near-terminus velocity increasing by 49% between 2018 and 2021. The onset of re-acceleration occurred prior to the arrival of warmer water, and was likely facilitated by the near-terminus being close to flotation and thus highly sensitive to reductions in effective pressure. Such reductions likely resulted from ice surface lowering, driven by both negative surface mass balance and dynamic thinning. During winter 2020/2021, ice velocities remained elevated, with sustained thinning and iceberg calving observed. This unusual behavior corresponded with a significant decrease in rigid mélange extent, likely driven by increased ocean temperatures observed in Disko Bay and Ilulissat Icefjord. This study thus further emphasizes the complexity of climatic forcing at the ice-ocean interface, highlighting that both oceanic *and* atmospheric forcing must be considered when projecting the future behavior of marine-terminating outlet glaciers.

Plain Language Summary Jakobshavn Isbræ (*Sermeq Kujalleq*) is Greenland's largest marine-terminating outlet glacier and has been losing mass rapidly over the past 30 years. The majority of research has suggested that ocean forcing controls ice dynamics at Jakobshavn, with recent deceleration and thickening linked to lower ocean temperatures. In this study, we extend observations of ice dynamics at Jakobshavn Isbræ between 2018 and 2023. We show that between 2018 and 2021, the mean annual speed at the near-terminus increased by nearly 50%. This rapid re-acceleration was initiated before the arrival of warmer water and was likely promoted by glacier thinning, whereby a reduction in the weight of overlying ice enabled the glacier to slide over the bed more easily. Typically, Jakobshavn slows and advances during winter as a rigid mélange forms adjacent to the terminus and inhibits calving. However, over the winter of 2020/2021, ice velocities remained elevated and iceberg calving was sustained, preventing the terminus from advancing down-fjord. We attribute this atypical winter behavior to a concurrent reduction in rigid ice mélange within the Ilulissat Icefjord, likely driven by higher ocean temperatures. We thus emphasize that both oceanic *and* atmospheric forcing must be considered when projecting future ice dynamics at marine-terminating outlet glaciers.

1. Introduction

The Greenland Ice Sheet (GrIS) is drained by ∼280 fast-flowing marine-terminating outlet glaciers (Catania et al., 2020). Dynamic change across these tidewater glaciers accounted for ∼50% of total mass loss from the GrIS between 1992 and 2018, contributing an estimated eustatic sea level equivalent (SLE) of 10.8 ± 0.9 mm (The IMBIE Team, 2020). Situated at the ice-ocean interface, such glaciers are dynamically sensitive to both oceanic and atmospheric conditions. The role of oceanic forcing has been investigated over recent decades, with the enhanced intrusion of relatively warm Atlantic Water widely implicated as the primary driver of the widespread retreat observed across Greenland's tidewater glaciers since the mid-1990s (Straneo & Heimbach, 2013; Wood et al., 2021). However, more recent studies have recognised the complexity of ice-ocean-atmosphere interactions

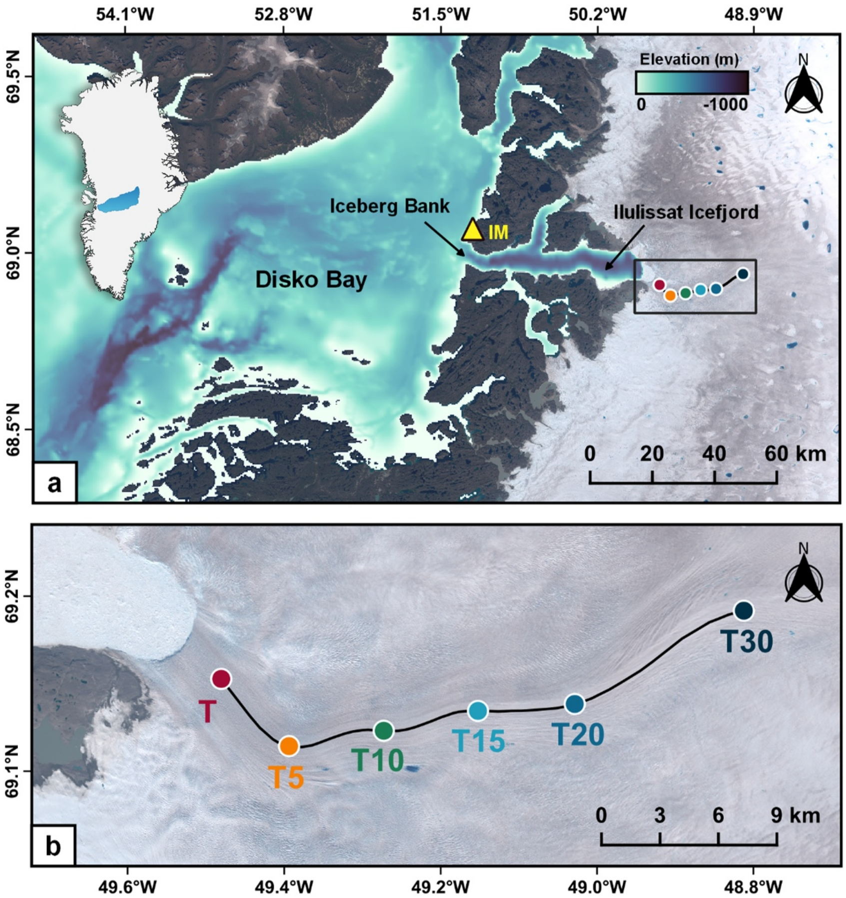

Figure 1. (a) Location map of Disko Bay, Iceberg Bank, and Ilulissat Icefjord. The International Bathymetric Chart of the Arctic Ocean (IBCAO) (Jakobsson et al., 2020) is displayed and accessed using QGreenland (Fisher et al., 2022; Moon et al., 2022). The inset box is positioned over the primary flow of Jakobshavn Isbræ (panel b). Inset map of Greenland shows the main hydrological basin of Jakobshavn Isbræ, highlighted in blue. Location of Ilulissat Mittarfik (IM) meteorological station is also shown. (b) Centerline digitised along the primary flow of Jakobshavn Isbræ, with sampling locations displayed; T is positioned immediately upstream of the minimum observed terminus position, whilst T5, T10, T15, T20, and T30 are positioned 5, 10, 15, 20 and 30 km along the centerline, respectively. Background satellite imagery displayed in both (a) and (b) is a Sentinel-2 image mosaic from 2019 (MacGregor et al., 2020) accessed using QGreenland (Fisher et al., 2022; Moon et al., 2022).

(Cowton et al., 2018; Fahrner et al., 2021; Mankoff et al., 2016; Motyka et al., 2013), with Slater and Straneo (2022) noting that increased atmospheric temperatures can enhance rates of submarine melting, even in the absence of oceanic warming. With ice dynamics also influenced by internal factors, such as fjord geometry (Åkesson et al., 2018) and bed topography (Catania & Felikson, 2022; Enderlin et al., 2013; Herzfeld et al., 2012), tidewater glaciers often exhibit heterogeneous behavior at local scales (Catania et al., 2018; Williams et al., 2021). Improving our understanding of ice dynamics across Greenland's outlet glaciers, particularly those contributing disproportionately to mass loss (Enderlin et al., 2014; Mouginot et al., 2019), is therefore critical in order to inform future projections of sea level rise (Beckmann et al., 2019).

1.1. Jakobshavn Isbræ—Background

Jakobshavn Isbræ (Greenlandic: *Sermeq Kujalleq*) holds a SLE of 0.6 m (An et al., 2017) and has been the greatest single contributor to mass loss from the GrIS over recent decades, losing 327 ± 40 Gt of ice between 1972 and 2018 (Mouginot et al., 2019). The fast-flowing outlet glacier, situated in central west Greenland, terminates in Ilulissat Icefjord (*Ilulissat Kangerlua*; Figure 1), a deep fjord basin renewed by water originating from Disko Bay (*Qeqertarsuup tunua*; Gladish, Holland, Rosing-Asvid, et al., 2015). Disko Bay is influenced by two major ocean currents, the West Greenland Current (WGC) and the Baffin Current (Gladish, Holland, & Lee, 2015). A flat-topped bathymetric sill located at the mouth of Ilulissat Icefjord, Iceberg Bank (or *Isfjeldsbanken*) (Schumann et al., 2012), exerts a significant control on the properties of water entering the fjord (Gladish, Holland, & Lee, 2015). With a maximum depth of 245 m (Beaird et al., 2017), this sill inhibits the intrusion of the warmest subsurface waters of the WGC (Gladish, Holland, & Lee, 2015), sourced from the North Atlantic via the Irminger Current (IC) (Wangner et al., 2018). Nonetheless, benthic foraminiferal data shows that the frontal position of Jakobshavn has been closely correlated with subsurface ocean temperatures over centennial (Lloyd et al., 2011) and millennial (Wangner et al., 2018) timescales. Indeed, research consistently emphasizes that oceanic forcing has played a critical role in controlling contemporary ice dynamics at Jakobshavn Isbræ (Holland et al., 2008; Joughin et al., 2020; Khazendar et al., 2019; Motyka et al., 2011; Muresan et al., 2016).

1.2. Jakobshavn Isbræ—Contemporary Ice Dynamics

Jakobshavn Isbræ was generally stable throughout the 1990s (Howat et al., 2011), with a consistent ice velocity of 5.7 km/yr between 1992 and 1997 (Joughin et al., 2004). However, in 1998, the lower regions of Jakobshavn began to accelerate and thin rapidly (Luckman & Murray, 2005; Thomas et al., 2003), doubling in speed to reach a velocity of 11.9 km/yr by summer 2002 (Joughin et al., 2004). Whilst Van der Veen et al. (2011) attributed this rapid acceleration to lateral shear margin weakening, the dramatic switch in ice dynamics has been more widely attributed to the intrusion of warmer Atlantic water into Disko Bay in spring 1997 (Holland et al., 2008), with subsurface ocean temperatures increasing from 1.30 to 2.25°C (Hansen et al., 2012). Such increased oceanic thermal forcing is thought to have enhanced submarine melting of Jakobshavn's floating tongue (Motyka et al., 2011) with high average thinning rates of 80 m/yr (1997–2001; Thomas, 2004), forcing the ungrounding of previously stabilizing ice rumples (Thomas et al., 2003). The ensuing terminus retreat led to the eventual disintegration of Jakobshavn's floating tongue by May 2003 (Joughin et al., 2004; Podlech & Weidick, 2004), thus removing a significant backstress formerly exerted against glacier flow. The northern and southern branches of Jakobshavn subsequently disconnected, with Jakobshavn hereafter used to refer to the primary southern ice stream.

Over the next decade, Jakobshavn was observed to retreat, accelerate and thin in response to the break-up of Jakobshavn's floating tongue (Bondzio et al., 2017; Joughin et al., 2020; Khazendar et al., 2019), with variations in the ice front position exerting a dominant control on ice flow (Bondzio et al., 2017; Cassotto et al., 2019). A pronounced seasonal velocity cycle also developed, with ice velocity observed to peak in summer 2012, when the terminus reached ∼17.5 km/yr (Joughin et al., 2020). Between 2013 and 2016, the average ice velocity decreased slightly (Khazendar et al., 2019; Lemos et al., 2018; Mankoff, Solgaard, et al., 2020), although the magnitude of seasonal velocity variation remained high (Joughin et al., 2020; Riel et al., 2021).

Over the winter of 2016/2017, ice velocity near the terminus of Jakobshavn began to decelerate (Lemos et al., 2018), with a maximum speed of ∼10 km/yr observed during summer 2017 (Joughin et al., 2018). Jakobshavn transitioned to a period of net annual thickening over the next 2 years (2016–2018; Khazendar et al., 2019), with the terminus advancing ∼6 km further than any winter since 2008–2009 (Joughin et al., 2020). For the first time in several decades, Helheim Glacier (*Helheim Gletsjer*) thus usurped Jakobshavn Isbræ as the largest single contributor to mass loss from the GrIS in early 2018 (Mankoff, Solgaard, et al., 2020). Such a dramatic switch in ice dynamics has been widely attributed to reduced oceanic thermal forcing, with subsurface ocean temperatures in Disko Bay estimated to have decreased by ∼ 2°C between 2014 and 2016 (Khazendar et al., 2019). This effectively represented a reversal of the oceanic warming postulated to have previously triggered the extensive retreat, acceleration and thinning of Jakobshavn Isbræ in 1997.

Whilst oceanic forcing has been recognised as an important control on ice dynamics at Jakobshavn (Holland et al., 2008; Lloyd et al., 2011; Motyka et al., 2011; Muresan et al., 2016; Wangner et al., 2018), debate regarding the specific mechanism through which such oceanic forcing exerts an influence has become more nuanced in recent years. Khazendar et al. (2019) emphasize the role of submarine melting, suggesting that the reduction in subsurface ocean temperatures within Disko Bay, in combination with reduced subglacial discharge, likely led to a reduction in the dynamic component of thinning. However, Joughin et al. (2020) instead highlight the role of reduced ocean temperatures on increasing the rigidity of mélange observed proximal to the glacier front. Such ice mélange has been shown to suppress calving and thus influence glacier flow (Amundson et al., 2010; Cassotto et al., 2015; Krug et al., 2015; Xie et al., 2019), facilitating deceleration and thickening (Joughin et al., 2020). Jakobshavn Isbræ therefore exemplifies the difficulty faced when attempting to disentangle the complex interplay of atmospheric and oceanic processes influencing contemporary marine-terminating margins (Jackson, 2019).

In this paper, we use satellite imagery and remotely sensed data sets to extend observations of ice dynamics at Jakobshavn Isbræ between 2018 and 2023. We provide timeseries of key glaciological parameters, analyzing variations in ice surface velocity, ice surface elevation, ice discharge, terminus position, and rigid mélange extent. Using a combination of hydrographic data obtained from conductivity-temperature-depth (CTD) sensors, surface air temperature data measured at a local weather station, and modeled estimates of surface runoff, we then explore the potential influence of oceanic and atmospheric forcing on ice dynamics at Jakobshavn Isbræ over this most recent 5-year period.

2. Data and Methods

2.1. Ice Surface Velocity

A timeseries of ice surface velocity was obtained for Jakobshavn Isbræ using NASA's MEaSUREs Inter-Mission Time Series of Land Ice Velocity and Elevation (ITS_LIVE) Sentinel-1 image-pair products (Lei, Gardner, Kennedy, et al., 2022). Each image-pair velocity product was processed using the "*autoRIFT*" offset tracking module at 120 m resolution (Lei, Gardner, & Agram, 2022). The velocity magnitude uncertainty varies spatially but averages ∼61 m/yr within the Jakobshavn region (Lei, Gardner, & Agram, 2022). As short temporal baselines are preferred in regions of fast ice-flow (Friedl et al., 2021; Solgaard et al., 2021), we sampled all available 6-day and 12-day image-pair velocities between 2018 and 01-01 and 2022-12-31. Ice velocity was then extracted at six point locations along the centerline of Jakobshavn Isbræ; T was positioned immediately upstream of the minimum observed terminus position, whilst T5, T10, T15, T20, and T30 were positioned 5, 10, 15, 20, and 30 km along the centerline, respectively (Figure 1).

2.2. Ice Surface Elevation

A timeseries of ice surface elevation was obtained using ATL15 (Smith, Sutterley, et al., 2023), a gridded data set of ice sheet surface height change derived from the ATLAS/ICESat-2 L3B Slope-Corrected Land Ice Height Time Series product (ATL11; Smith, Dickinson, et al., 2023). ATL15 provides height-change maps at 3-month intervals, with each surface height calculated relative to 01/01/2020. The data set was downloaded at a spatial resolution of 1 km. As the accuracy of the surface height estimates is determined by the spatial coverage of the ICESat-2 tracks, we sampled ice surface elevation at the point at which the "*data_count*" was highest (T15; Figure 1).

Ice surface elevation was also derived using 2-m resolution ArcticDEM strips (Porter et al., 2022). These strips were downloaded and co-registered using the *pDEMtools* software package (Chudley & Howat, 2024). Co-registration was performed against the ArcticDEM v4.1 mosaic (Porter et al., 2023) following the method of Nuth and Kääb (2011), with the bedrock mask from BedMachine v5 (Morlighem et al., 2022) being used to identify stable terrain. All strips were geoid-corrected using the EIGEN-6C4 geoid (Foerste et al., 2014). Due to significant variations in the availability of ArcticDEM strips covering Jakobshavn between 2018 and 2023, we selected one strip per year, prioritizing the strip that most closely aligned with the mid-date of that respective year (Table S1 in Supporting Information S1). Each strip was sampled at 2 m intervals along the near-terminus section of the centerline (Figure S1 in Supporting Information S1). In order to allow subsequent assessment of the relative contributions of surface mass balance (SMB) and dynamic processes to any observed changes in ice surface elevation, we also applied the same methodology to a nearby land-terminating margin (Figure S1 and Table S1 in Supporting Information S1). Changes in ice surface elevation across such land-terminating glaciers predominantly reflect variations in the local SMB (Sole et al., 2008) and can thus be used to provide a robust assessment of this component of elevation change (Tepes et al., 2021).

2.3. Ice Discharge

Estimated solid ice discharge from Jakobshavn Isbræ was extracted from Mankoff, Solgaard, and Larsen (2020). This data set provides estimates of ice discharge and associated uncertainty through algorithmically generated gates located 5 km upstream from the baseline terminus of all fast-flowing ice (>100 m/yr; Mankoff, Solgaard, et al., 2020). Following Mankoff, Solgaard, et al. (2020), we did not include any discharge estimates derived where data coverage across the gate of Jakobshavn Isbræ was <50%.

2.4. Terminus Position

Black and Joughin (2022) have previously manually digitised the terminus position of Jakobshavn Isbræ at a weekly (6-day) resolution between 2015 and 01-01 and 2021-12-31, using Sentinel-1A and Sentinel-1B synthetic aperture radar (SAR) mosaics (Joughin, 2021; Joughin et al., 2016). In order to extend this timeseries to 2022-12-31, we carried out the same manual digitization procedure as Black and Joughin (2022), also employing SAR mosaics downloaded from the National Snow and Ice Data Center (NSIDC; Joughin, 2021). Due to the failure of Sentinel-1B on 2021-12-23, these most recent terminus positions were instead sampled at 12-day resolution (Table S2 in Supporting Information S1). As outlined by Black and Joughin (2023), the uncertainty associated with such manually digitised front positions is typically 25 m; this may however be higher at heavily crevassed termini or at tidewater glaciers which discharge into adjacent mélange or sea ice.

Once digitised, the terminus position change was quantified using the curvilinear box method, applied using MaQiT (Margin change Quantification Tool; Lea, 2018). Here, an open-ended box with a fixed width is positioned across the glacier, extending upstream to an arbitrary reference line. Each digitised terminus position effectively 'closes' this open-ended box; the difference in box area between two given digitizations is then divided by the fixed box width to produce a width-averaged linear change in the terminus position. We use a curvilinear rather than a rectilinear box to allow for the non-linear fjord geometry of the Ilulissat Icefjord to be incorporated (Figure 1).

2.5. Rigid Mélange Extent

The presence of a rigid ice mélange proximal to the terminus of Jakobshavn Isbræ is postulated to exert a significant control on calving behavior and thus influence ice dynamics, but has only been assessed previously using a binary presence/absence classification (Joughin et al., 2020). Here, we provide an estimate of the extent of the proglacial rigid mélange at monthly intervals using the ITS_LIVE 6- and 12-day image-pair velocities between 2018 and 01-01 and 2022-12-31 (Lei, Gardner, Kennedy, et al., 2022). Such velocity pairs can be used to identify rigid mélange (Bevan et al., 2019; Chudley et al., 2023; Kehrl et al., 2017) based on the assumption that a rigid mélange will maintain coherence and hence can be observed as a uniform velocity field when feature tracking is applied. In contrast, the individual constituents of a non-rigid mélange will move randomly relative to each other, thereby preventing a coherent velocity signal from being observed.

If observed, the extent of the proglacial rigid mélange was quantified by measuring the distance between the outermost continuous limit of the rigid ice mélange with the contemporaneous terminus position of Jakobshavn Isbræ, along an extended central flowline (Figure S2 in Supporting Information S1). The rigid mélange and frontal terminus position were considered to be contemporaneous if the date of the SAR image from which the terminus position was manually digitised fell within the dates covered by the 6-day or 12-day ITS_LIVE image-pair. However, it should be noted that such feature-tracking algorithms are only able to capture rigid mélange that remains coherent across the two successive images used within the image-pair (Bevan et al., 2019). Due to the failure of Sentinel-1B on 2021-12-23, the rigid mélange sustained for <12 days will thus not have been captured during the final year of the study period.

2.6. Surface Runoff

Daily estimates of surface runoff across the main hydrological basin of Jakobshavn Isbræ (Figure 1) were extracted from Mankoff (2020). These estimates were derived from two regional climate models (RCMs) (Mankoff, Noël, et al., 2020): (a) Modèle Atmosphérique Régional (MAR; Fettweis et al., 2017), and (b) Regional Atmospheric Climate Model (RACMO; Noël et al., 2019). MAR and RACMO were run at resolutions of 7.5 and 5.5 km, respectively, however both RCM outputs have been statistically downscaled to a higher gridded resolution of 1 km (Fettweis et al., 2020; Noël et al., 2016). The estimated surface runoff has an uncertainty of ±15% (Mankoff, Noël, et al., 2020).

2.7. Air Temperature

A near-continuous record of daily surface air temperature was downloaded from Ilulissat Mittarfik (IM) (Figure 1), provided by the Danish Meteorological Institute (Jensen, 2023). Observations were sampled at three-hour intervals, with daily mean surface air temperatures calculated if there were more than four observations within a single day. Monthly mean surface air temperatures were then computed when there were at least 25 daily observations within a given month. For the study period, monthly surface air temperature anomalies were calculated relative to the 1992–2018 mean.

2.8. Ocean Temperature

Ilulissat Icefjord is often congested with icebergs and rigid mélange, making the fjord inaccessible to ships for most of the year (Kajanto et al., 2023). Observations of subsurface ocean temperatures within the fjord are therefore primarily limited to those measured using airborne expendable CTD (AXCTD) instruments jettisoned from aircraft (Gladish, Holland, Rosing-Asvid, et al., 2015), or those transmitted from instrumented seals (Mernild et al., 2015). As part of NASA's Oceans Melting Greenland (OMG) project, four AXCTD probes were deployed in Ilulissat Icefjord during the study period (Fenty et al., 2016; OMG, 2019), in either August or September. We extracted profiles of both temperature and salinity from each of these probes, thereby providing insights into the oceanic conditions at Jakobshavn Isbræ between 2019 and 2021.

In order to derive a more complete timeseries of ocean temperature, we also employed CTD data collected in the adjacent Disko Bay (Figure 1; specific locations shown in conjunction with data in Figure 8), as utilized in previous research (e.g., Joughin et al., 2020; Khazendar et al., 2019). Analysis by Gladish, Holland, Rosing-Asvid, et al. (2015) indicates that Iceberg Bank (Figure 1) exerts a significant control on fjord-shelf water exchange, with water properties at depth (>300 m) in the Illulissat Icefjord basin typically corresponding with those observed at intermediate depths (100–300 m) within Disko Bay. As Iceberg Bank has a maximum depth of 245 m (Beaird et al., 2017), we sampled all available CTD data from Disko Bay at a depth of 240 m. If not provided, depth was calculated from pressure measurements, using the *gsw_z_from_p* function defined by the Gibbs SeaWater Oceanographic Toolbox (McDougall & Barker, 2011).

The CTD measurements collected in Disko Bay were all obtained as part of either (a) the Greenland Ecosystem Monitoring (GEM) program (GEM, 2024) or (b) NASA's OMG project (Fenty et al., 2016). The GEM program has collected repeat CTD measurements near the coast of Disko Island from February 2018 (Topp-Jørgensen et al., 2019), whilst the OMG project deployed three autonomous floats in Disko Bay during the study period: (a) APEX F9184 (September 2020), (b) ALAMO F9250 (April 2021), and (c) ALAMO F9313 (August 2022) (OMG, 2021, 2022).

3. Results

3.1. Jakobshavn Isbræ Ice Dynamics (2018–2023)

3.1.1. Ice Surface Velocity

Between 2018 and 2022, Jakobshavn Isbræ was observed to re-accelerate, with the mean annual ice surface velocity across the near-terminus region (T) increasing from 7.9 to 11.8 km yr^{-1} (Figure 2a). This acceleration was sustained over the 4-year period, with year-on-year increases in mean annual velocity of 13.6%, 9.9%, and 19.0%, respectively. Ice speed was characterized by substantial seasonal variability during this period; in 2019, ice velocity increased from a minimum of 6.8 km yr^{-1} (2019-04-21) to a maximum of 10.8 km yr^{-1} (2019-07-05) and in 2020, ice velocity increased from 7.2 km yr^{-1} (2020-03-25) to 13.8 km yr^{-1} (2020-08-04). However, after a brief period of deceleration between August and September 2020, ice velocity then stabilized between September 2020 and January 2021. During this 3-month period, mean ice velocity was 11.0 km yr^{-1}, exceeding the peak summer velocity previously observed in 2019. This unusual period of wintertime stabilization was also recorded at T5, was particularly distinct at T10 (Figure S3 in Supporting Information S1) and at T15, ice velocity

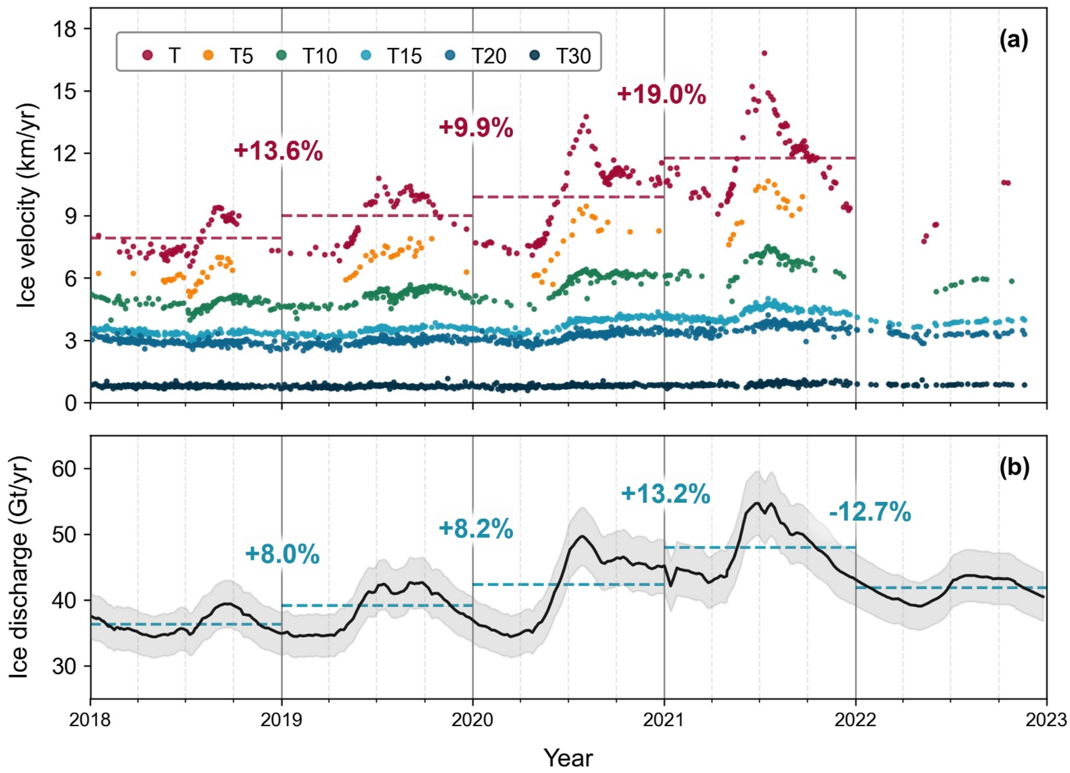

Figure 2. (a) Ice surface velocity at T, T5, T10, T15, T20, and T30, sampled from NASA's MEaSUREs ITS_LIVE 6-day and 12-day image-pair velocities (Lei, Gardner, Kennedy, et al., 2022). Red dashed lines show the mean annual ice surface velocity at T for each year, and the corresponding year-on-year percentage change is also given. Note that the mean annual ice surface velocity is not shown for 2022 due to the limited data availability. (b) Estimated solid ice discharge from Jakobshavn Isbræ, extracted from Mankoff, Solgaard, and Larsen (2020), with the shaded area representing the associated uncertainty. Blue dashed lines represent the mean ice discharge for each given year and the corresponding year-on-year percentage change is also given.

was even seen to increase, rising from 3.9 km yr^{-1} (2020-09-02) to 4.3 km yr^{-1} (2021-01-04) (Figure S3 in Supporting Information S1).

Following the delayed onset of winter deceleration at the terminus (Figure 2a), ice surface velocity reached an annual minimum of 9.1 km yr^{-1} (2021-04-13). As observed in 2020, rapid acceleration then occurred; ice surface velocity increased by 85%, reaching a peak of 16.8 km yr^{-1} (2021-07-11). However, in contrast to the previous year, deceleration was sustained throughout the autumn and winter months. Whilst coherent data coverage over the near-terminus region was scarce in 2022, observations from T10, T15, T20 and T30 show that the ice surface velocity decreased at a consistent rate between July 2021 and April 2022 (Figure S3 in Supporting Information S1).

3.1.2. Ice Surface Elevation

At T15, ice surface elevation was estimated to increase by 1.2 m between October 2018 and March 2019 (2.4 m/yr; Figure 3). Ice surface lowering then occurred between March and October 2019 with the surface height decreasing by 4.0 m (8.0 m/yr). Following a period of stabilization, surface lowering resumed from March 2020. However, in contrast to the two previous winters, such ice surface lowering continued beyond October, being sustained throughout the winter of 2020/2021. The magnitude of thinning was high, with ice surface elevation estimated to decrease by 21.1 m between March 2020 and January 2022 (12.1 m/yr). In 2022, this pattern was reversed and minor thickening was observed, with ice surface elevation estimated to increase by 2.4 m between January 2022 and January 2023.

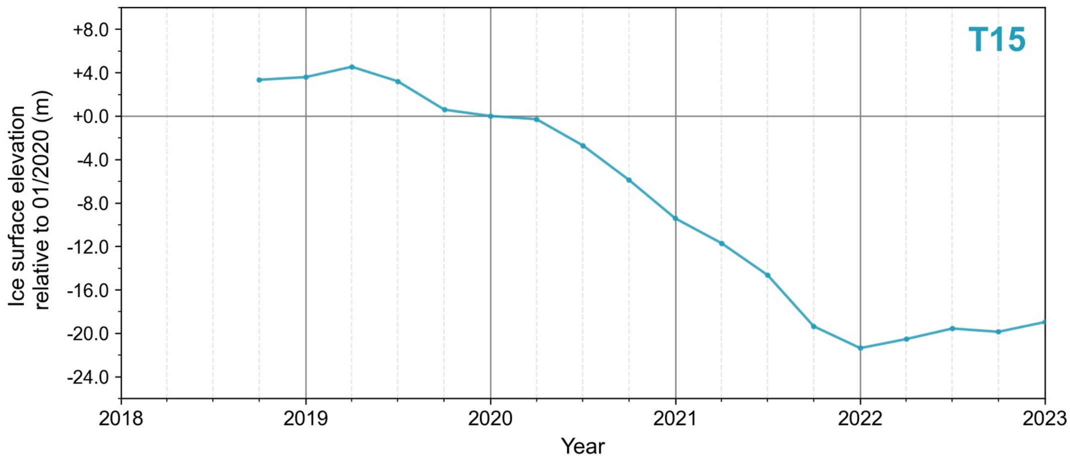

Figure 3. Ice surface elevation at T15 relative to January 2020. Ice surface elevation extracted from ATL15 (Smith, Sutterley, et al., 2023) with observations provided at 3-month intervals.

Further analysis of ArcticDEM profiles shows that in 2018 (2018-06-27), the surface elevation of the near-terminus region (~0.5 km) of Jakobshavn Isbræ was less than the estimated height of flotation, indicating that the calving front was afloat (Figure 4). The terminus was also estimated to be at flotation in both May 2020 (2020-05-07) and May 2022 (2022-05-26) (Figure 4), with subsequent sustained calving observed on both occasions (Figure 5).

In contrast, in both June 2019 (2019-06-08) and June 2021 (2021-06-04), the surface elevation of the near-terminus region exceeded the estimated height of flotation, indicating that the calving front was grounded (Figure 4). The ice surface elevation profiles from June 2019 (2019-06-08) and May 2022 (2022-05-26), when the terminus was located in a near-identical position, reveal pronounced thinning over the lower 6.6 km of Jakobshavn Isbræ, averaged at ~29 m (Figure 4).

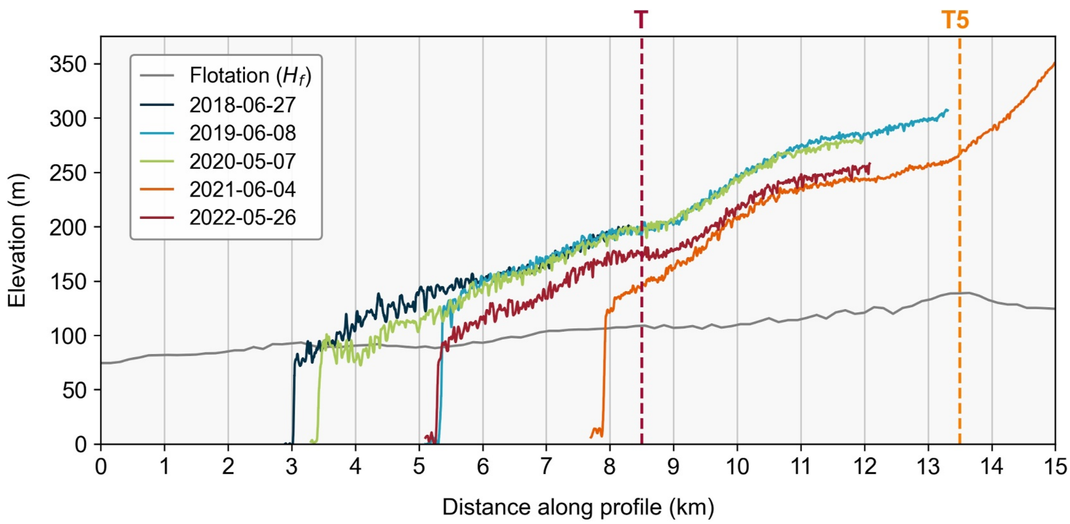

Figure 4. Ice surface elevation profiles along the near-terminus centerline of Jakobshavn Isbræ (Figure S1 in Supporting Information S1), sampled from ArcticDEM 2-m resolution strips (Porter et al., 2022). Height of flotation (H_f) is also shown and estimated using BedMachine v5 bed topography (Morlighem et al., 2017, 2022); the density of ice and seawater is assumed to be 917 and 1,025 kg m^{-3}, respectively. Dashed red and orange vertical lines show the along-profile locations of T and T5, respectively.

3.1.3. Ice Discharge

As expected, the variability in solid ice discharge from Jakobshavn Isbræ shows a close correlation with the observed variability in ice surface velocity over the study period (Figure 2); year-on-year increases in mean annual discharge were observed between 2018 and 2021, calculated at 8.0%, 8.2%, and 13.2%, respectively (Figure 2b). In 2020, ice discharge increased by 41% between 2020 and 04-24 and 2020-07-31, rising from 35.1 to 49.6 Gt yr^{-1}. Following a typical decrease in ice discharge during August, the rate of decline decelerated over the winter of 2020/2021, concurrent with the unusual stabilization in ice velocity (Figure 2a). As a result, the minimum rate of ice discharge recorded over winter 2020/2021 (42.1 Gt yr^{-1}) was comparable to the *maximum* rate recorded in 2019 (42.7 Gt yr^{-1}) (Figure 2b). High velocities observed in early 2021 (Figure 2a), in combination with the subsequent summer acceleration, thus resulted in the mean annual ice discharge peaking at 48.0 Gt yr^{-1} (Figure 2b), reflecting a 32.2% increase relative to 2018. A sustained decrease in ice discharge was then observed during the winter of 2021/2022, with a minimum rate of 39.1 Gt yr^{-1} recorded (2022-05-01). The increase in ice discharge over the subsequent summer was small, with a maximum rate of just 43.7 Gt yr^{-1} observed (2022-08-03).

3.1.4. Terminus Position

In 2018 and 2019, the terminus of Jakobshavn Isbræ exhibited a typical seasonal pattern (Black & Joughin, 2023), advancing to a maximum late "winter" position in April, before retreating over-summer by ~4.5 and 4.0 km, respectively (Figure 5). During the "winter" of 2020/2021, however, this cyclical pattern was disrupted, with frequent calving events seen between October 2020 and March 2021. As a result, Jakobshavn failed to advance significantly, with the terminus instead observed to be quasi-stationary from September to April. Ensuing retreat between April and June 2021 (~3.0 km) resulted in Jakobshavn reaching its most retreated position seen during the study period, ~6.8 km up-fjord of the most advanced position in April 2018. Following a significant calving 'event' between 2021 and 09-16 and 2021-09-22, Jakobshavn then resumed sustained advance over the winter of 2021/2022, advancing ~3.3 km down-fjord between October 2021 and March 2022. In 2022, Jakobshavn reached its most retreated position on 2022-08-06, before advancing once more between August and December (~2.3 km).

Short-term variations in terminus position and behavior are also reflected in the terminus profiles in relation to the height of flotation. For example, in 2018 (2018-06-27), when the near-terminus region was less than the estimated height of flotation (Figure 4), the terminus experienced a period of pronounced calving over the subsequent 61 days, retreating ~2.8 km (Figure 5). Similar sustained calving and retreat was also observed after the terminus was estimated to be at flotation in May 2020 (2020-05-07) and May 2022 (2022-05-26) (Figure 4; 5). In contrast, when the terminus was observed to exceed the estimated height of flotation (Figure 4), the terminus underwent minimal subsequent calving in 2019 (2019-06-08), while in 2021 (2021-06-04), the terminus advanced ~1 km over the subsequent 26 days (Figure 5).

3.1.5. Rigid Mélange Extent

In 2018 and 2019, the formation and disintegration of rigid mélange proximal to the terminus of Jakobshavn Isbræ followed a clear seasonal pattern; the rigid mélange formed over the late summer and early autumn, persisted throughout the winter and then disintegrated rapidly during April/May (Figure 5). In 2020, however, increasing rigid mélange extent was not sustained over the autumnal months. As a result, the rigid mélange extent observed in September 2020 (~3.7 km) was markedly lower than in September 2018 (~16.0 km) and September 2019 (~24.7 km), respectively. Whilst the rigid mélange extent increased in November 2020, a further atypical mid-winter episode of mélange disintegration was observed between December 2020 and January 2021. The maximum winter extent was subsequently reached in February 2021, extending ~28.0 km down-fjord. This rigid mélange persisted until April, before disintegrating once more.

In Autumn 2021, atypical mélange disintegration was observed between August and September; however, in contrast to the previous year, the rigid mélange then reformed, extending ~24.3 km down-fjord by November. The mélange persisted for a relatively short period, with gradual disintegration seen throughout January–April 2022. An absence of rigid mélange was then observed for a prolonged duration in 2022, persisting for nearly the entirety of May–October. Nonetheless, rigid mélange reformed rapidly between October and November, extending ~27.3 km down-fjord.

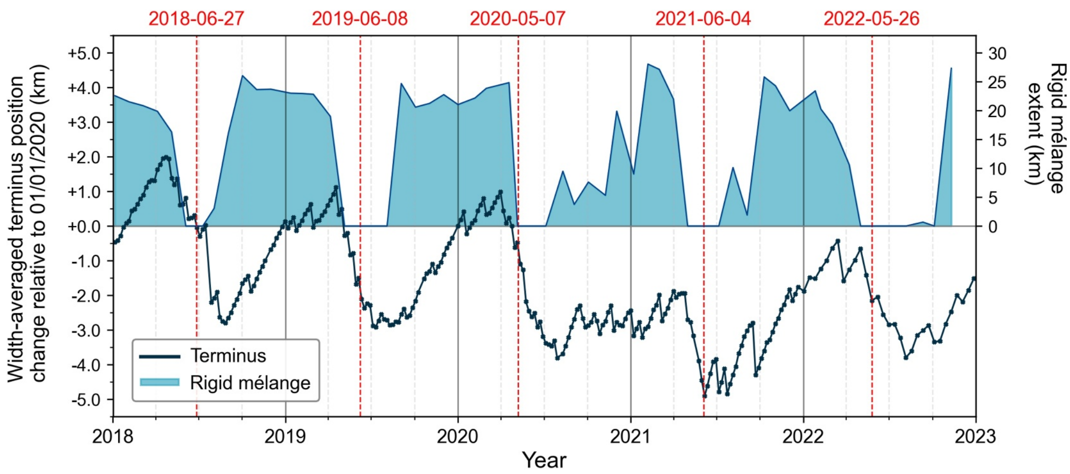

Figure 5. Width-averaged terminus position change relative to 01/01/2020. Note that terminus positions plotted between 2018-01-01 and 2021-12-31 were provided by Black and Joughin (2022). The extent of the proglacial rigid mélange is also shown, measured along an extended central flowline at monthly resolution (Figure S2 in Supporting Information S1). For reference, the labeled dashed vertical red lines correspond to the date of acquisition of each respective ice surface elevation profile shown in Figure 4.

3.2. Jakobshavn Isbræ Climatic Forcing (2018–2023)

3.2.1. Atmospheric Forcing

In 2018, negative surface air temperature anomalies were sustained between May and November (Figure 6), with the annual surface runoff estimated at 5.8 × 10^9 m^3 by RACMO, and 7.3 × 10^9 m^3 by MAR (Figure 7b). Whilst the absolute magnitude of surface runoff estimated using RACMO was consistently lower than that estimated by MAR, the timing of peak events was similar across both RCMs (Figure 7a). In 2019, positive surface air temperature anomalies were recorded across most of the year, exceeding +3.0°C in February, April, May and November (Figure 6). As a result, surface runoff increased significantly; the estimated annual cumulative runoff ranged from 1.2 × 10^{10} m^3 (RACMO) to 1.6 × 10^{10} m^3 (MAR)

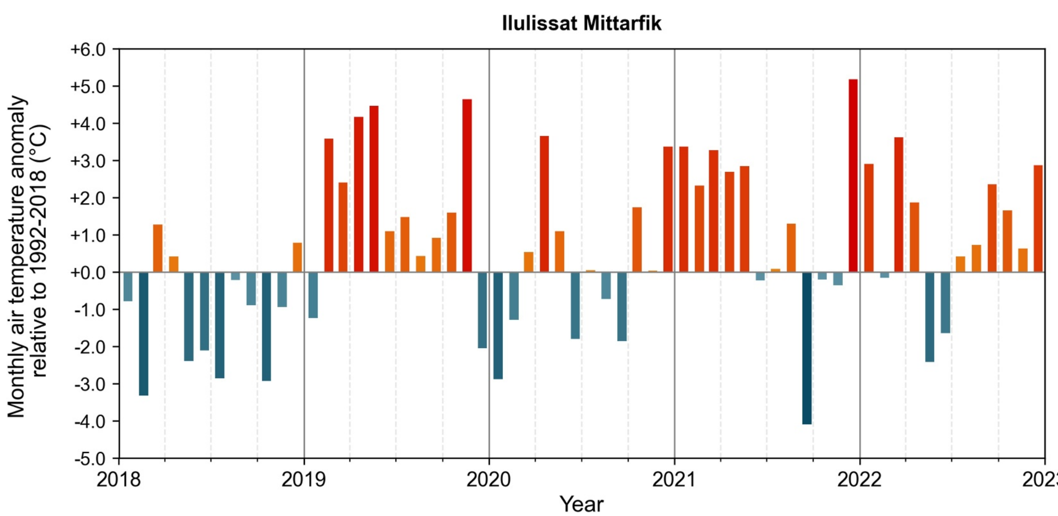

Figure 6. Monthly surface air temperature anomalies observed at Ilulissat Mittarfik (IM), calculated relative to the 1992–2018 monthly means. Air temperature data provided by the Danish Meteorological Institute (Jensen, 2023). Note that red colors represent positive surface air temperature anomalies, whilst blue colors reflect negative surface air temperature anomalies.

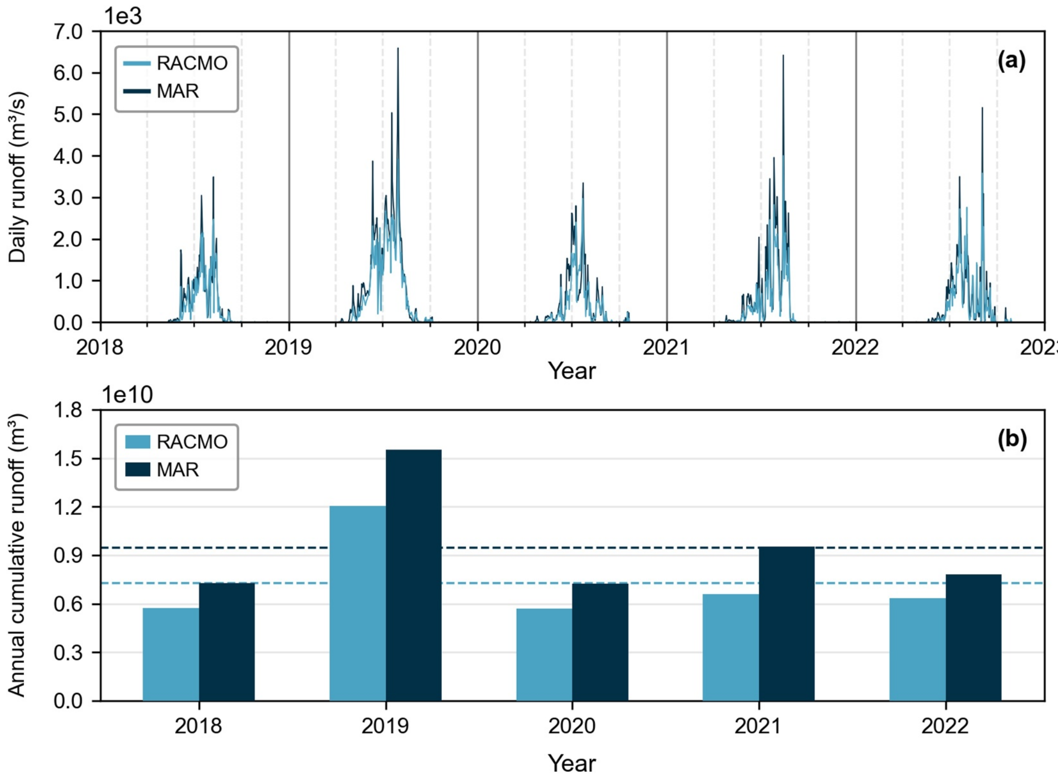

Figure 7. (a) Estimated daily surface runoff and (b) annual cumulative surface runoff from both RACMO (Noël et al., 2019) and MAR (Fettweis et al., 2017), across the main hydrological basin of Jakobshavn Isbræ. Dashed lines in (b) represent the mean annual cumulative runoff between 2018 and 2023, calculated for RACMO and MAR respectively. Note that all RCM outputs were extracted from Mankoff (2020).

(Figure 7b), representing an increase of 110% and 114%, respectively, relative to 2018. Daily runoff peaked on 2019-07-31 (MAR), exceeding an estimated 6,500 m^3 s^{-1} (Figure 7a). Further high magnitude peaks in daily runoff were also recorded on 2021-08-14 and 2022-09-03 (Figure 7a); however, the estimated annual cumulative runoff was relatively consistent across 2020, 2021, and 2022, remaining between 39% and 53% lower than in 2019 (Figure 7b).

3.2.2. Oceanic Forcing

Temperature and salinity profiles sampled within Ilulissat Icefjord are displayed in Figure 8. Each profile is qualitatively consistent with previous observations (Beaird et al., 2017; Gladish, Holland, Rosing-Asvid, et al., 2015; Straneo et al., 2012), whereby the upper 200 m is substantially colder and fresher than the largely homogenous waters filling the fjord basin at depth. Although the timing of a seasonal cycle may vary, each profile was obtained on comparable dates in the year, so that we may cautiously consider inter-annual variations. In the 2019 and 2021 profiles, the average water temperature in the Ilulissat Icefjord basin (200–700 m) was similar, measured at 1.57 and 1.60°C, respectively; according to the classification of Gladish, Holland, Rosing-Asvid, et al. (2015), such water temperatures would be regarded as "cool" (≤1.70°C). However, in the 2020 profile, a notable warming was observed in the basin, with the average water temperature (200–700 m) increasing to 2.09°C.

The timeseries of ocean temperature within Disko Bay is more temporally extensive, with 210 measurements extracted at a depth of 240 m throughout the study period (Figure 9). However, the temporal coverage remains sparse; many of the measurements were obtained by autonomous ALAMO floats deployed in 2021 and 2022, making it somewhat difficult to discern seasonal variations in 2018, 2019, and 2020 with certainty. Similarly, the

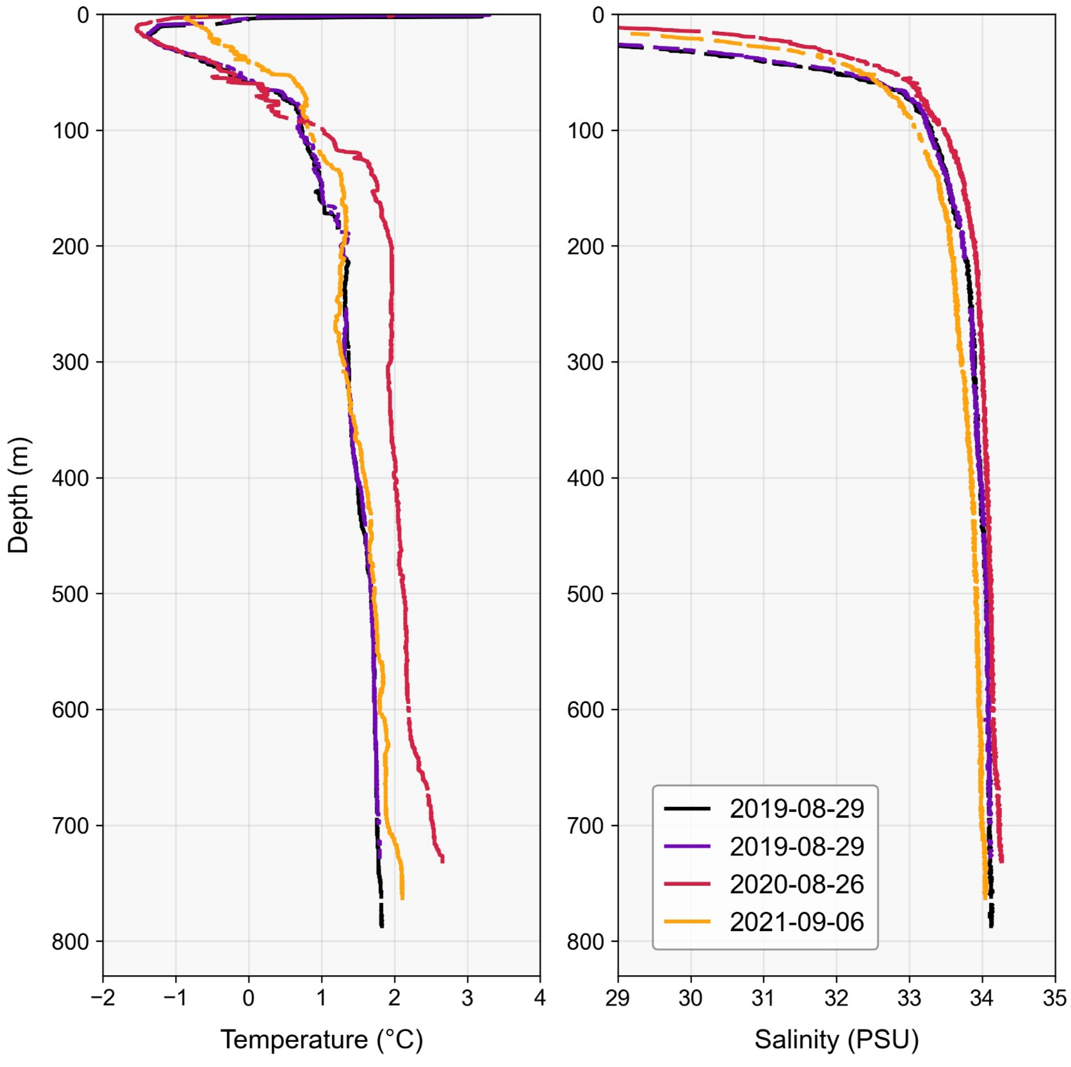

Figure 8. Temperature and salinity profiles collected from AXCTD probes deployed in Ilulissat Icefjord as part of the OMG mission (OMG, 2019). The location at which each profile was sampled is shown in Figure 9a.

differing sampling location of the observations (Figure 9a) complicates the interpretation, though observations collected in different locations but at the same time broadly agree (Figure 9b), suggesting that much of Disko Bay experiences coherent temperature variability at 240 m depth.

With these temporal and spatial limitations in mind, comparison of ocean temperatures observed at similar times in the year nonetheless appears to support the inference from Ilulissat Icefjord (Figure 8) that 2020 was indeed characterized by warmer oceanic conditions, relative to previous years. In 2018 and 2019, the maximum recorded ocean temperature in Disko Bay was similar, measured at 2.14°C (2018-05-30) and 2.12°C (2019-07-22), respectively (Figure 9). However, in 2020, the ocean temperature recorded on 2020-07-15 was 2.65°C, reflecting an increase of +0.53°C, relative to the previous year. In 2021, the seasonal cycle in Disko Bay was more apparent; ocean temperatures decreased from a maximum of 2.58°C (2021-05-29) to a minimum of 1.70°C (2021-08-22), before warming resumed over the subsequent autumn and winter. In 2022, the magnitude of seasonal variability measured by ALAMO F9313 was higher, with ocean temperatures increasing from a minimum of 1.72°C (2022-09-29) to a maximum of 3.15°C (2022-12-11).

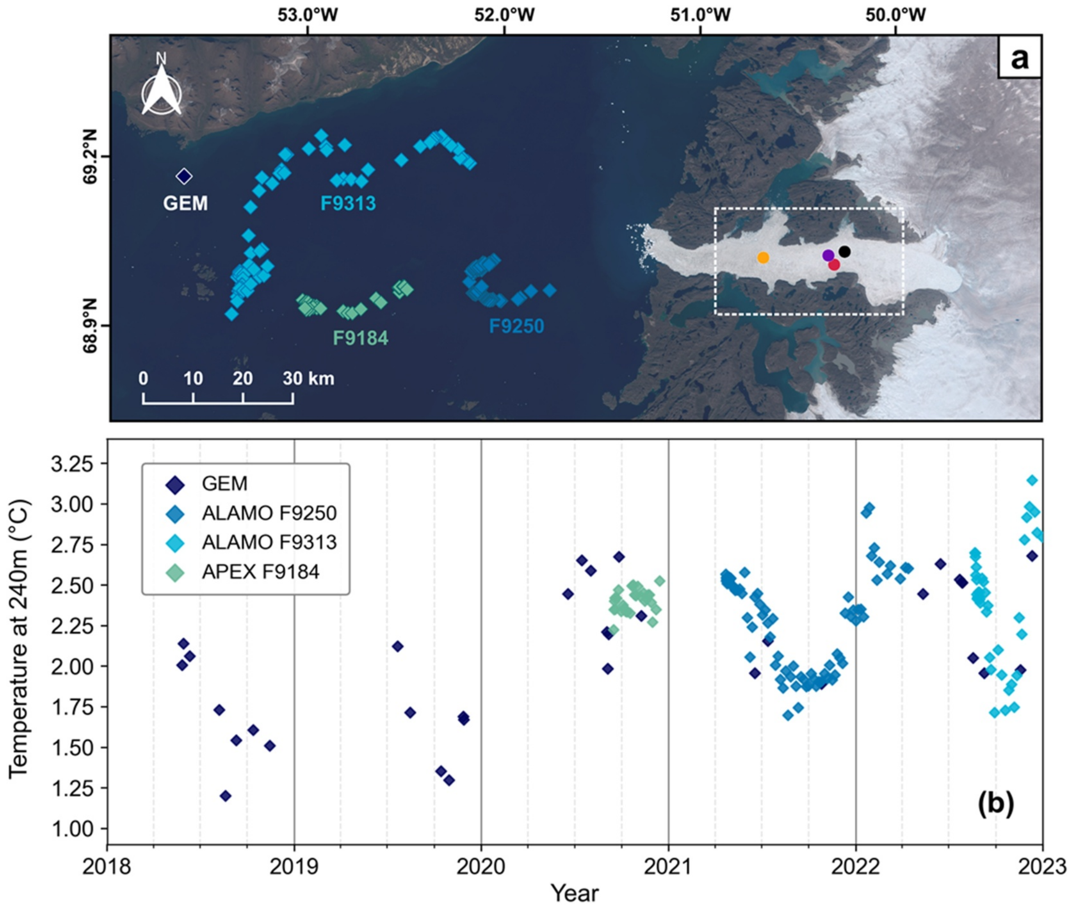

Figure 9. (a) Location map of CTD (diamonds) and AXCTD (circles) profiles used in this study. Background satellite imagery is a Sentinel-2 image mosaic from 2019 (MacGregor et al., 2020), accessed using QGreenland (Fisher et al., 2022; Moon et al., 2022). (b) Timeseries of ocean temperature in Disko Bay, sampled at a depth of 240 m; symbols correspond with the location map displayed in (a).

4. Discussion

4.1. Recent Ice Dynamics at Jakobshavn Isbræ

Following over a decade of sustained frontal retreat, flow acceleration and thinning at Jakobshavn Isbræ, ice dynamics were reversed between 2016 and 2018, with terminus re-advance, ice flow deceleration, and thickening observed (Joughin et al., 2020; Khazendar et al., 2019). This marked reversal was attributed to regional ocean cooling, although the specific mechanism through which such oceanic forcing influenced ice dynamics remains under debate. Khazendar et al. (2019) emphasize the role of reduced plume-driven submarine melting, whilst Joughin et al. (2020) highlight the influence of reduced ocean temperatures on increasing the rigidity of the mélange observed proximal to the glacier front. In this paper, we further explore the potential role of both oceanic and atmospheric forcing in driving dynamic change across Jakobshavn Isbrae, providing observational evidence that the recent reversal in ice dynamics was short-lived (2016–2018). We show that between 2018 and 2022, Jakobshavn underwent sustained ice flow acceleration (Figure 2a), with widespread thinning (Figures 3 and 4) and terminus retreat (Figure 5) also observed.

4.2. Re-Acceleration of Jakobshavn Isbræ: The Role of Thinning-Induced Reductions in Basal Effective Pressure

Our results show that between 2018 and 2022, Jakobshavn underwent a significant acceleration, with the mean annual ice surface velocity near the terminus increasing by nearly 50%, rising from 7.9 to 11.8 km yr^{-1}

(Figure 2a). Previous studies have attributed such periods of accelerated ice flow across the lower regions of Jakobshavn Isbræ to thinning-induced reductions in the effective pressure (Bondzio et al., 2017; Joughin et al., 2012; Podrasky et al., 2012; Van der Veen et al., 2011). The effective pressure across the ice-bed interface is defined as the ice overburden pressure, determined by the weight of the overlying ice, minus the subglacial water pressure (Bindschadler, 1983). The effective pressure controls the local basal traction and thus modulates the rate of basal sliding (Benn et al., 2007). It is estimated that such basal sliding accounts for 60%–100% of ice motion at Jakobshavn Isbræ (Bondzio et al., 2017).

Glaciers that are at or close to flotation are highly sensitive to any driver of ice-thinning, with the associated reduction in effective pressure, and thus basal drag, promoting an acceleration of ice flow (Benn et al., 2007; Enderlin et al., 2013; Williams et al., 2020). Our results support previous work (Amundson et al., 2010; Cassotto et al., 2019) that indicates Jakobshavn Isbræ is often at or very close to flotation (Figure 4). Indeed, in 2020 (2020-05-07), the terminus was characterized by a notable reverse surface slope, indicative of flotation and buoyant flexure often seen prior to large calving events (Cassotto et al., 2019; James et al., 2014; Joughin et al., 2020; Rosenau et al., 2013).

With the perturbation sensitivity of a marine or lake-terminating outlet glacier dependent on its thickness relative to flotation (Enderlin et al., 2013; Holt et al., 2024; Pfeffer, 2007; Sugiyama et al., 2011), Jakobshavn would have been highly sensitive to variations in effective pressure. Indeed, Cassotto et al. (2019) have previously outlined the criticality of Jakobshavn Isbrae's proximity to flotation in relation to changes in ice dynamics. The sustained thinning signal observed between 2019 and 2022 (Figure 3) would thus be expected to drive ice flow acceleration, through a reduction in effective pressure, and terminus retreat; both of which we observed (Figures 2a and 5). The driver of this thinning signal may be forced directly through surface or submarine melting, or indirectly, in response to either dynamic-thinning or retreat of the calving front (Nick et al., 2009).

Separating the potential drivers of the observed thinning signal (Figure 3) remains challenging. However, analysis of ice surface elevation change at a nearby land-terminating margin (Figure S1 in Supporting Information S1) shows evidence of sustained surface lowering; between 2018 and 2021, the near-terminus thinned at an average rate of 2.9 m/yr (Figure S4 in Supporting Information S1). As outlined previously, changes in ice surface elevation across land-terminating glaciers predominantly reflect variations in the local SMB (Sole et al., 2008; Tepes et al., 2021) and thus such thinning can be largely attributed to atmospheric forcing. Our results indicate that such atmospheric forcing was likely similar across the land-terminating margin and Jakobshavn Isbræ, with the maximum rate of ice thinning (4.8 m/yr; 2019-06-05 - 2020-05-19) observed at the land-terminating glacier (Figure S4 in Supporting Information S1) aligning closely with the maximum peak in surface runoff seen within the Jakobshavn catchment (Figure 7). As such, we argue that a negative SMB likely contributed to the sustained surface thinning observed at Jakobshavn (Figure 3). Such ice surface lowering likely reduced the effective pressure across the grounded near-terminus region (Benn et al., 2007), thus contributing to the sustained year-on-year ice flow acceleration observed (Figure 2a).

Whilst it remains difficult to accurately measure submarine melt rates, our results provide evidence that ocean temperatures were higher in Disko Bay during summer 2020, relative to previous years (Figure 9b). Such oceanic warming was also observed within the Ilulissat Icefjord basin, with the average water temperature (200–700 m depth) increasing by 0.52°C between 2019 and 08-29 and 2020-08-26 (Figure 8). It can therefore be hypothesized that enhanced submarine melting, driven by increased ocean temperatures, likely increased rates of glacier undercutting, and reduced the along-flow resistive stress exerted at Jakobshavn Isbræ. This likely initiated dynamic thinning upstream, triggering a positive feedback between effective pressure and accelerated ice flow. However, we emphasize that this increase in ocean temperature occurred *after* the onset of sustained acceleration at Jakobshavn Isbræ; indeed, mean annual ice velocity was observed to increase by 13.6% between 2018 and 2019 (Figure 2a), during which time no notable change in ocean temperature was seen (Figure 9). We therefore argue that whilst increased ocean temperatures likely contributed to the ice flow acceleration between 2020 and 2021 (Figure 2a), they were not the *trigger* for the initial re-acceleration observed at Jakobshavn Isbrae from 2018 through 2019.

4.3. The Influence of Oceanic Forcing on Mélange Rigidity and Ice Dynamics

Previous work (Joughin et al., 2020) emphasizes that subsurface ocean temperatures can also pace ice velocity at Jakobshavn Isbræ through the modulation of proglacial mélange rigidity. A number of studies support this proposed forcing, both at Jakobshavn (Cassotto et al., 2015), and at other large marine-terminating outlet glaciers, such as Kangerlussuaq (Barnett et al., 2022; Bevan et al., 2019; Brough et al., 2023). Indeed, Bevan et al. (2019) argue that the failure of Kangerlussuaq to advance over the winters of 2016/17 and 2017/18 likely resulted from weakening of the proglacial mélange. Our results indicate that a similar pattern occurred at Jakobshavn Isbræ over the winter of 2020/21 (Figure 5), with sustained over-winter calving coinciding with a marked reduction in the extent of rigid proglacial mélange, relative to previous winters. Whilst the rigid mélange had recovered by February 2021, the ice velocity remained elevated throughout the winter, thereby facilitating the high peak velocity of 16.8 km/yr in July 2021, following the onset of summer re-acceleration (Figure 2a). These observations therefore provide evidence supporting the recent suggestion of Brough et al. (2023) that the delayed formation of rigid mélange can exert a critical control on ice dynamics at marine-terminating glaciers.

The formation of a rigid mélange is understood to be influenced by both atmospheric and oceanic temperatures (Amundson et al., 2020; Barnett et al., 2022; Brough et al., 2023; Howat et al., 2010; Joughin et al., 2020), with "cooler" winters typically associated with a denser proglacial mélange, capable of inhibiting calving (Cassotto et al., 2015). However, our results show that in September 2020, when the rigid mélange extent within Ilulissat Icefjord was significantly reduced relative to previous years (Figure 5), the monthly average surface air temperature was −1.86°C colder relative to the 1992–2018 monthly mean (Figure 6). In contrast, AXCTD and CTD data collected in both Ilulissat Icefjord (Figure 8) and Disko Bay (Figure 9) show that ocean temperatures were elevated, relative to previous years, concurrent with the reduced rigid mélange extent. We therefore suggest that the increase in ocean temperature likely played a crucial role in minimizing the development of an extensive rigid mélange proximal to the terminus of Jakobshavn Isbræ, supporting the ocean forcing mechanism previously argued by Joughin et al. (2020). However, with ocean temperatures in Disko Bay evidenced to exhibit significant intra-annual variability (Figure 8), we emphasize that consideration of the temporal resolution of the CTD data used to analyze such trends is highly important. Indeed, the strategic deployment of autonomous CTD probes capable of providing near-continuous observations would be invaluable to fully capture oceanic conditions at Jakobshavn Isbræ, lending support to proposed frameworks such as the Greenland Ice sheet-Ocean Observing System (GrIOOS) (Straneo et al., 2018).

4.4. A Reassessment of Climatic Forcing at Jakobshavn Isbræ

In light of the above discussion regarding the recent thinning, re-acceleration and retreat observed at Jakobshavn Isbræ between 2018 and 2022, we argue for a reassessment of the relative importance of atmospheric and oceanic forcing on ice dynamics. With sustained thinning observed between 2018 and 2022 (Figure 3; Figure S4 in Supporting Information S1), we infer that atmospheric forcing played a key role in driving the initial 2018–2019 ice flow acceleration, before likely contributing to the ongoing year-on-year acceleration seen (Figure 2a). The sustained negative SMB, as inferred from surface lowering across a nearby land-terminating margin (Figure S4 in Supporting Information S1), will have reduced the effective pressure across the grounded near-terminus region of Jakobshavn Isbræ, thus facilitating reduced basal traction and hence accelerated ice flow (Benn et al., 2007). We also emphasize that Jakobshavn Isbræ's proximity to flotation (Figure 4) likely amplified the dynamic response seen in response to such perturbations (Cassotto et al., 2019; Enderlin et al., 2013; Holt et al., 2024; Pfeffer, 2007; Sugiyama et al., 2011; Williams et al., 2020). Whilst our results indicate that the onset of ice flow acceleration occurred *prior* to the arrival of warm water into Ilulissat Icefjord (Figure 8) and Disko Bay (Figure 9), we suggest that the notable increase in ocean temperature contributed to the further increase in mean annual ice-motion observed between 2020 and 2021 (Figure 2a). The incursion of relatively warm water will not only have enhanced rates of submarine melt, but also prevented the formation of an extensive rigid mélange (Figure 5), thereby facilitating high velocities and sustained iceberg calving throughout "winter" 2020/2021. We thus emphasize that *both* atmospheric and oceanic forcing can exert a critical influence on ice dynamics at Jakobshavn Isbræ.

Here, we provide an example from a previous study in which the specific role of atmospheric forcing in driving dynamic change across Jakobshavn may have been overlooked. It has been widely reported that exceptional melt occurred across the GrIS in the summer of 2012, with annual runoff exceeding that observed in 2019 (Tedesco & Fettweis, 2020). As a result, the magnitude of summer re-acceleration observed at Jakobshavn in 2012 significantly exceeded that of previous years (Joughin et al., 2014), and high rates of thinning (>25 m/yr) were recorded (Khazendar et al., 2019). Whilst Khazendar et al. (2019) acknowledge that the increase in surface melting likely contributed to the enhanced ice flow observed at Jakobshavn Isbræ, their analysis focusses solely on the influence of increased subglacial discharge on the modulation of submarine melt. Crucially, the potential impact of increased surface melt on rates of ice surface lowering, and thus effective pressure across the ice-bed interface, was not considered. We argue that this serves as an important example in which the impact of atmospheric forcing on ice dynamics, specifically through the modulation of effective pressure and thus basal traction (Benn et al., 2007), has been overlooked.

Over longer timescales, Khazendar et al. (2019) show that Jakobshavn Isbræ experienced sustained acceleration for over a decade from the early 2000s. As has been the case for the vast majority of Greenland's marine-terminating outlet glaciers also undergoing long-term retreat (Fahrner et al., 2021; Straneo & Heimbach, 2013; Wood et al., 2021), the role of oceanic warming has been widely implicated as the primary driver of this dynamic change (Holland et al., 2008; Joughin et al., 2020; Khazendar et al., 2019; Motyka et al., 2011; Muresan et al., 2016). However, ocean temperatures in Disko Bay were highly variable during this period, lacking any sustained warming trend (Khazendar et al., 2019; their Figure 3d). For example, between 2002 and 2007, despite the peak flow speed increasing by ~27%, ocean temperatures in Disko Bay are estimated to have decreased by ~0.6°C (Khazendar et al., 2019). Although this continued flow acceleration may reflect a longer-term response to the disintegration of Jakobshavn's floating tongue (Joughin et al., 2004; Podlech & Weidick, 2004), it could also indicate that other factors, such as the sustained negative SMB (The IMBIE Team, 2020), were influential in driving dynamic change at Jakobshavn Isbræ.

In recent years, there has been growing awareness that ice dynamics at marine-terminating glaciers can also be strongly influenced by atmospheric forcing (Cowton et al., 2018; Fahrner et al., 2021), with significant attention given to the role of enhanced surface melt, and thus subglacial discharge, in driving increased submarine melting (Catania et al., 2020; Motyka et al., 2013; Slater & Straneo, 2022). However, our results highlight that enhanced surface melt can also influence ice dynamics through the modulation of the ice-overburden pressure. Whilst the input of surface melt can initiate a dynamical response, we emphasize that sustained surface lowering driven by negative SMB conditions, as observed around Greenland's margins for at least two decades (Smith et al., 2020), can also force enhanced basal sliding at the ice-bed interface, and thus increased ice flow. With the perturbation sensitivity of a marine-terminating outlet glacier dependent on its thickness relative to flotation (Enderlin et al., 2013), the potential for such variations in effective pressure to initiate dynamic change will only continue to increase as glaciers undergo further thinning in response to climatic warming. It is therefore crucial that the influence of atmospheric forcing, particularly through the modulation of the ice-overburden pressure, is considered when projecting future ice dynamics at Greenland's marine-terminating outlet glaciers.

5. Conclusions

Here, we provide remotely sensed observations of ice dynamics at Jakobshavn Isbræ, Greenland's largest marine-terminating outlet glacier in terms of ice flux, between 2018 and 2023. Following a short-lived period of deceleration, thickening, and terminus advance (2016–2018; Khazendar et al., 2019; Joughin et al., 2020), we show that Jakobshavn exhibited a year-on-year increase in mean annual ice velocity between 2018 and 2022 (Figure 2a), accelerating by almost 50%. Whilst the majority of research has emphasized the role of oceanic forcing in controlling ice dynamics at Jakobshavn Isbræ (Holland et al., 2008; Joughin et al., 2020; Khazendar et al., 2019; Motyka et al., 2011; Muresan et al., 2016), we provide a reassessment of this view, arguing that the re-acceleration observed was likely driven by both oceanic *and* atmospheric forcing.

We show that the initial re-acceleration of Jakobshavn Isbrae preceded the arrival of warmer water into Ilulissat Icefjord and thus postulate that ice surface lowering, driven by both negative SMB and dynamic thinning, resulted in a reduction in the ice-overburden pressure across the grounded near-terminus region. The consequent decrease in effective pressure, and thus local basal traction, likely contributed to the year-on-year ice flow acceleration observed (Figure 2). We also suggest that the re-acceleration of Jakobshavn was likely facilitated by the near-terminus region being frequently at or close to flotation (Figure 3), and thus highly sensitive to small variations in the effective pressure. With the sensitivity of marine-terminating outlet glaciers dependent on their thickness relative to flotation (Cassotto et al., 2019; Enderlin et al., 2013), we emphasize that such variations in effective pressure will have an increasing influence on ice dynamics as glaciers continue to undergo thinning in a warming climate. At marine-terminating glaciers close to flotation, such as Jakobshavn Isbrae, the potentially influential role of atmospheric forcing must thus not be overlooked.

Nonetheless, our results also provide evidence that sustained calving and elevated velocities during the winter of 2020/2021 were likely driven by oceanic forcing, supporting the argument of Joughin et al. (2020) that ocean temperatures can influence the rigidity of ice mélange formed adjacent to the glacier terminus. Such an ice mélange is understood to suppress iceberg calving and thus influence ice dynamics (Amundson et al., 2010). The increase in oceanic temperature likely also enhanced the rates of glacier undercutting, thereby contributing to the continued ice flow acceleration observed from 2020 through 2022. Therefore, our results also highlight the critical importance of considering the temporal resolution of oceanic data used when trying to disentangle the complex ice-ocean-atmosphere interactions influencing marine-terminating outlet glaciers. With significant intra-annual variations in ocean temperatures observed in Disko Bay, our study supports the notion that continuous monitoring of ocean temperatures is required in order to facilitate the accurate assessment of oceanic forcing at Greenland's marine-terminating glaciers.

Data Availability Statement

The ITS_LIVE Sentinel-1 image-pair velocity products are available from Lei, Gardner, Kennedy, et al. (2022). Ice surface elevation profiles were sampled from ArcticDEM strips (Porter et al., 2022), using the python package *pdemtools* (Chudley & Howat, 2024). The gridded surface elevation data used (ATL15) is available from Smith, Sutterley, et al. (2023) and estimates of solid ice discharge are available from Mankoff, Solgaard, and Larsen (2020). The terminus positions derived between 2018-01-01 and 2021-12-31 can be downloaded from Black and Joughin (2022), and the terminus positions digitised between 2022-01-01 and 2022-12-31 can be downloaded from the UK Polar Data Center (Picton, 2024a). The SAR mosaics used to manually digitise each terminus position are available from the NSIDC (Joughin, 2021). Daily estimates of surface runoff are available from Mankoff (2020) and surface air temperatures recorded at Ilulissat Mittarfik meteorological station are provided by the Danish Meteorological Institute (Jensen, 2023). Data collected from CTD and AXCTD profiles deployed as part of NASA's OMG project are available from the NSIDC (OMG, 2019, 2021, 2022). CTD data collected as part of the GEM programme are available from GEM (2024) and were provided by the Greenland Institute of Natural Resources (Nuuk), in collaboration with the Department of Bioscience (Aarhus University, Denmark) and the University of Copenhagen, Denmark. The code used to process, analyse and plot the data presented in this manuscript is freely available on GitHub (Picton, 2024b).

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