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REVIEW

Advances in monitoring glaciological processes in Kalallit Nunaat (Greenland) over the past decades

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Abstract

Greenland's glaciers have been retreating, thinning and accelerating since the mid-1990s, with the mass loss from the Greenland Ice Sheet (GrIS) now being the largest contributor to global sea level rise. Monitoring changes in glacier dynamics using in-situ or remote sensing methods has been and remains therefore crucial to improve our understanding of glaciological processes and the response of glaciers to changes in climate. Over the past two decades, significant advances in technology have provided improvements in the way we observe glacier behavior and have helped to reduce uncertainties in future projections. This review focuses on advances in in-situ monitoring of glaciological processes, but also discusses novel methods in satellite remote sensing. We further highlight gaps in observing, measuring and monitoring glaciers in Greenland, which should be addressed in order to improve our understanding of glacier dynamics and to reduce in uncertainties in future sea level rise projections. In addition, we review coordination and inclusivity of science conducted in Greenland and provide suggestion that could foster increased collaboration and co-production.

1 Introduction

Starting in the early 19th century, publications describe glaciological processes that were observed at mountain glaciers in the Alps, the Karakoram, and in the Alaskan mountain ranges [1–6]. The monitoring of Greenlandic glaciers by foreign scientists started in the late 1880s, with expeditions making observations about single glaciers [7–11]. The Thule people, who settled in Greenland around 945 AD, made observations about glacier and ice dynamics centuries before foreign explorers reached Greenland [12]. European explorers relied on their knowledge to navigate Greenland; however, as their observations are passed down orally, they are not well known in the western world [13]. With the establishment of the International

Glacier Commission in 1895, which developed into the World Glacier Monitoring Service (WGMS), the observations and measurements of glacier dynamics made by individual expeditions were collected and eventually standardized [14, 15]. These early observations of glacier behavior are still used as references; however, as only a few glaciers were surveyed, characterizing overall dynamics of the GrIS in the early 19th century from in-situ observations alone remains challenging. Using methods such as identifying morphological and glaciological features from aerial (stereo-) photographs, previous studies were able to reconstruct GrIS-wide mass loss since the Little Ice Age (LIA; 1250–1900 AD) maximum [16, 17]. For those glaciers, where in-situ observations are available, glacier dynamics since the LIA maximum extent have been determined, showing the retreat of these glaciers over the 19th century [18–21].

Over the first half of the 20th century, reconstructions of GrIS surface mass balance (SMB), which is the difference between accumulation and ablation without iceberg calving and thinning, show that following their initial retreat from the LIA maximum, glaciers remained relatively stable [22, 23]. Over the later half of the 20th century, observations on the GrIS increased, mass balance estimates were recorded, and new in-situ and remote sensing methods became available to monitor glaciers continuously (Fig 1) [24–27]. Starting in the 1990s, marine-terminating glaciers around the GrIS began to accelerate, thin and retreat, which has been attributed to a change in climate and is also apparent in the SMB estimates (Fig 1) [28].

The Gravity Recovery and Climate Experiment (GRACE) was one of the first remote sensing missions to provide data that allowed to quantify the mass balance (accumulation and ablation) of the Greenland Ice Sheet, which significantly improved our understanding of glacier dynamics in Greenland [29–31]. This mission was followed by further satellite-based missions such as IceSat, IceSat-2 and CryoSat-2, which collect surface elevation data over the Greenland Ice Sheet [32, 33]. The collected data has helped to improve our understanding of surface mass balance [34, 35], but also allowed to derive novel insights into e.g. aerodynamic roughness over the GrIS [36]. This highlights the importance of considering the appropriate spatio-temporal resolution for investigating glacier dynamics. As shown in Fig 1B, previous studies have used different approaches to quantify the mass balance of the GrIS, and while the overall negative trend is apparent, the uncertainties remain relatively high.

In comparison to satellite remote sensing data, in-situ measurements provide a higher spatio-temporal resolution, thereby allowing to investigate processes such as iceberg calving and crevasse formation, which occur on shorter timescales [37–40] This data can further be useful to determine local stress and strain fields, surface mass balance and assess the response of an individual glacier to short term changes in atmospheric or oceanic forcings, or mélange [41, 42]. While some methods have not significantly changed since the beginning of glacier monitoring (e.g. surface ablation is still measured with stakes), others have seen improvements with the emergence of new technologies (Fig 2). Air-based photogrammetry has seen significant advances with the emergence of Unmanned Aerial Vehicles (UAV), which enable surveying comparatively large and inaccessible parts of the glacier (e.g. the glacier terminus). The data can be used to create three-dimensional models and i.e. assess calving dynamics, elevation changes, or crevassing [38, 43]. Ground-based photogrammetry has also seen improvements with solar panels charging digital cameras, so that they are able to take photos continuously over long periods of time without the need for maintenance [44, 45]. Over the past decades, the Global Positioning System (GPS) has been modernized with new satellites, which enabled more accurate in-situ measurements of glacier velocity and surface elevation change [46–48] and when installed on icebergs can even help to determine their melt rates [49, 50]. Satellite-based data transmission systems have significantly simplified data collection and accessibility from in-situ monitoring stations [51]. The transmitted data is usually averaged, uploaded to a remote server at given intervals and can be accessed in near-real-time [51]. However, this is

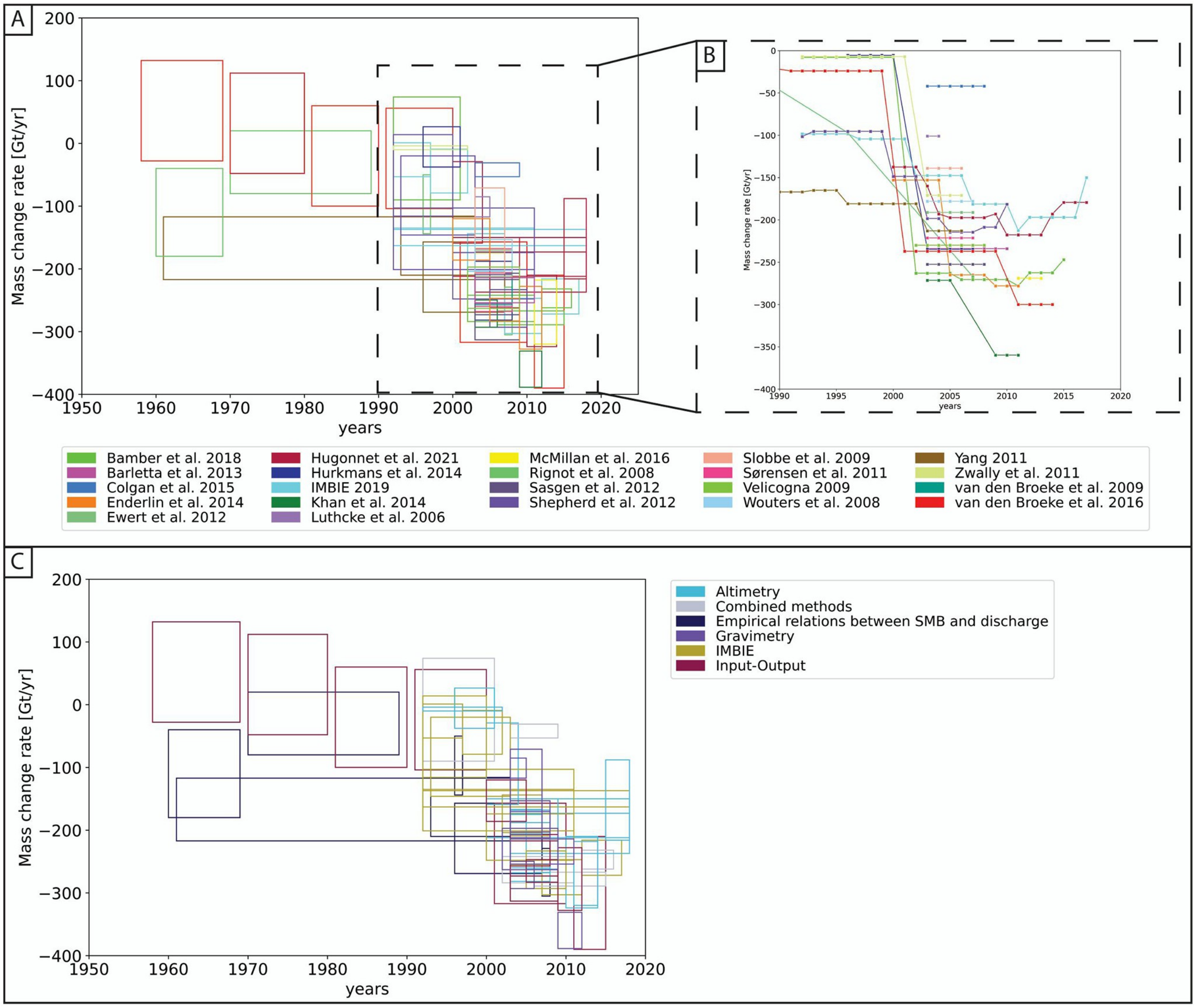

Fig 1. A) Mass Balance estimates for the period 1950–2020 with boxes indicating the time period for which these were calculated along the x-axis and uncertainties of estimates along the y-axis. Colors indicate publications of respective SMB estimates. B) Inset shows zoom of period 1990–2020 as a line plot to clarify overlaps between mass balance estimates. C) Methods used to derive mass balance estimates in A). Studies used to create this figure can be found in the supplementary material.

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currently only economically feasible for relatively small amounts of data, such as meteorological observations. Post-processing of in-situ data has also seen improvements with the increase of computational power and availability of software products [52, 53].

However, challenges still remain as the installation of monitoring equipment is often linked to significant logistical and economical costs. In addition, the complex interactions of climate forcings, glacier geometry, bedrock topography and other glacier specific factors means that observed dynamics can not be transferred to other glaciers or upscaled to all glaciers of the GrIS without introducing significant uncertainties [54]. This review is structured by glaciological process and discusses in each section how monitoring of this process using in-situ and, if applicable remote sensing data, has advanced over the past two decades. We also highlight

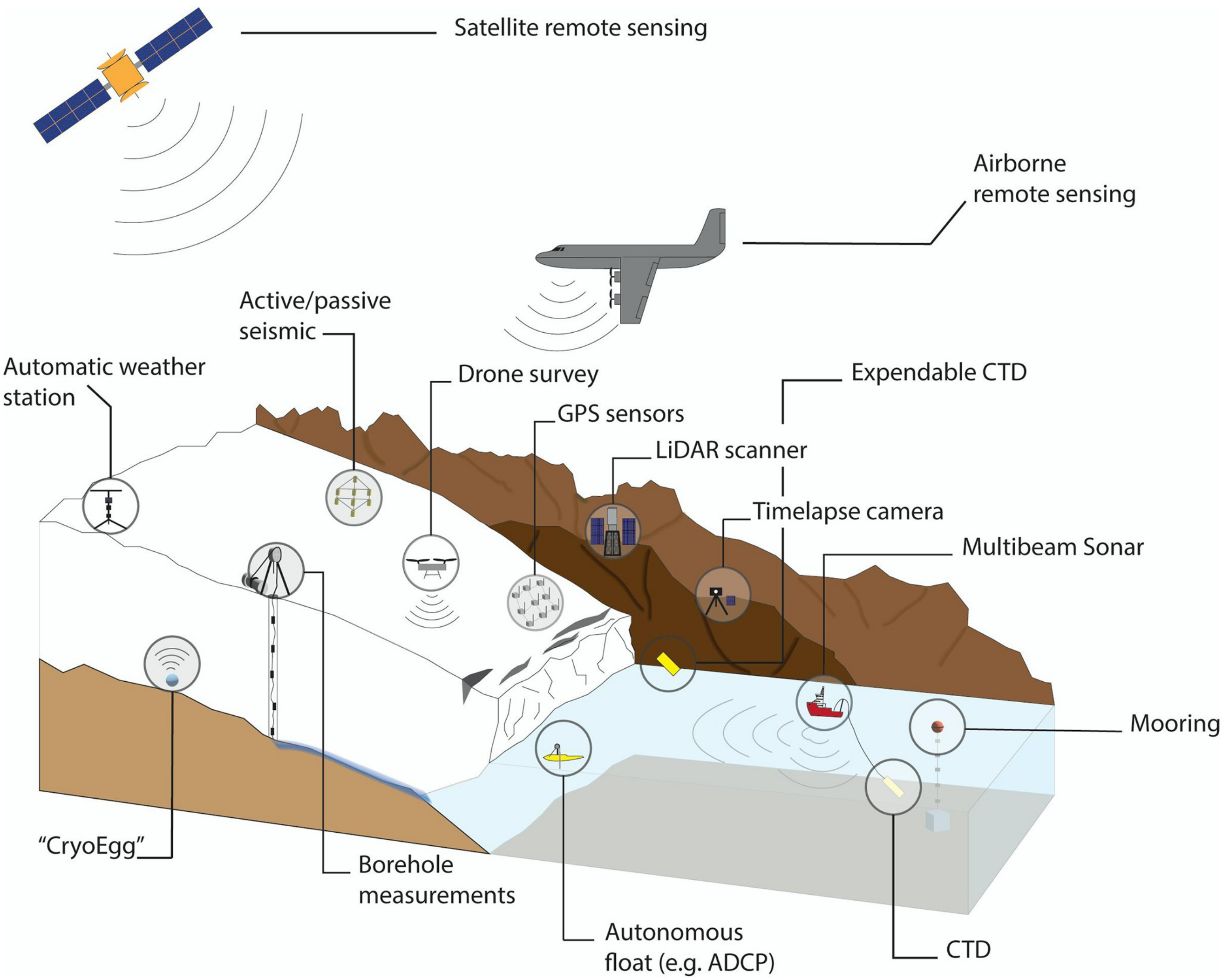

Fig 2. Sketch outlining current in situ and remote sensing methods to observe glaciological processes at tidewater glaciers.

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where monitoring of glacier behavior should be improved in order to better our understanding of glacier dynamics and gain insights into the drivers of glacier retreat in Greenland.

2 Monitoring ice flux

Seasonal/sub-seasonal thickness and velocity changes

Glacier thickness and velocity changes have been monitored increasingly, and with a coordinated effort, in valley and mountain glaciers around the world since the start of the 20th century [55–58]. The first observations were made using surface features or markers to estimate flow [55–57], which were soon replaced by the emergence of photogrammetry [58]. Over the later 20th century, these methods became more advanced with the use of GPS, and in the past decades, velocity measurements of Greenlandic outlet glaciers on large spatial scales have mainly been obtained from remotely-sensed data using Synthetic Aperture Radar (SAR) or optical data (e.g. ice velocities in NASA's Making Earth System Data Records for Use in Research Environments (MEaSUREs) program [59, 60]). These glacier velocity products are derived using cross-correlation feature-/speckle-tracking or interferrometry algorithms with their temporal resolution being dependent on the revisit times of satellites [61, 62]. The revisit times for most openly accessible satellite imagery is seven days for optical imagery (e.g. Landsat), and 11 days for SAR imagery (e.g. TanDEM-X/TerraSAR-X). The recent introduction of twin satellites and satellite constellations has reduced the revisit cycle to five days or less, which has allowed sub-seasonal glacier dynamics to be monitored using satellite imagery [63]. The PlanetScope constellation, for example, consists of approximately 200 Dove CubeSat satellites and provides optical imagery with a spatial resolution of $\tilde{4}$ meters and a revisit time of up to one day [64]. CubeSats are comparatively cheap to produce and launch so that more satellites can be placed into orbit and revisit times can be reduced [65].

This high resolution data has been successfully utilized to monitor icebergs in Greenlandic fjords and determine mass loss at a glacier terminus [66, 67]. Image acquisition is currently spatially limited in the interior of Greenland due to the lack of ground control points and temporally due to the darkness in the Arctic winter [63]. The spatial resolution of satellite imagery can be as high as centimeters [68], and while this can provide important information for the monitoring of individual glacier dynamics, this high-resolution data is often only available as tasked acquisition and usually not openly accessible.

Volume change over time (hereafter referred to as ice flux) is mostly estimated from ice velocities (e.g. [69]) by calculating ice flow through a virtual gate upstream of the terminus and inferring ice thickness from digital elevation models (Difference between surface elevation and bedrock elevation). While this offers good approximations of volume change, the necessary parameters are often not based on in-situ measurements but are derived from remote sensing data and thus contain uncertainties. These uncertainties are particularly high where bedrock elevation has not been measured but is rather estimated using methods like krigging (Gaussian regression) or inversion, which leads to over- or underestimates of ice thickness [70–72]. Current ice flux estimates often also do not take changes in terminus position into account, which leads to further uncertainties [69, 73]. Deriving ice flux estimates from in-situ observations is theoretically possible, but due to the logistical challenges of installing instrumentation, obtaining observations with these methods is not economically sensible in remote locations or over large spatial scales [74, 75]. In general, the use of satellite data, while still temporally limited by the revisit time, has significantly simplified the large scale monitoring of ice velocities and ice flux in Greenland [54, 76–80]. Advances in technology are anticipated to improve the spatio-temporal resolution of satellite imagery, thereby further reducing uncertainties in ice flux estimates.

On seasonal, sub-seasonal and sub-daily time scales, GPS data is often used to determine glacier velocities and surface elevation change [79, 81]. Although this method enables the calculation of ice velocities for each glacier, it necessitates installing a GPS sensor network on the glacier. This approach carries substantial risks of sensor loss due to factors like crevassing, iceberg calving, surface melting, or storms [47, 79]. Sensors can collect data over annual time-scales, depending on their location on the glaciers, but near the termini of marine terminating glaciers, data collection is usually limited to the summer months [79, 82–84]. GPS measurements on the glacier are also important to validate surface elevation change and ice velocities derived from satellite observations, and reduce uncertainties of these data products [47]. Ground-based photogrammetry is another method to determine ice velocities and, similar to GPS sensors, necessitates the installation of equipment in the field [44, 79]. Once the camera is installed, it can acquire data continuously for long periods of time, facilitating the monitoring of evolving ice dynamics (Fig 3). Depending on the frequency of image acquisition, this form of photogrammetry can provide insights into the short-term response of tidewater glaciers to

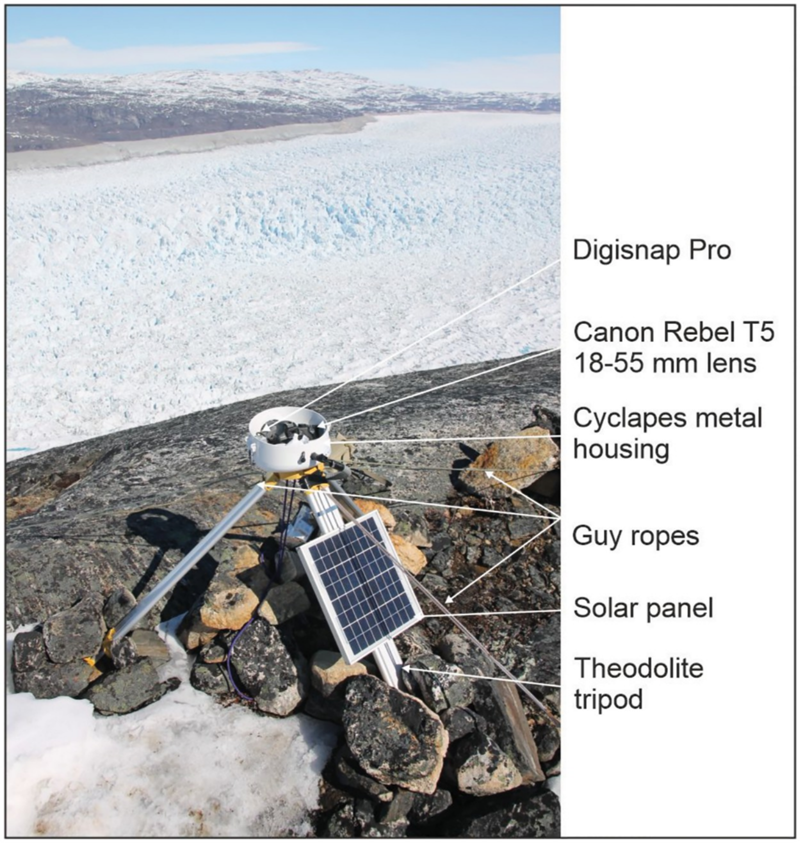

Fig 3. Time lapse camera setup at Narsap Sermia, SW Greenland, to monitor iceberg calving, ice velocities and terminus dynamics (image credit: Dominik Fahrner).

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changes in runoff and ice mélange, as well as monitor iceberg calving and ice-dammed lakes long-term [37, 39, 41, 85, 86]. In recent years, the popularity of UAV-based photogrammetry has increased, not only because it facilitates the measurement of ice velocities but also because it allows for the creation of three-dimensional models of features such as glacier termini and digital elevation models, utilizing structure from motion (SfM) software. [43, 87–89]. However, UAV photogrammetry only provides glacier velocities for a given time period as it requires repeat surveys to derive imagery, therefore it is currently not feasible to use it as continuous monitoring tool.

Ice thickness changes over time are difficult to obtain from in-situ observations as it would require to determine the bedrock topography either by borehole drilling, seismic surveys or using ice penetrating radar [90]. While measurements of ice thickness have been taken using either method, successful data collection is strongly dependent on the accessibility of the glacier, glacier surface, and suitability for drilling [91, 92]. Thus, the application of these methods has been limited to a few selected glaciers around the GrIS. However, surface elevation change can be monitored using ground and UAV-based photogrammetry [79, 84].

In-situ monitoring of ice velocities and thickness changes comes with logistical, economical and technological challenges, but it is crucial to improve our understanding of fundamental glaciological processes and the response of glaciers to changes in their environment. Advances in instrumentation and software applications over the next decade are anticipated to provide considerable new insights into glacier dynamics [53, 88, 93, 94].

The importance of spatio-temporal resolution

Glaciological processes are influenced by forces that act on millimeter (e.g. ice damage, stress) to kilometer scales (e.g. crevasse formation, calving) and over days (e.g. iceberg calving) to decades (e.g. glacier advance and retreat influenced by climate) [95–99]. The variability of these forces can result in neighboring glaciers showing vastly different behavior, which makes it difficult to project future dynamics and determine influential drivers of change [54, 100, 101]. It is therefore important to consider the appropriate spatio-temporal resolution of data when investigating glacier dynamics.

Long-term, low spatial resolution data is sufficient to investigate overarching responses of the GrIS to changes in climate [54, 78], but might not be suitable to investigate individual calving events. Ice sheet-wide studies are however important to determine trends in glacier behavior, which can help to reduce the computational power needed to project future GrIS variability in response to climate [54, 73, 78, 102]. When investigating individual glacier dynamics, especially more local parameters such as strain rates and stresses, the use of medium resolution data can lead to inaccurate estimates [62, 103]. Studies that investigate individual glacier dynamics are however crucial to further our understanding of processes such as basal sliding, calving or subglacial drainage. To address this gap in spatio-temporal resolution, 'mega-site' efforts have taken place at Helheim Glacier to study geometry, atmospheric, ocean, and glacier variability through a combination of observations and numerical models [104, 105]. Novel observational techniques such as autonomous terrestrial laser scanners (Fig 4; TLS) to study calving dynamics, and geoPebble systems [106], an interconnected seismic and GPS sensor nodes, to examine ice fracture and subglacial processes have been deployed at Helheim Glacier. The deployment of these instruments are in part to start addressing the call for a sustained ice sheet wide ice-ocean observing system in Greenland for long-term monitoring [107].

3 Monitoring terminus processes

The ice-ocean interface is a region where many processes occur involving interactions between the ice, ocean, atmosphere, and the subglacial substrate. However, many of these processes are difficult to observe because several happen at depth, below the fjord surface, but also because the region is challenging to survey with in-situ observations.

Changing boundary conditions

The GrIS has experienced unprecedented retreat of the ice-ocean boundary over the satellite era [78, 108, 109] with some glaciers experiencing near simultaneous retreat of up to several kilometers each. In the case of outlet glaciers that reside in overdeepened fjords, the terminus remains ocean-terminating throughout this retreat, but in some instances, glacier termini have retreated out of the ocean altogether. This causes a fundamental change in the processes acting on glacier termini. For example, the grounding lines of outlet glaciers in the Canadian Arctic are much shallower (>400 m) than in Greenland and as a result the dominant control on retreat is atmospheric processes (e.g. temperature) [110] compared to Greenland, where retreat appears to be triggered by both atmospheric and oceanic warming [72, 111, 112].

Because the GrIS contains nearly 300 outlet glaciers, monitoring changes in the terminus boundary condition is most easily done using satellite observations, however the sheer volume of data to examine has grown exponentially in recent years. Traditionally, glacier terminus positions were hand-delineated, but this led to lack of consistent results and overlapping data sets [109]. As a result, many authors have made use of machine learning to automatically delineate glacier termini from optical and SAR satellites (e.g. [113–123]). In the polar winter,

Fig 4. An autonomous terrestrial laser scanner system at Helheim Glacier, SE Greenland used to study calving dynamics (image credit: Cold Regions Research and Engineering Lab).

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terminus observations are not possible from optical satellite images because the region is not illuminated. The launch of Sentinel-1/2 in 2014 provides SAR data over the poles, which enables a full picture of glacier terminus seasonality for the first time [114].

Calving

Terminus change occurs as a result of an imbalance between ice flux into the terminus and terminus ablation, which includes both calving and melt losses, both of which have been the subject of intense, recent study. Calving of icebergs refers to the process of mechanical separation of ice at the termini of outlet glaciers and has been monitored through a variety of methods [97], including remote sensing techniques that make use of satellite-derived terminus positions and ground-based measurements. High-resolution satellite imagery allows researchers to determine the flux of ice due to icebergs by measuring the sizes and volumes of individual icebergs [67, 124] or the change in the terminus over time [125]. Further, satellite observations of variables that serve as data input to possible calving laws (ice velocity, surface and bed topography, terminus position) can be used to model calving size and rates [126]. While satellite data can provide long-term estimates of iceberg flux, they are often biased from the spatial resolution of imagery and are less likely to produce information at the exact time of a calving event due to temporal frequency of image acquisition. This can be overcome through the use of in-situ time-lapse photography or TLS deployed near glacier fronts (e.g. Figs 3 and 4). With time-lapse photography, these cameras capture images at regular intervals, enabling scientists to study the frequency and magnitude of icebergs breaking off across a range of sizes [127, 128] and changes to the ice surface, for example, Helheim Glacier, in order to delineate the mechanism for calving for that glacier [79, 129].

Acoustic and seismic monitoring of glacier terminal environments can also produce records of calving events [130–132]. In each case a monitoring instrument (or suite of instruments) are placed such that they can identify the location of events along the terminus with the seismic/acoustic signals providing insight into the timing and intensity of calving [127, 133]. In many cases the signals identified in these data sets come from the interaction between the iceberg and the sea surface [127] although many studies are challenged to differentiate between different seismic signals generated by calving events. This makes it more critical to group observations by acoustic/seismic instruments with some visual data covering the same time period. Further, visual observations provide critical information about the specific mechanisms involved in the calving process that are recorded by seismic/acoustic sensors. Large calving events, which are associated with glacial earthquakes, can be detected by regional seismic networks, therefore allowing monitoring over large spatial scales [134, 135].

Submarine melting

Submarine melting of glacier termini has emerged as an important mechanism that influences glacier terminus ablation rates and may be responsible for long-term retreats of outlet glaciers in Greenland [72]. Submarine melt was theorized by Jenkins (2011) and depends on oceanographic conditions at the terminus (salinity, temperature, velocity), subglacial discharge emerging at the terminus (in turn, this is a function of ice sheet surface melt and subglacial discharge routing), and the shape of the terminus [136]. Testing of this initial theory can be accomplished with in-situ observations (described below) and also in the laboratory, where melting from turbulent plumes can be closely measured and monitored [137].

Monitoring submarine melt has been challenging owing to changing terminus conditions and the near complete lack of long-term moorings in close proximity to glacier termini. Many campaign-style moorings have been deployed in a number of fjords in Greenland. When coupled with ship-based Acoustic Doppler Current Profilers (ADCP) and conductivity-temperature-depth (CTD) profilers, these measurements can help to identify the presence of buoyant melt plumes near the glacier terminus and assess the potential of these plumes to cause submarine melt [138–140]. Recent observations suggest that plume-related melt may not be the only important mechanism for submarine terminus melt. Sutherland et al. (2019) used repeat multibeam observations of the submarine terminus face to estimate the time-varying melt and calving patterns [141]. Similar methods were previously used to quantify the amount and pattern of submarine melt using a single-pass of multibeam data [142, 143]. Other novel techniques include the use of remotely operated or autonomous underwater vehicles (ROVs and AUVs), equipped with instruments that can navigate close to submarine termini collecting high-resolution data on ice-ocean interactions and the spatial distribution of melting. Recent studies further used UAVs or sensors deployed from the calving front to measure subglacial discharge plume properties and other terminus processes, thereby providing insights into the dynamics at the ice-ocean interface and valuable data for the further investigation of submarine melting [144, 145]. Often, the expense of operating and deploying these instruments makes their data less available. Finally, acoustic sensors can be used to monitor submarine melt [146] by placing passive hydrophones in front of glaciers. The sounds of bubbles under pressure popping as they are melted are captured by the sensors. While acoustic sounding provides valuable time-series data related to melt, further work is needed to compute absolute melt estimates from this method. In part, this is because determining and isolating the melt signature in acoustic recordings compared to other sources is challenging.

Mélange and sedimentation

While much of the research focus has been on quantifying calving and submarine melt processes, there are other processes acting at glacier termini that may be important to quantify, but remain poorly constrained. Ice mélange is common in glacier fjords in winter and during calving events and a few glaciers have persistent mélange cover all year because of fjord geometry and the frequency of calving events. The strength of mélange may be an important source of backstress on the terminus if the mélange configuration at the terminus is tightly packed [147]. Satellite-derived ice velocities are not typically processed over iceberg mélange, and so on-ice GPS [39] or ground-based radar interferometers [148] have been used to capture velocities either on the solid ice of the terminus, or the mélange itself, which give estimates of mélange backstress on the order of 10s of kPa. While this is an order of magnitude less than the driving stress, mélange does impart some flow resistance of termini, particularly where it is persistent [42]. Particularly useful, portable ground-based radar interferometers provide high-frequency (one per several minutes) scans across a frame to determine speeds and strain rates of ice mélange. These data have been useful to resolve ice mélange motion and have led to models of mélange as granular materials that have been helpful in understanding how mélange can mechanically resist calving [148, 149]. While most of these novel observations have occurred in fjords with persistent mélange, less is known about the importance of seasonal mélange. Fried et al. (2018) used satellite and ground-based terminus change observations and mélange presence to determine if seasonal mélange is an important control on seasonal terminus position change [150]. The authors conclude that terminus position is less dependent on mélange conditions for serac-failing calving glaciers, but instead correlated with processes related to terminus geometry such as calving style and ice flux.

Sedimentation has been shown to be influential on terminus stability by e.g. creating wedges that obstruct warm Atlantic water to reach the calving front or changing submarine fjord geometry [151, 152]. In-situ measurements of active terminus sedimentation are challenging by the nature of the grounding line environment, thus relatively few observations have been made near active calving fronts in Greenland. One approach involves the use of sediment traps deployed in the water column or the seafloor [153, 154] near the glacier front to collect accumulated sediment over a specific period. These traps can be designed to capture sediment from various depths and equipped with instruments to measure water column properties as well. In order to improve our current understanding of the role of sedimentation in the behavior of tidewater glaciers in Greenland, increased monitoring is necessary. These increased efforts should focus on areas that have seen high sedimentation rates in the past (e.g. Disko Bay) [155].

In-situ monitoring of boundary conditions of tidewater glaciers in Greenland remains challenging, despite advances in technology and increases in spatio-temporal resolution of measurements. The inaccessibility of active calving fronts makes it difficult to install, retain and maintain instrumentation, so that satellite remote sensing observations are often easier to obtain. Recent studies have shown, that autonomous measurements could be the key to access these challenging environments, which could lead to significant advances in our understanding of tidewater glacier termini [156, 157].

4 Monitoring surface mass balance

The surface mass balance (SMB) of the GrIS, defined as the difference between surface accumulation and ablation, has been monitored on large scales since the mid-1950s [158]. Then, measurements near the glacier edge were taken by probing the surface layer, whereas further inland, stakes were planted and monitored for multiple seasons to determine changes in surface elevation [159]. These methods are still in use today to determine SMB on local scales [160], whereas on ice sheet-wide scales, SMB components can be estimated from regional climate model (RCMs) outputs [161]. Recent studies have found that over the past three decades, the ablation zone has increased, especially in northern Greenland, and a reduction in surface mass balance has driven over half of the mass loss of the GrIS, highlighting the importance of accurately determining ablation and accumulation [162, 163].

Ablation

Monitoring of surface ablation, which comprises runoff, evaporation, sublimation, and erosion, has been conducted in the past by stake measurements which had significant spatial and temporal limitations [164, 165]. Nowadays, evaporation and sublimation can be measured by automated weather stations, which are placed across the GrIS (see section on atmospheric forcing) [166]. Drifting snow erosion can also be measured in-situ, however it only accounts for a relatively small amount of ablation compared to runoff [167]. In-situ observations of runoff can be obtained by measuring water flow in supraglacial rivers or monitoring proglacial lake water levels, yet acquiring measurement remains challenging and data are scarce [168–170]. Where it is not possible to conduct these measurements, due to inaccessibility or lack of lakes, runoff is either taken from RCM outputs or assumed to occur when temperatures are above 0˚C. The RCMs, such as the Modèle Atmosphérique Règional (MAR) and the Regional Atmospheric Climate Model (RACMO), are used to determine surface melting (i.e. runoff) on GrIS-wide scales. These models are informed by observational data, which shows the necessity to conduct in-situ measurements. While the spatial resolution of these models is usually in the order of 5 to 10 km, recent studies have shown that they can be down-scaled to 100 meters, which is sufficient to determine surface runoff for most glaciers in Greenland [170, 171]. Current numerical models struggle, though, to accurately represent the retention of melt water in the firn layer, due to a lack of observational data, so that a lag in runoff onset is not accounted for and all generated melt water is assumed to be runoff [172]. In general, observation informed RCMs currently provide the most accurate data to quantify surface ablation across the GrIS. However, increases of in-situ measurements of surface ablation parameters, especially runoff, melt water percolation and retention, could help to further reduce model uncertainties.

Accumulation

Surface accumulation can be measured in the interior of the GrIS (accumulation zone) using ice cores [173, 174], GPS [175] or stakes [176] (Fig 5). Installing equipment in the accumulation zone can come with financial and logistical challenges, yet taking in-situ measurements is comparatively straightforward as instruments can be maintained for long periods of time, measurements can be taken annually, and long-term accumulation records can be revealed within a field season from ice cores [158, 177].

In the ablation zone, measuring accumulation is more complicated as the terrain is often inaccessible, and measurements have to be repeated annually [158]. While in-situ measurements provide valuable information about local changes in accumulation and are crucial to validate numerical model estimates, they are spatially and temporally limited [178]. Thus, ground-based and airborne radar are used to cover larger spatial areas, which can also overlap with in-situ measurements for validation and density information [177, 179]. Numerical models (RCMs) and reanalysis products are currently the only source of long-term, GrIS-wide estimates of accumulation rates, but their outputs show significant variance depending on the model [161, 177]. This highlights that in-situ measurements remain necessary to validate model outputs, and suggests that a coordinated effort of large scale accumulation measurements could aid in reducing uncertainties.

The mass balance of the GrIS, which is the difference between surface mass balance, ice discharge and basal mass balance, can be determined using space/airborne altimetry (using e.g. CryoSat, IceSat), satellite gravimetry (GRACE) or the input-output method [180–182]. Mass change on regional and ice-sheet wide scales can be quantified directly from gravimetry data, whereas with altimetry data it is necessary to make assumptions about ice/firn/snow density

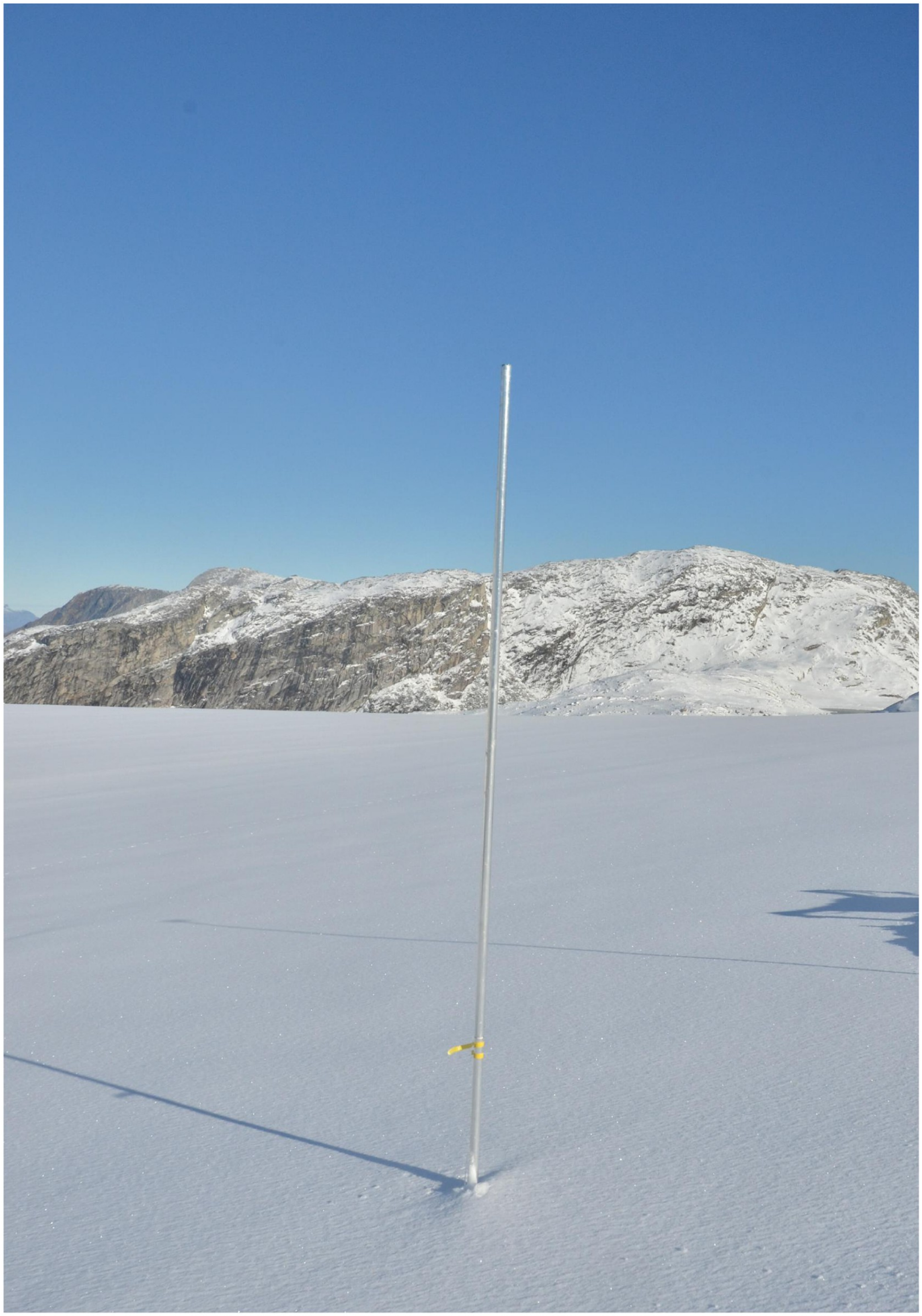

Fig 5. Example of an ablation stake installed at Qassinnguit Sermiat in Kobbefjord, SW Greenland (image credit: Jakob Abermann).

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for the volume to mass conversion [181, 183]. The input-output method on the other hand requires the estimation of SMB from RCMs, the measurement of ice discharge by determining ice flow and ice thickness at the grounding line [181, 183]. Basal mass balance has only recently been included in mass balance estimates as it remains difficult to accurately quantify [183, 184]. A comparison of outputs of the above methods has shown that they are generally in good accordance with each other, however discrepancies remain based on the respective strengths and weaknesses of each method [162].

Recent advances in quantifying SMB for the GrIS have mainly been made in the modeling, and satellite and airborne remote sensing realms, which have seen increases in spatial and temporal resolution. In-situ observations of SMB remain crucial to validate modeling and remote sensing data products, and while improvements have been made to methods and instrumentation, conducting these measurements is challenging. Future advances could see increased automation of in-situ measurements (as has been seen in weather stations), or the development of novel instruments that can be deployed autonomously.

5 Monitoring basal processes

Basal motion drives ice speeds in Greenland, yet it presents a major source of uncertainty when modeling ice flow [185]. The structural makeup of the bed [186], the temperature of basal ice [187], and distribution of basal water pressure [188, 189] all govern the mechanics of slip, but are notoriously difficult to assess in-situ. Over the past decades, two lines of inquiry have motivated extensive research into Greenland's basal processes: i) the percentage of the bed undergoing slip, and ii) the relationship between ice speed and basal traction (commonly referred to as the slip law). In recent years, emerging evidence also suggests that transient forcings occurring on timescales of days to weeks may push sliding dynamics beyond "steady state" conditions typically assumed in ice flow models [190–194]. Given the scale of this problem, diverse methodologies have been used to probe these questions over the past two decades, such as custom borehole instrumentation [195, 196], geophysics [197–200], laboratory experiments [201], and large-scale inversions for basal drag using satellite imagery [202–204].

Bed topography and composition

For much of Greenland, the landscape beneath the ice is a first-order control on ice dynamics [196]. Glacier beds exist on a spectrum spanning rigid bedrock (hard beds) and unconsolidated sediment (soft beds), with many being an intermediate mixture of both. The composition and geometry of the bed determines the form of slip law [203, 205, 206], dictates the architecture and evolution of the basal hydrologic system [188], controls the stability of the grounding zone [152], and regulates sediment production and erosion [207]–among myriad other critical processes. Thus, accurately characterizing these attributes is vital for understanding ice sheet behavior and refining predictive models of ice flow.

Mapping Greenland's subglacial topography has been a monumental undertaking, encompassing decades of research across spatial scales spanning orders of magnitude [208–210]. Bed elevation can be estimated as the difference between known ice thickness and the corresponding ice surface elevation. Since the early 1970s, radar echo sounding (RES) has been the primary means of measuring ice thickness, inferring thickness based on two-way travel times of transmitted radio waves reflected off the ice-bed interface. Over the past two decades, significant advances in radar technology and processing workflows for both surface and airborne surveys have revealed unprecedented detail into the morphology of Greenland's bed, though much uncertainty remains [210, 211]. With the launch of NASA's Operation IceBridge (2009–2019), airborne radar coverage of Greenland increased by more than threefold, adding more than 580,000 km of new flight tracks [212]. Additionally, the development of ground-based swath-imaging radar systems [213, 214] and detailed analysis of wide-band airborne acquisitions [215, 216] have resolved fine-scale bed morphologies absent in bed-map products but which contribute meaningfully to basal friction [187].

For meaningful application in numerical ice-sheet models, discrete observations of bed elevation must be integrated into a unified bed-map. The culmination of this work to date is BedMachine, a digital elevation model of Greenland's subglacial topography interpolated from available ice thickness/surface elevation data and informed by considerations of mass conservation [70]. In its current form, it provides a map of bed topography/bathymetry at a 150-m horizontal grid resolution, with seamless transitions at the ice-ocean interface. Accuracy across the bed is inconsistent due to variable spatial coverage of radar acquisitions, but as future work continues to fill in regions with sparse data, model resolution and accuracy will continue to improve. Overlaying geostatistical models of bed roughness derived from deglaciated terrain over the BedMachine's coarser topography has also proven successful for adding further realism to sliding models [187].

Established methods to constrain subglacial topography can be applied across Greenland through airborne surveys, but discriminating bed composition at the ice-sheet scale presents far greater challenges. The most prominent methods, namely borehole experiments or active seismic surveys, require on-ice instrument deployment and consequently yield datasets with comparatively limited spatial coverage. Boreholes offer direct access to the ice-bed interface but are limited to a point. Numerous campaigns have drilled to Greenland's bed since the 1960s [217], but the frequency and spatial coverage of this work has increased in recent years as hot-water drilling technology improved [218]. These studies have revealed both hard [195] and soft [219] bed conditions beneath Greenland's ice streams. Obtaining physical samples of the substrate can be invaluable, as they provide direct insight into past climatic conditions [220], subglacial geology [186], and physical properties of the bed that impact ice dynamics, such as sediment grain size distribution [205] or permeability [221]. To date, only two campaigns have successfully recovered significant volumes of subglacial material, including the recently rediscovered basal till of the Camp Century core [217]. However, ongoing work by the GreenDrill project aims to recover subglacial bedrock cores along multiple transects, making it the most extensive sampling campaign attempted in Greenland to date [222].

Active seismic methods are commonly used to characterize bed conditions over spatial scales on the order of 1–10 km [223]. Bed properties, such as porosity and material composition, directly influence the strength of acoustic waves reflected off the ice-bed interface and thus can be inferred by analyzing the amplitudes of seismic returns. Established techniques use 1) normal incident reflections to derive acoustic impedance of the bed or 2) analyze the seismic amplitude variation with offset (AVO) (alternatively referred to as amplitude variation with angle), which identifies bed type based on the relationship between the reflection coefficient and the angle of incidence [224]. Both techniques have successfully delineated regions of dilatant till, stiff/dewatered till, and bedrock on Greenland's ice streams [225, 226]. Additionally, an emerging technology known as distributed acoustic sensing has demonstrated its viability in characterizing the physical properties of the bed (Fig 6) [227, 228]. To significantly expand spatial coverage across the ice sheet, a future path forward may involve coupling active seismic data with airborne radar, as was recently demonstrated on Rutford Ice Stream, West Antarctica [229]. By calibrating radar reflectivity data with sediment properties derived from overlapping active seismic experiments, bed properties can be constrained beyond the footprint of the seismic survey.

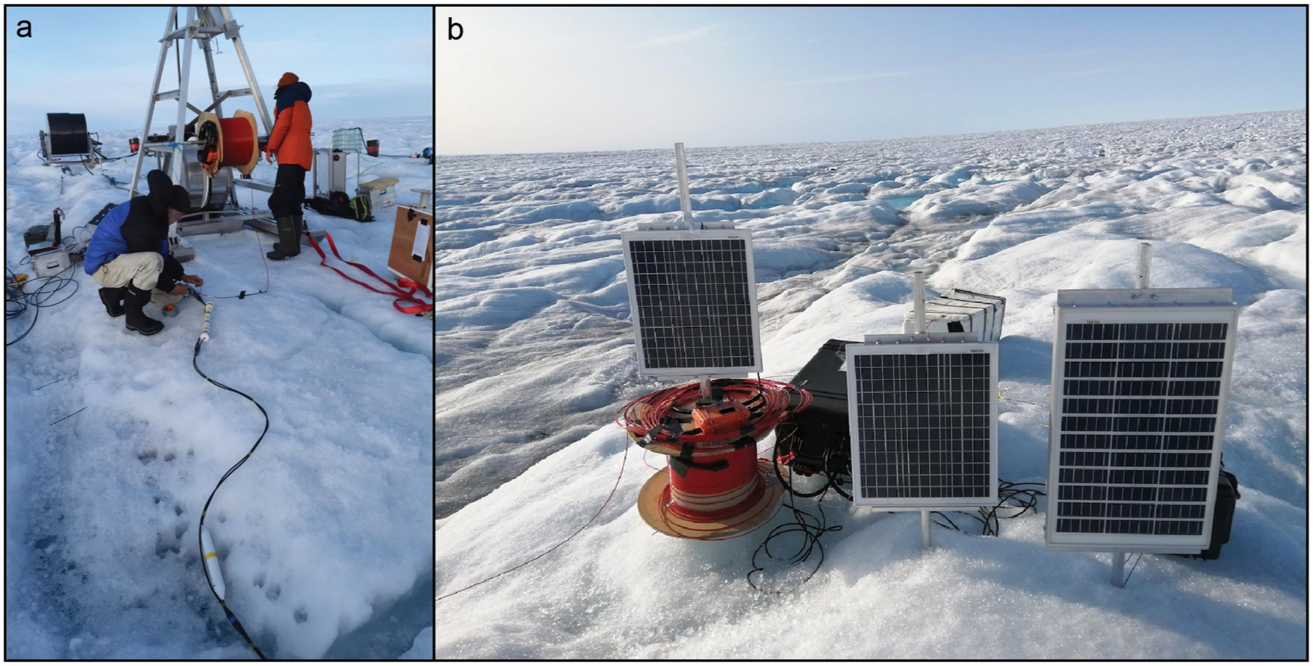

Fig 6. a) Distributed Acoustic Sensing (DAS) and Distributed Temperature Sensing (DTS) cables being installed down a borehole in Sermeq Kujalleq (Store Glacier), Greenland. Both are contained in the red cable on the spool, and discrete temperature and pressure sensors (black cable) are deployed alongside it (image credit: Adam Booth/RESPONDER team). b) Power supply and spooled DTS cable for remote deployment (image credit: Robert Law/ RESPONDER team) [244].

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Basal sliding

Ice velocities observed at a glacier's surface arise from strain in the ice column, displacement along the ice-bed interface and potentially deformation in a subglacial sediment layer if present. Understanding how forward motion is partitioned between these processes is crucial for determining key properties such as ice viscosity, rheology, basal drag, or the correct form of the slip law—elements that collectively represent the largest sources of uncertainty in modeling ice dynamics. Surface velocities are increasingly well-constrained through satellite imagery; however, direct measurements of basal motion remain sparse. Furthermore, efforts to invert for basal drag are encumbered by large uncertainties related to temperature and rheology of ice [230]. It is evident that slip plays a significant role for rapid, marine-terminating outlet glaciers, as the observed surface speeds in these regions are unlikely to be attributed to viscous creep alone. However, the situation is more opaque for slower land-terminating glaciers along Greenland's margins, where observed surface velocities could arise solely from deformation in warm, low viscosity ice, basal sliding, or a combination of both. Over the past two decades, borehole arrays equipped with inclinometers, temperature probes, and basal sensors have constrained basal motion for numerous glaciers in Greenland [92, 196, 219, 231, 232]. These studies revealed significant and spatially variable basal slip, accounting for 40% to 96% of observed surface velocities and highlighted the importance of enhanced deformation in pre-Holocene basal ice. Perhaps most surprisingly, basal motion was shown to constitute over 90% of the observed surface speeds for grounded glaciers along Greenland's western margin, even under winter conditions with minimal meltwater flux to the glacier bed [196].

The relationship between drag at the glacier bed and ice speed is an area of active research concerning Greenland's glaciers. Numerical models often employ a Weertman-style slip law, where basal traction scales proportionally with the speed of ice, raised to an exponent, 1/m (typically, m is around 3 for hard beds and exceeds 10 for soft beds). However, applying this relationship uniformly across Greenland's varied bed conditions raises doubts about its physical basis [202]. Subglacial cavities that form in the lee of bed obstacles with irregular bed geometry or soft-sediment deformation can lead to a rate independence between basal drag and ice velocity, giving rise to the "regularized Coulomb" slip relationship [205, 206, 233]. In this case, drag is tied to the effective stress at the bed but remains independent of slip speed once a certain threshold velocity is reached. At the ice-sheet scale, the slip law has been estimated across Greenland by inverting for basal drag with a hierarchical approach that integrated multiple methods to reduce uncertainties in model parameters and then related to multi-year average surface velocities [203]. These findings suggest that hard-bed physics dominate over much of Greenland's grounded ice, well-characterized by a Weertman-style slip law with m = 3. Nevertheless, significant portions of the bed, particularly in fast-flowing areas in the northeast, more closely resemble Coulomb behavior. Subsequent work in the northwest sector, however, showed that the regularized Coulomb slip law best fit their observations [204]. Given these discrepancies and the importance of the problem, further work on this topic is warranted.

Lastly, a persistent source of uncertainty in parameterizing glacier sliding is the role that entrained basal debris ice plays in modulating friction at the ice-bed interface. This could include both a basal layer of frozen sediment ("frozen fringe"), isolated abrading clasts, or sparse, silt-sized debris. Experimental and modeling efforts suggest that these could set bed strength [234], influence slip stability [235–237], increase basal drag [238, 239], control erosion rates [240, 241], explain seismic tremors proportional to ice velocity [200], alter the form of the slip law [242], and significantly change ice viscosity [243]. However, little is currently known about the relevance of these processes at the ice-sheet scale in Greenland. Constraining the volumetric concentration of basal debris and its spatial distribution, and then incorporating these physics into ice sheet models would be valuable.

Subglacial hydrology

Previous studies have shown that subglacial hydrology is a key driver of seasonal ice flow velocities in Greenland, which highlights the importance of monitoring and measuring parameters pertaining to the base of glaciers [245–247]. Direct observations of the subglacial hydrologic system however remain difficult to obtain. Past efforts to directly observe subglacial freshwater flux necessitated the drilling of boreholes and lowering sensors attached to cables into the system. However, the movement of the glacier and the presence of thick cold ice further complicates repeat observations, as cables might fail due the strain exerted by the ice and boreholes can close rapidly (< 1 day) [248]. While these methods have allowed to improve our understanding of subglacial hydrology, they are usually conducted on relatively small spatio-temporal scale. Recent advances in technology have allowed to measure parameters at depth, with data being transferred in real-time [93]. The Cryoegg, which is a new device that is currently being field tested, would allow to measure electric conductivity, temperature and pressure at depth, with the data being transmitted using radio transmission up to a thickness of 500 m [93]. Technological advances like this are anticipated to reveal new insights into the subglacial hydrology as well as ice dynamics at depth. Using airborne and satellite observations, recent studies identified subglacial lakes within the ablation and accumulation zone, thereby improving our understanding of subglacial hydrology [249, 250]. While remote sensing data is the most sensible method to investigate subglacial hydrology on an ice sheet-wide scale, in-situ observations remain crucial to corroborate these data products.

6 Monitoring climate forcings

Glacier variability in Greenland is significantly influenced by oceanic and atmospheric forcings thus sustained monitoring of these parameters is crucial to gain insights into the response of glaciers to changes in climate. In recent years, advances in technology have enabled automation of weather stations around the GrIS with data being transmitted via satellite and available in near-real time. In-situ measurements of oceanographic parameters have also increased over the last decades but data is more difficult to obtain as will be discussed in the following paragraph.

Oceanic forcings

Previous studies have found that marine-terminating glaciers in Greenland are highly sensitive to the influx of warm ocean waters [107, 251, 252], and that submarine melting at the terminus is considerably larger than previously thought [253, 254]. To improve our understanding of submarine processes at glacier termini, increased efforts have been made to measure and monitor oceanographic parameters in Greenlandic fjords [255]. NASA's Oceans Melting Greenland (OMG) mission, which started in 2015, has been one of the most comprehensive long-term collection of ocean parameters in recent years [256]. The project conducted annually repeated measurements at approximately 250 glaciers over the past five years using CTD probes [257]. The project has provided crucial data to improve our understanding of the influence of ocean forcing on the marine-terminating glaciers of the Greenland Ice Sheet [72, 258]. On smaller spatio-temporal scales, oceanographic data in fjords is often collected for specific sites using ship-deployed measurements, longer-term anchored moorings (e.g. Sermilik fjord, SE Greenland or in Nuup Kangerlua (Godthåbsfjord), SW Greenland) [259, 260]. These measurements can provide valuable information to investigate the influence of ocean forcings on marine-terminating glacier variability [111], and can be useful to improve our understanding of the influence of warm Atlantic waters on in-fjord conditions [261]. A recent study however showed, that processes at the ice-ocean interface are highly dynamic and suggested that increased efforts should be made to collect high temporal resolution data [144].

Other localised efforts have been made by attaching sensors, which record ocean temperature, pressure, conductivity, and other parameters, to e.g. seals [262], narwhals [263], and halibut (pers.conv. David Holland & Aqqalu Rosing-Asvid). These methods have been successfully applied in Sermilik fjord, SE Greenland, and Illulisat Icefjord, CW Greenland, and produced up to annual timeseries of ocean parameters. These methods can produce up to annual timeseries, but they have not yet been applied on larger scales. Many current studies rely on reanalysis data products such as the Arctic Subpolar Gyre sTate Estimate (ASTE), Estimating the Circulation and Climate of the Ocean (ECCO) or EN4, which have seen a significant increase in spatial resolution over the past decade [72, 139, 264–266]. These data products are often informed by observational data, however the difference in resolution and general lack of data complicates these efforts [264]. While these reanalysis datasets have comparatively good coverage on the continental shelf areas of Greenland, they are not able to sufficiently resolve conditions at the fjord level, which makes investigating ice-ocean interactions challenging [107].

The increase in efforts to observe and monitor oceanographic parameters has provided crucial data to improve our understanding of the response of glaciers to changes in ocean forcing. Yet, sustained measurements of oceanographic data near glacier termini and within fjords remain scarce and are often focused on areas with highly dynamic tidewater glaciers [107, 267]. In order to gain further insights into the processes at the ice-ocean boundary and to reduce uncertainties in sea level rise projections, long-term monitoring of ocean parameters is needed. Observations should ideally be acquired within all fjords that contain tidewater glaciers around the GrIS, and the establishment of a Greenland-wide monitoring network has been proposed in the past [107]. However, due to the immense effort that would be required to install, maintain and finance such a project, it has not been implemented yet.

We suggest that increased efforts should be made to measure oceanic parameters at tidewater glaciers, that have been identified to contribute the most to mass loss from the GrIS by previous studies and that are currently not established megasites [54, 78, 268]. Where possible, permanent moorings could be installed to acquire long-term observations, which could provide insights into the influence of submarine melting on tidewater glacier retreat as well as ocean heat transfer and storage [260, 261, 269, 270]. At sites where this is not possible, repeated ship- or airborne CTD measurements on annual or shorter timescales would be beneficial to improve our understanding of ice-ocean interaction processes [271, 272].

Atmospheric forcings

Glacier dynamics are undoubtedly influenced by the atmosphere through air temperatures, surface albedo and precipitation. Over the past decades, the warming climate has contributed significantly to the retreat, thinning and acceleration of glaciers and Arctic Amplification is expected to increase this impact [273, 274]. While the number of weather stations in Greenland has increased over the past decades, there are still relatively few sustained long-term atmospheric monitoring stations around the GrIS. The Geological survey of Denmark and Greenland (GEUS) maintains 25 automated weather stations through the Program for Monitoring of the Greenland Ice Sheet (PROMICE) since 2007. These stations are strategically placed around the GrIS to provide information on surface air temperatures, wind speed, precipitation, solar radiation and other parameters, which are transmitted via satellite and can be accessed in near-real time. A similar program is conducted by the University of Utrecht's Institute for Marine and Atmospheric Research (IMAU), which started monitoring climate parameters in 1996. The stations are located along the K-transect, central western Greenland and on the eastern ice margin, with four of their eight automated weather stations still being operational. Amongst temperature, wind speed, radiation and precipitation, the IMAU weather stations also measure snow temperature, melt and surface height with data being transmitted in near real-time. Another long-term monitoring program is maintained through the Danish Meteorological Institute (DMI), which maintains 91 weather stations around Greenland since 1958 [275]. These weather stations record similar parameters as the PROMICE program, however the DMI also provides historical blended weather data products which start as early as 1748 and is useful to investigate long-term trends in glacier dynamics [276]. The data collected by these large-scale monitoring programs provide valuable information to advance our understanding of the relationship between atmospheric forcings and glaciers of the GrIS, and is also important to validate reanalysis data products. Other seasonal to multi-annual weather stations are often installed by individual research groups and are maintained by researchers rather than institutions (e.g. [277] in NW Greenland; University of Liverpool at Narsap Sermia; University of Edinburgh at Kangiata Nunaata Sermia; pers.conv). There is currently no overview of atmospheric monitoring stations that have been installed by individual research groups, though the data could help to create a more complete picture of climate and weather conditions around Greenland.

Atmospheric monitoring stations are mostly positioned across the interior of the GrIS, and near large, dynamic tidewater glaciers. While monitoring climate conditions at all tidewater is neither economically feasible nor necessary, as neighboring tidewater glaciers often experience similar conditions, there is still room for improving current monitoring efforts [152]. The currently operating weather station networks could be expanded to include tidewater glaciers that have seen a recent increase in mass loss, which would allow to investigate the relationship between climate forcings and glacier retreat in more detail [54, 78, 268]. Instrumentation for a network expansion might be readily available, however the installation and maintenance of additional weather stations comes at a significant economical cost, i.e. funding for institutions that operate these networks should be increased. Another, less costly step would be the establishment of a database that combines atmospheric observations from institutions as well as individual research groups to make data easily available.

7 Research in Greenland: Best practices

Scientists from all around the world conduct research in Greenland to study different aspects of the GrIS and climate change. This research was, and still often is, conducted without formal coordination between international institutions or inclusion of Greenlandic institutions and researchers. We therefore consider it necessary to address some of the issues with conducting field-based research in Greenland in this review.

Coordination and inclusivity of science

The latest Greenland Research Strategy report states that future research in Greenland should be conducted in cooperation with Greenlandic research organizations such as the Greenland Institute of Natural Resources, Asiaq Greenland Survey or the Arctic Hub [278]. In the current academic landscape, research projects are often funded by national bodies which only provide funding to researchers that are based within the country of the national body [279]. This prevents the inclusion of Greenlandic-based researchers in projects at the proposal stage and their participation in international collaborative research [280]. The continued efforts from the international research community to include Greenland-based researchers in future or ongoing projects, without including them at the proposal stage, has led to an overwhelming amount of requests for collaboration without distinct funding [280]. It should be noted, that Greenlandic based researchers often conduct more applied research, which has a more direct impact on society, whereas international research is focused on answering fundamental questions [280]. While this difference in approaches might appear as an impediment to future collaboration, it could also be seen as a chance toward the development of co-productive research [280]. More recent funding programs, such as the National Science Foundations' Navigating the New Arctic (NNA), have recognized this issue and allowed funding to be awarded to foreign organizations [281]. While funding agencies are providing more and more such opportunities, they still remain relatively sparse in the global academic landscape.

Field-based studies conducted by international scientists are largely not coordinated with Greenland-based institutions or local communities, and relevant research findings are thus often not available to those that are most impacted [282]. The government of Greenland is currently exploring legal options to ensure that all future research projects are registered in a central portal, similar to the Danish-operated Isaaffik, by the end of 2024 [278]. While the government is working on achieving this goal, we suggest that the science community should strongly consider registering ongoing and future research projects on Isaaffik. Contributing to these Greenlandic research overview efforts will allow researchers to find potential overlap with other projects, thereby fostering collaboration, and also improve the dissemination of results to and communication with local communities. The government further aims to make the results of research conducted in Greenland accessible and usable for the general public, policymakers and businesses [278].

In recent years, science communication and outreach has become more popular amongst international scientists and increased efforts have been made towards disseminating research findings in Greenlandic communities, however there is still potential for improvement [283]. In principle, funding bodies need to increase the number of project solicitations that allow the funding and inclusion of foreign/Greenlandic researchers, which will lead to collaboration and co-production of research [284]. A recent study found that the Greenlandic youth are particularly unaware of the anthropogenic causes of climate change, thus scientists that conduct research in Greenland are encouraged to reach out to local schools to engage students in polar science, embed climate change in the curriculum and raise awareness about their ongoing research [283]. A successful example of inclusion of coastal communities and schools in science can be found at Petersburg High School, Alaska, where students have been surveying LeConte Glacier since 1983. These surveys do not only provide valuable information for scientific research, but are also used to inform the general public about the state of the glacier [285]. Outreach could further be improved by increasing the number of international and collaborative summer schools or educational workshops such as the Joint Science Education Project (JSEP). Since its initiation in 2007, the JSEP brings together students and teachers from Denmark, Greenland and the USA with the aim to engage students in (polar) science and establish relationships that could lead to future collaborations. We suggest that such outreach efforts should be increased, as projects like JSEP have shown to be a great way to disseminate science in communities and across cultural borders, and establish relationships between research organizations [286]. We further strongly encourage international scientists to dedicate time for outreach in Greenland in their project proposal, establish relationships with Greenlandic institutions and communities where possible, and support the government of Greenland in their efforts of making research findings available for Greenlandic people.

Additionally, we recommend research teams working in Greenland to conduct pre-field discussions of expectations and roles within the group and to follow the lessons learned summary from [287]. This can lead to an increased level of respect and member belonging which in return creates safer work environments and better science outcomes [287, 288].

8 Conclusion

This review shows that in-situ monitoring of most glaciological processes has seen significant advances in the past decades, and that the cryosphere community has made considerable progress in gaining new insights into Greenland climate and glacier dynamics. New technologies in particular have allowed to develop improved instrumentation, which includes novel data acquisition and transmission methods. This, combined with an increase in spatial extent of measurements and in temporal resolution, has provided the basis to provide significant new insight into glacier dynamics over the past decades.

However, we also identified processes that would greatly benefit from an increase in in-situ monitoring in order to answer fundamental questions of ice dynamics, and to provide additional data for validation of numerical model output. As has been shown by previous studies, the monitoring of ocean conditions at the termini of marine-terminating glaciers remains challenging and only few observations exist. Long-term and large scale observations are however necessary to better understand the influence of submarine melting on glacier retreat and reduce uncertainties in sea level rise projections [107]. Relatively few in-situ observations also exist for processes that occur at the bed of glaciers, as access is inherently difficult. Future advances in in-situ instrumentation are anticipated to provide new insights into basal processes, while increases in airborne surveys and in-situ measurements might help to better constrain bedrock topography. Satellite data as well as numerical models and reanalysis products have seen improvements in spatio-temporal resolution, however in-situ observations remain crucial for validation of models and reanalysis data. Hence, current programs that provide in-situ measurements of glacier and climate dynamics should be expanded, and data access should be simplified. As GrIS-wide in-situ monitoring of the above discussed processes is not economically viable, increased monitoring efforts should particularly be considered at those tidewater glaciers that have been shown to significantly contribute to mass loss from the GrIS, or that have seen significant changes in their dynamics in the past.

The authors of this review further wanted to address some of the practices that could be improved when conducting research in Greenland. We identified five key points that international researchers should take into consideration when conducting field-based research:

1. Register Greenland-based research on Isaaffik to support the efforts of the government of Greenland, and share your results via the platform with the general public.
2. Lobby with funding agencies for inclusivity of local and indigenous minorities, and direct financial flow to those.
3. Include Greenlandic researchers in projects at the proposal stage when possible to enable them to receive funding for their involvement.
4. Include outreach in the proposal and increase outreach efforts when conducting field-based research, especially amongst the youth.
5. Increase cross-collaborative projects for students, teachers and researchers by providing summer schools or similar opportunities.

In general, the review has shown that collaboration across countries and institutions, and the sharing of data and results, is crucial for future progression in the cryosphere field.

Supporting information

S1 Text. References for Fig 1.
(PDF)

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References

1. Agassiz L.Études sur les glaciers. Aux frais de l'auteur. En commission chez Jent et Gassmann, libraires; 1840.
2. Agassiz L. The glacial theory and its recent progress. The Edinburgh New Philosophical Journal. 1842; 33.
3. Forbes JD. Travels through the Alps of Savoy and other parts of the Pennine chain: with observations on the phenomena of glaciers. A. and C. Black; 1845.
4. Godwin-Austen HH. On the glaciers of the Mustakh Range. The Journal of the Royal Geographical Society of London. 1864; 34:19–56. https://doi.org/10.2307/1798464
5. Muir J. The Discovery of Glacier Bay. The Century Magazine. 1895; 5(2).

6. Russell IC. The glaciers of North America. The Geographical Journal. 1898; 12(6):553–564. https://doi.org/10.2307/1774274
7. Tare RS. Former extension of Cornell Glacier near the southern end of Melville Bay. Bulletin of the Geological Society of America. 1896; 8(1):251–268. https://doi.org/10.1130/GSAB-8-251
8. Nordenskiöld AE. I.–Account of an Expedition to Greenland in the year 1870. Geological Magazine. 1872; 9(97):289–306. https://doi.org/10.1017/S0016756800465143
9. Chamberlin TC. Recent glacial studies in Greenland. Bulletin of the Geological Society of America. 1894; 6(1):199–220. https://doi.org/10.1130/GSAB-6-199
10. Chamberlin TC. Glacial studies in Greenland. X. The Journal of Geology. 1897; 5(3):229–240. https://doi.org/10.1086/607767
11. Rink H. On the discharge of water from the interior of Greenland, through springs underneath the ice. In: Proceedings of the Royal Geographical Society of London. vol. 7. JSTOR; 1862. p. 76–78.
12. Berglund J. The Decline of the Norse Settlements in Greenland. Arctic Anthropology. 1986; 23(1/2):109–135.
13. Watt-Cloutier S. It's time to listen to the Inuit on climate change; 2018.
14. Haeberli W, Cihlar J, Barry RG. Glacier monitoring within the Global Climate Observing System. Annals of Glaciology. 2000; 31:241–246. https://doi.org/10.3189/172756400781820192
15. Haeberli W. Into the second century of worldwide glacier monitoring: prospects and strategies: a contribution to the International Hydrological Programme (IHP) and the Global Environment Monitoring System (GEMS). UNESCO; 1998. Available from: https://api.semanticscholar.org/CorpusID:126717381.
16. Kjeldsen KK, Korsgaard NJ, Bjørk AA, Khan SA, Box JE, Funder S, et al. Spatial and temporal distribution of mass loss from the Greenland Ice Sheet since AD 1900. Nature Communications. 2015-12; 528(7582):1–17. https://doi.org/10.1038/nature16183 PMID: 26672555
17. Bjørk AA, Kjær KH, Korsgaard NJ, Khan SA, Kjellerup KK, Andresen CS, et al. An aerial view of 80 years of climate-related glacier fluctuations in southeast Greenland. Nature Geoscience. 2012; 5(6):427–432. https://doi.org/10.1038/ngeo1481
18. Lea JM, Mair DWF, Rea BR. Evaluation of existing and new methods of tracking glacier terminus change. Journal of Glaciology. 2014; 60(220):323–332. https://doi.org/10.3189/2014JoG13J061
19. Weidick A. Glacial variations in West Greenland in historacil time. Part I: Southwest Greenland M o Gr. 1959; 158(4).
20. Briner JP, Stewart HAM, Young NE, Philipps W, Losee S. Using proglacial-threshold lakes to constrain fluctuations of the Jakobshavn Isbræ ice margin, western Greenland, during the Holocene. Quaternary Science Reviews. 2010-12; 29(27-28). https://doi.org/10.1016/j.quascirev.2010.09.005
21. Csatho B, Schenk T, Van Der Veen CJ, Krabill WB. Intermittent thinning of Jakobshavn Isbræ, West Greenland, since the Little Ice Age. Journal of Glaciology. 2008; 54(184):131–144. https://doi.org/10.3189/002214308784409035
22. Fettweis X, Box JE, Agosta C, Amory C, Kittel C, Lang C, et al. Reconstructions of the 1900–2015 Greenland ice sheet surface mass balance using the regional climate MAR model. The Cryosphere. 2017; 11(2):1015–1033. https://doi.org/10.5194/tc-11-1015-2017
23. Box JE. Greenland Ice Sheet Mass Balance Reconstruction. Part II: Surface Mass Balance (1840–2010). Journal of Climate. 2013-09; 26(18):6974–6989. https://doi.org/10.1175/JCLI-D-12-00546.1
24. Bamber JL, Tedstone AJ, King MD, Howat IM, Enderlin EM, van den Broeke MR, et al. Land Ice Freshwater Budget of the Arctic and North Atlantic Oceans: 1. Data, Methods, and Results. Journal of Geophysical Research: Oceans. 2018; 123(3):1827–1837. https://doi.org/10.1002/2017JC013605 PMID: 29938150
25. Kirchner G. Observations at Bore Holes Sunk through the Schuchert Gletscher in North-East Greenland. Journal of Glaciology. 1963; 4(36):817–818. https://doi.org/10.3189/S0022143000028409
26. Battle WRB. Glacier Movement in North-East Greenland, 1949: With a Note on Some Subglacial Observations. Journal of Glaciology. 1951; 1(10):559–563. https://doi.org/10.3189/S0022143000026253
27. Olesen OB, Reeh N. Preliminary report on glacier observations in Nordvestfjord, East Greenland. Rapport Grønlands Geologiske Undersøgelse. 1969; 21:41–53. https://doi.org/10.34194/rapggu.v21.7213
28. Rignot E, Box JE, Burgess E, Hanna E. Mass balance of the Greenland ice sheet from 1958 to 2007. Geophysical Research Letters. 2008; 35(20). https://doi.org/10.1029/2008GL035417
29. Tapley BD, Bettadpur S, Watkins M, Reigber C. The gravity recovery and climate experiment: Mission overview and early results. Geophysical Research Letters. 2004; 31(9). https://doi.org/10.1029/2004GL019920

30. Velicogna I, Wahr JJ. Greenland mass balance from GRACE. Geophysical Research Letters. 2005; 32(L18505). https://doi.org/10.1029/2005gl023955

31. Khan SA, Wahr JJ, Bevis MM, Velicogna I, Kendrick EE. Spread of ice mass loss into northwest Greenland observed by GRACE and GPS. Geophysical Research Letters. 2010; 37(L06501). https://doi.org/10.1029/2010gl042460

32. Abdalati W, Zwally HJ, Bindschadler R, Csatho B, Farrell SL, Fricker HA, et al. The ICESat-2 Laser Altimetry Mission. Proceedings of the IEEE. 2010; 98(5):735–751. https://doi.org/10.1109/JPROC.2009.2034765

33. Helm V, Humbert A, Miller H. Elevation and elevation change of Greenland and Antarctica derived from CryoSat-2. The Cryosphere. 2014; 8(4):1539–1559. https://doi.org/10.5194/tc-8-1539-2014

34. Smith BE, Medley B, Fettweis X, Sutterley T, Alexander P, Porter D, et al. Evaluating Greenland surface-mass-balance and firn-densification data using ICESat-2 altimetry. The Cryosphere. 2023; 17 (2):789–808. https://doi.org/10.5194/tc-17-789-2023

35. McMillan M, Leeson A, Shepherd A, Briggs K, Armitage TWK, Hogg A, et al. A high-resolution record of Greenland mass balance. Geophysical Research Letters. 2016; 43(13):7002–7010. https://doi.org/10.1002/2016GL069666

36. van Tiggelen M, Smeets PCJP, Reijmer CH, Wouters B, Steiner JF, Nieuwstraten EJ, et al. Mapping the aerodynamic roughness of the Greenland Ice Sheet surface using ICESat-2: evaluation over the K-transect. The Cryosphere. 2021; 15(6):2601–2621. https://doi.org/10.5194/tc-15-2601-2021

37. Bunce C, Nienow P, Sole A, Cowton T, Davison B. Influence of glacier runoff and near-terminus subglacial hydrology on frontal ablation at a large Greenlandic tidewater glacier. Journal of Glaciology. 2021; 67(262):343–352. https://doi.org/10.1017/jog.2020.109

38. van Dongen E, Jouvet G, Walter A, Todd J, Zwinger T, Asaji I, et al. Tides modulate crevasse opening prior to a major calving event at Bowdoin Glacier, Northwest Greenland. Journal of Glaciology. 2020; 66(255):113–123. https://doi.org/10.1017/jog.2019.89

39. Walter JI, Box JE, Tulaczyk S, Brodsky EE, Howat IM, Ahn Y, et al. Oceanic mechanical forcing of a marine-terminating Greenland glacier. Annals of Glaciology. 2012; 53(60):181–192. https://doi.org/10.3189/2012AoG60A083

40. Podolskiy EA, Sugiyama S, Funk M, Walter F, Genco R, Tsutaki S, et al. Tide-modulated ice flow variations drive seismicity near the calving front of Bowdoin Glacier, Greenland. Geophysical Research Letters. 2016; 43(5):2036–2044. https://doi.org/10.1002/2016GL067743

41. Amundson JM, Truffer M. A unifying framework for iceberg-calving models. Journal of Glaciology. 2010; 56(199):822–830. https://doi.org/10.3189/002214310794457173

42. Cassotto R, Fahnestock M, Amundson JM, Truffer M, Joughin I. Seasonal and interannual variations in ice mélange and its impact on terminus stability, Jakobshavn Isbræ, Greenland. Journal of Glaciology. 2015; 61(225):76–88. https://doi.org/10.3189/2015JoG13J235

43. Ryan JC, Hubbard AL, Box JE, Todd J, Christoffersen P, Carr JR, et al. UAV photogrammetry and structure from motion to assess calving dynamics at Store Glacier, a large outlet draining the Greenland ice sheet. The Cryosphere. 2015; 9(1):1–11. https://doi.org/10.5194/tc-9-1-2015

44. Ahn Y, Box JE. Instruments and Methods: Glacier velocities from time-lapse photos: technique development and first results from the Extreme Ice Survey (EIS) in Greenland. Journal of Glaciology. 2010; 56:723–734. https://doi.org/10.3189/002214310793146313

45. Medrzycka D, Benn DI, Box JE, Copland L, Balog J. Calving Behavior at Rink Isbræ, West Greenland, from Time-Lapse Photos. Arctic, Antarctic, and Alpine Research. 2016; 48(2):263–277. https://doi.org/10.1657/AAAR0015-059

46. Tsutaki S, Sugiyama S, Sakakibara D, Sawagaki T. Surface elevation changes during 2007–13 on Bowdoin and Tugto Glaciers, northwestern Greenland. Journal of Glaciology. 2016; 62(236):1083–1092. https://doi.org/10.1017/jog.2016.106

47. Ahlstrøm AP, Andersen SB, Andersen ML, Machguth H, Nick FM, Joughin I, et al. Seasonal velocities of eight major marine-terminating outlet glaciers of the Greenland ice sheet from continuous in situ GPS instruments. Earth System Science Data. 2013; 5(2):277–287. https://doi.org/10.5194/essd-5-277-2013

48. U S Space Force. Current and Future Satellite Generations; 2023. Available from: https://www.gps.gov/systems/gps/space/#recent [cited 25.08.2023].

49. Sutherland DA, Straneo F, Pickart RS. Characteristics and dynamics of two major Greenland glacial fjords. Journal of Geophysical Research Ocean. 2014-06; 119(6):3767–3791. https://doi.org/10.1002/2013JC009786

50. Schild KM, Sutherland DA, Elosegui P, Duncan D. Measurements of Iceberg Melt Rates Using High-Resolution GPS and Iceberg Surface Scans. Geophysical Research Letters. 2021; 48(3): e2020GL089765. https://doi.org/10.1029/2020GL089765

51. Rysgaard S, Bjerge K, Boone W, Frandsen E, Graversen M, Thomas HÃ, et al. A mobile observatory powered by sun and wind for near real time measurements of atmospheric, glacial, terrestrial, limnic and coastal oceanic conditions in remote off-grid areas. HardwareX. 2022; 12:e00331. https://doi.org/10.1016/j.ohx.2022.e00331 PMID: 35795086

52. Messerli A, Grinsted A. Image georectification and feature tracking toolbox: ImGRAFT. Geoscientific Instrumentation, Methods and Data Systems. 2015; 4(1):23. https://doi.org/10.5194/gi-4-23-2015

53. Mallalieu J, Carrivick JL, Quincey DJ, Smith MW, James WHM. An integrated Structure-from-Motion and time-lapse technique for quantifying ice-margin dynamics. Journal of Glaciology. 2017; 63 (242):937–949. https://doi.org/10.1017/jog.2017.48

54. Fahrner D, Lea JM, Brough S, Mair DWF, Abermann J. Linear response of the Greenland ice sheet's tidewater glacier terminus positions to climate. Journal of Glaciology. 2021; 67(262):193–203. https://doi.org/10.1017/jog.2021.13

55. Palmer H. Observations on the Freshfield Glacier, Canadian Rockies. The Journal of Geology. 1924; 32(5):432–441. https://doi.org/10.1086/623115

56. Odell NE. Observations on the rocks and glaciers of Mount Everest. The Geographical Journal. 1925; 66(4):289–313. https://doi.org/10.2307/1782942

57. Washburn B, Goldthwait R. Movement of South Crillon Glacier, Crillon Lake, Alaska. Bulletin of the Geological Society of America. 1937; 48(11):1653–1664. https://doi.org/10.1130/GSAB-48-1653

58. Finsterwalder R. Geschwindigkeitsmessungen an Gletchern mittels Photogrammetrie. Zeitschrift fur Gletscherkunde. 1931; 19:251–262.

59. Joughin I, Smith BE, Howat IM, Scambos T, Moon T. Greenland flow variability from ice-sheet-wide velocity mapping. Journal of Glaciology. 2010; 56(197):415–430. https://doi.org/10.3189/002214310792447734

60. Joughin I, Howat I, Smith B, Scambos T. MEaSUREs Greenland Ice Velocity: Selected Glacier Site Velocity Maps from InSAR, Version 4.; 2021.

61. Joughin I, Tulaczyk S, Bindschadler R, Price SF. Changes in West Antarctic ice stream velocities: Observation and analysis. Journal of Geophysical Research: Earth Surface. 2002;. https://doi.org/10.1029/2001JB001029

62. Rohner C, Small D, Henke D, Lüthi MP, Vieli A. Multisensor validation of tidewater glacier flow fields derived from sar intensity tracking. Cryosphere Discuss. 2019; 2019:1–27.

63. Roy DP, Huang H, Houborg R, Martins VS. A global analysis of the temporal availability of PlanetScope high spatial resolution multi-spectral imagery. Remote Sensing of Environment. 2021; 264:112586. https://doi.org/10.1016/j.rse.2021.112586

64. Planet PIPS. Available online: https://assets.planet.com/docs.Planet_Combined_Imagery_Product_Specs_letter_screen.pdf (accessed on 28 August 2023). 2022;.

65. Chin J, Coelho R, Foley J, Johnstone A, Nugent R, Pignatelli D, et al. CubeSat101—Basic Concepts and Processes for First-Time CubeSat Developers. NASA; 2017.

66. Altena B, Kääb A. Glacier ice loss monitored through the Planet cubesat constellation. In: 2017 9th International Workshop on the Analysis of Multitemporal Remote Sensing Images (MultiTemp); 2017. p. 1–4.

67. Rezvanbehbahani S, Stearns LA, Keramati R, Shankar S, van der Veen CJ. Significant contribution of small icebergs to the freshwater budget in Greenland fjords. Communications Earth & Environment. 2020; 1(1):31. https://doi.org/10.1038/s43247-020-00032-3

68. HDS Team. PAZ Image Product Guide; 2019.

69. Mankoff KD. Ice discharge for the Greenland ice sheet; 2019. Available from: https://doi.org/10.22008/PROMICE/DATA/ICE_DISCHARGE.

70. Morlighem M, Williams CN, Rignot E, An L, Arndt JE, Bamber JL, et al. BedMachine v3: Complete bed topography and ocean bathymetry mapping of Greenland from multibeam echo sounding combined with mass conservation. Geophysical research letters. 2017; 44(21). https://doi.org/10.1002/2017GL074954 PMID: 29263561

71. Morlighem M, Williams C, Rignot E, An L, Arndt JE, Bamber J, et al. IceBridge BedMachine Greenland, Version 4; 2021.

72. Wood M, Rignot E, Fenty I, An L, Bjørk A, van den Broeke M, et al. Ocean forcing drives glacier retreat in Greenland. Science Advances. 2021; 7(1):eaba7282. https://doi.org/10.1126/sciadv.aba7282 PMID: 33523831

73. Kochtitzky W, Copland L, Van Wychen W, Hugonnet R, Hock R, Dowdeswell JA, et al. The unquantified mass loss of Northern Hemisphere marine-terminating glaciers from 2000–2020. Nature Communications. 2022; 13(1):5835. https://doi.org/10.1038/s41467-022-33231-x PMID: 36220807

74. Mayer C, Schaffer J, Hattermann T, Floricioiu D, Krieger L, Dodd PA, et al. Large ice loss variability at Nioghalvfjerdsfjorden Glacier, Northeast-Greenland. Nature Communications. 2018; 9(1):1–11. https://doi.org/10.1038/s41467-018-05180-x PMID: 30018326

75. Seroussi H, Morlighem M, Rignot EJ, Larour EY, Aubry D, Dhia HB, et al. Ice flux divergence anomalies on 79north Glacier, Greenland. Geophysical Research Letters. 2011; 38(9). https://doi.org/10.1029/2011GL047338

76. Bevan SL, Murray T, Luckman AJ, Hanna E, Huybrechts P. Stable dynamics in a Greenland tidewater glacier over 26 years despite reported thinning. Annals of Glaciology. 2012; 53(60):241–248. https://doi.org/10.3189/2102AoG60A076

77. Brough S, Carr JR, Ross N, Lea JM. Exceptional retreat of Kangerlussuaq Glacier, east Greenland, between 2016 and 2018. Frontiers in Earth Science. 2019; 7(123).

78. King MD, Howat IM, Candela SG, Noh MJ, Jeong S, Noël BPY, et al. Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat. Communications Earth & Environment. 2020; 1 (1):1. https://doi.org/10.1038/s43247-020-0001-2

79. Murray T, Selmes N, James TD, Edwards S, Martin I, O'Farrell T, et al. Dynamics of glacier calving at the ungrounded margin of Helheim Glacier, southeast Greenland. Journal of Geophysical Research: Earth Surface. 2015; 120. https://doi.org/10.1002/2015JF003531 PMID: 27570721

80. Cowton TR, Todd JA, Benn DI. Sensitivity of Tidewater Glaciers to Submarine Melting Governed by Plume Locations. Geophysical Research Letters. 2019; 46(20):11219–11227. https://doi.org/10.1029/2019GL084215

81. Bartholomew ID, Nienow PW, Sole AJ, Mair DWF, Cowton TR, King M. Short-term variability in Greenland Ice Sheet motion forced by time-varying meltwater inputs: Implications for the relationship between subglacial drainage system behavior and ice velocity. Journal of Geophysical Research. 2012; 117(F03002). https://doi.org/10.1029/2011jf002220

82. Ahlstrøm A. Previous glaciological activities related to hydropower at Paakitsoq, Ilulissat, West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport. 2007; 2007(25). https://doi.org/10.22008/gpub/26535

83. Andersen ML, Nettles M, Elosegui P, Larsen TB, Hamilton GS, Stearns LA. Quantitative estimates of velocity sensitivity to surface melt variations at a large Greenland outlet glacier. Journal of Glaciology. 2011; 57(204):609–620. https://doi.org/10.3189/002214311797409785

84. van Dongen ECH, Jouvet G, Sugiyama S, Podolskiy EA, Funk M, Benn DI, et al. Thinning leads to calving-style changes at Bowdoin Glacier, Greenland. The Cryosphere. 2021; 15(2):485–500. https://doi.org/10.5194/tc-15-485-2021

85. Kjeldsen KK, Mortensen J, Bendtsen J, Petersen D, Lennert K, Rysgaard S. Ice-dammed lake drainage cools and raises surface salinities in a tidewater outlet glacier fjord, west Greenland. Journal of Geophysical Research: Earth Surface. 2014; 119(6):1310–1321. https://doi.org/10.1002/2013JF003034

86. Carrivick JL, Tweed FS, Ng F, Quincey DJ, Mallalieu J, Ingeman-Nielsen T, et al. Ice-Dammed Lake Drainage Evolution at Russell Glacier, West Greenland. Frontiers in Earth Science. 2017; 5. https://doi.org/10.3389/feart.2017.00100

87. Bhardwaj A, Sam L, Akanksha, Martín-Torres FJ, Kumar R. UAVs as remote sensing platform in glaciology: Present applications and future prospects. Remote Sensing of Environment. 2016; 175:196–204. https://doi.org/10.1016/j.rse.2015.12.029

88. Jouvet G, Weidmann Y, van Dongen E, Lüthi MP, Vieli A, Ryan JC. High-Endurance UAV for Monitoring Calving Glaciers: Application to the Inglefield Bredning and Eqip Sermia, Greenland. Frontiers in Earth Science. 2019; 7. https://doi.org/10.3389/feart.2019.00206

89. Jones C, Ryan J, Holt T, Hubbard A. Structural glaciology of Isunguata Sermia, West Greenland. Journal of Maps. 2018; 14(2):517–527. https://doi.org/10.1080/17445647.2018.1507952

90. Gätner-Roer I, Naegeli K, Huss M, Knecht T, Machguth H, Zemp M. A database of worldwide glacier thickness observations. Global and Planetary Change. 2014; 122:330–344. https://doi.org/10.1016/j.gloplacha.2014.09.003

91. Sugiyama S, Sakakibara D, Tsutaki S, Maruyama M, Sawagaki T. Glacier dynamics near the calving front of Bowdoin Glacier, northwestern Greenland. Journal of Glaciology. 2015; 61(226):223–232. https://doi.org/10.3189/2015JoG14J127

92. Doyle SH, Hubbard B, Christoffersen P, Young TJ, Hofstede C, Bougamont M, et al. Physical conditions of fast glacier flow: 1. Measurements from boreholes drilled to the bed of Store Glacier, West Greenland. Journal of Geophysical Research: Earth Surface. 2018; 123(2):324–348. https://doi.org/10.1002/2017JF004529

93. Prior-Jones MR, Bagshaw EA, Lees J, Clare L, Burrow S, Werder MA, et al. Cryoegg: development and field trials of a wireless subglacial probe for deep, fast-moving ice. Journal of Glaciology. 2021; 67 (264):627–640. https://doi.org/10.1017/jog.2021.16

94. Chudley TR, Christoffersen P, Doyle SH, Abellan A, Snooke N. High-accuracy UAV photogrammetry of ice sheet dynamics with no ground control. The Cryosphere. 2019; 13(3):955–968. https://doi.org/10.5194/tc-13-955-2019

95. Benn D, Evans DJA. Glaciers and glaciation. Routledge; 2014.

96. Borstad CP, Khazendar A, Larour E, Morlighem M, Rignot E, Schodlok MP, et al. A damage mechanics assessment of the Larsen B ice shelf prior to collapse: Toward a physically-based calving law. Geophysical Research Letters. 2012; 39(18). https://doi.org/10.1029/2012GL053317

97. Benn DI, Warren CR, Mottram RH. Calving processes and the dynamics of calving glaciers. Earth-Science Reviews. 2007; 82(3-4):143–179. https://doi.org/10.1016/j.earscirev.2007.02.002

98. Benn DI, Hulton NRJ, Mottram RH. 'Calving laws','sliding laws' and the stability of tidewater glaciers. Annals of glaciology. 2007; 46:123–130. https://doi.org/10.3189/172756407782871161

99. Pralong A, Funk M. Dynamic damage model of crevasse opening and application to glacier calving. Journal of Geophysical Research: Solid Earth. 2005; 110(B1). https://doi.org/10.1029/2004JB003104

100. Motyka RJ, Cassotto R, Truffer M, Kjeldsen KK, Van As D, Korsgaard NJ, et al. Asynchronous behavior of outlet glaciers feeding Godthåbsfjord (Nuup Kangerlua) and the triggering of Narsap Sermia's retreat in SW Greenland. Journal of Glaciology. 2017; 63(238):288–308. https://doi.org/10.1017/jog.2016.138

101. Davison BJ, Sole AJ, Cowton TR, Lea JM, Slater DA, Fahrner D, et al. Subglacial drainage evolution modulates seasonal ice flow variability of three tidewater glaciers in southwest Greenland. Journal of Geophysical Research: Earth Surface. 2020; 125(9):e2019JF005492. https://doi.org/10.1029/2019JF005492

102. Moon T, Joughin I, Smith B, Van Den Broeke MR, Van De Berg WJ, Noël B, et al. Distinct patterns of seasonal Greenland glacier velocity. Geophysical research letters. 2014; 41(20):7209–7216. https://doi.org/10.1002/2014GL061836 PMID: 25821275

103. Choi Y, Morlighem M, Rignot EJ, Wood MH. Ice dynamics will remain a primary driver of Greenland ice sheet mass loss over the next century. Nature Communications Earth \& Environment. 2021; 2(1):26. https://doi.org/10.1038/s43247-021-00092-z

104. Cheng G, Morlighem M, Mouginot J, Cheng D. Helheim Glacier's Terminus Position Controls Its Seasonal and Inter-Annual Ice Flow Variability. Geophysical Research Letters. 2022; 49(5): e2021GL097085. https://doi.org/10.1029/2021GL097085

105. Downs J, Brinkerhoff D, Morlighem M. Inferring time-dependent calving dynamics at Helheim Glacier. Journal of Glaciology. 2023; 69(274):381–396. https://doi.org/10.1017/jog.2022.68

106. Anandakrishnan S, Bilén SG, Urbina JV, Bock RG, Burkett PG, Portelli JP. The geoPebble System: Design and Implementation of a Wireless Sensor Network of GPS-Enabled Seismic Sensors for the Study of Glaciers and Ice Sheets. Geosciences. 2022; 12(1). https://doi.org/10.3390/geosciences12010017

107. Straneo F, Sutherland DA, Stearns L, Catania G, Heimbach P, Moon T, et al. The Case for a Sustained Greenland Ice Sheet-Ocean Observing System (GrIOOS); 2019. Available from: https://www.frontiersin.org/article/10.3389/fmars.2019.00138.

108. Murray T, Scharrer K, Selmes N, Booth AD, James TD, Bevan SL, et al. Extensive Retreat of Greenland Tidewater Glaciers, 2000–2010. Arctic, Antarctic, and Alpine Research. 2015; 47(3):427–447. https://doi.org/10.1657/AAAR0014-049

109. Goliber S, Black T, Catania G, Lea JM, Olsen H, Cheng D, et al. TermPicks: A century of Greenland glacier terminus data for use in machine learning applications. The Cryosphere. 2022; 2021:1–41. https://doi.org/10.5194/tc-2021-311

110. Cook AJ, Copeland L, Noël BPY, Stokes CR, Bentley MJ, Sharp MJ, et al. Atmospheric forcing of rapid marine-terminating glacier retreat in the Canadian Arctic Archipelago. Science Advances. 2019; 5(3). https://doi.org/10.1126/sciadv.aau8507 PMID: 30891498

111. Murray T, Scharrer K, James TD, Dye SR, Hanna E, Booth AD, et al. Ocean regulation hypothesis for glacier dynamics in southeast Greenland and implications for ice sheet mass changes. Journal of Geophysical Research. 2010; 115(F03026). https://doi.org/10.1029/2009jf001522

112. Holland DM, Thomas RH, Young BD, Ribergaard MH, Lyberth B. Acceleration of Jakobshavn Isbræ triggered by warm subsurface ocean waters. Nature Geoscience. 2008; 1:659–664. https://doi.org/10.1038/ngeo316

113. Mohajerani Y, Wood MH, Velicogna I, Rignot EJ. Detection of Glacier Calving Margins with Convolutional Neural Networks: A Case Study. Remote Sensing. 2019; 11(1):74–13. https://doi.org/10.3390/rs11010074

114. Zhang E, Catania G, Trugman DT. AutoTerm: an automated pipeline for glacier terminus extraction using machine learning and a "big data" repository of Greenland glacier termini. The Cryosphere. 2023; 17(8):3485–3503. https://doi.org/10.5194/tc-17-3485-2023

115. Baumhoer CA, Dietz AJ, Kneisel C, Kuenzer C. Automated Extraction of Antarctic Glacier and Ice Shelf Fronts from Sentinel-1 Imagery Using Deep Learning. Remote Sensing. 2019; 11(21):2529–22. https://doi.org/10.3390/rs11212529

116. Cheng D, Hayes W, Larour E, Mohajerani Y, Wood M, Velicogna I, et al. Calving Front Machine (CALFIN): glacial termini dataset and automated deep learning extraction method for Greenland, 1972–2019. The Cryosphere. 2021; 15(3):1663–1675. https://doi.org/10.5194/tc-15-1663-2021

117. Holzmann M, Davari A, Seehaus T, Braun M, Maier A, Christlein V. Glacier Calving Front Segmentation Using Attention U-Net. 2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS. 2021; p. 3483–3486.

118. Marochov M, Stokes CR, Carbonneau PE. Image classification of marine-terminating outlet glaciers in Greenland using deep learning methods. The Cryosphere. 2021; 15(11):5041–5059. https://doi.org/10.5194/tc-15-5041-2021

119. Davari A, Islam S, Seehaus T, Hartmann A, Braun M, Maier A, et al. On Mathews Correlation Coefficient and Improved Distance Map Loss for Automatic Glacier Calving Front Segmentation in SAR Imagery. IEEE Transactions on Geoscience and Remote Sensing. 2021; 60:1–12. https://doi.org/10.1109/tgrs.2021.3115883

120. Periyasamy M, Davari A, Seehaus T, Braun M, Maier A, Christlein V. How to Get the Most Out of U-Net for Glacier Calving Front Segmentation. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing. 2022; 15:1712–1723. https://doi.org/10.1109/JSTARS.2022.3148033

121. Heidler K, Mou L, Loebel E, Scheinert M, Lefèvre S, Zhu XX. A Deep Active Contour Model for Delineating Glacier Calving Fronts. IEEE Transactions on Geoscience and Remote Sensing. 2023; 61:1–12. https://doi.org/10.1109/TGRS.2023.3296539

122. Loebel E, Scheinert M, Horwath M, Heidler K, Christmann J, Phan LD, et al. Extracting Glacier Calving Fronts by Deep Learning: The Benefit of Multispectral, Topographic, and Textural Input Features. IEEE Transactions on Geoscience and Remote Sensing. 2022; 60:1–12. https://doi.org/10.1109/TGRS.2022.3208454

123. Gourmelon N, Seehaus T, Braun M, Maier A, Christlein V. Calving fronts and where to find them: a benchmark dataset and methodology for automatic glacier calving front extraction from synthetic aperture radar imagery. Earth System Science Data. 2022; 14(9):4287–4313. https://doi.org/10.5194/essd-14-4287-2022

124. Scheick J, Enderlin EM, Hamilton GS. Semi-automated open water iceberg detection from Landsat applied to Disko Bay, West Greenland. Journal of Glaciology. 2019; 65(251):468–480. https://doi.org/10.1017/jog.2019.23 PMID: 31806917

125. O'Leary M, Christoffersen P. Calving on tidewater glaciers amplified by submarine frontal melting. The Cryosphere. 2013; 7(1):119–128. https://doi.org/10.5194/tc-7-119-2013

126. Amaral T, Bartholomaus TC, Enderlin EM. Evaluation of Iceberg Calving Models Against Observations From Greenland Outlet Glaciers. Journal of Geophysical Research: Earth Surface. 2019; 125(6). https://doi.org/10.1029/2019jf005444

127. Bartholomaus TC, Larsen CF, O'Neel S, West ME. Calving seismicity from iceberg–sea surface interactions. Journal of Geophysical Research: Earth Surface. 2012-12; 117(F4). https://doi.org/10.1029/2012JF002513

128. How P, Schild KM, Benn DI, Noormets R, Kirchner N, Luckman AJ, et al. Calving controlled by melt-under-cutting: detailed calving styles revealed through time-lapse observations. Annals of Glaciology. 2019; 60(78):20–31. https://doi.org/10.1017/aog.2018.28

129. James TD, Murray T, Selmes N, Scharrer K, O'Leary M. Buoyant flexure and basal crevassing in dynamic mass loss at Helheim Glacier. Nature Geoscience. 2014; 7(8):593–596. https://doi.org/10.1038/ngeo2204

130. Amundson JM, Truffer M, Lüthi MP, Fahnestock M, West M, Motyka RJ. Glacier, fjord, and seismic response to recent large calving events, Jakobshavn Isbræ, Greenland. Geophysical Research Letters. 2008; 35(22). https://doi.org/10.1029/2008GL035281

131. Evers LG, Smets PSM, Assink JD, Shani-Kadmiel S, Kondo K, Sugiyama S. Long-Term Infrasonic Monitoring of Land and Marine-Terminating Glaciers in Greenland. Geophysical Research Letters. 2022; 49(8):e2021GL097113. https://doi.org/10.1029/2021GL097113

132. Walter F, Olivieri M, Clinton JF. Calving event detection by observation of seiche effects on the Greenland fjords. Journal of Glaciology. 2013; 59(213):162–178. https://doi.org/10.3189/2013JoG12J118

133. Podolskiy EA, Walter F. Cryoseismology. Reviews of Geophysics. 2016; 54(4):708–758. https://doi.org/10.1002/2016RG000526

134. Olsen KG, Nettles M. Patterns in glacial-earthquake activity around Greenland, 2011–13. Journal of Glaciology. 2017; 63(242):1077–1089. https://doi.org/10.1017/jog.2017.78

135. Sergeant A, Mangeney A, Yastrebov VA, Walter F, Montagner JP, Castelnau O, et al. Monitoring Greenland ice sheet buoyancy-driven calving discharge using glacial earthquakes. Annals of Glaciology. 2019; 60(79):75–95. https://doi.org/10.1017/aog.2019.7

136. Jenkins A. Convection-Driven Melting near the Grounding Lines of Ice Shelves and Tidewater Glaciers. Journal of Physical Oceanography. 2011; 41(12):2279–2294. https://doi.org/10.1175/JPO-D-11-03.1

137. McCutchan A, Johnson B. Laboratory Experiments on Ice Melting: A Need for Understanding Dynamics at the Ice-Water Interface. Journal of Marine Science and Engineering. 2022; 10(8):1008. https://doi.org/10.3390/jmse10081008

138. Jackson RH, Shroyer EL, Nash JD, Sutherland DA, Carroll D, Fried MJ, et al. Near-glacier surveying of a subglacial discharge plume: Implications for plume parameterizations. Geophysical Research Letters. 2017; 44:6886–6894. https://doi.org/10.1002/2017GL073602

139. Slater DA, Straneo F, Felikson D, Little CM, Goelzer H, Fettweis X, et al. Estimating Greenland tidewater glacier retreat driven by submarine melting. The Cryosphere. 2019; 13(9):2489–2509. https://doi.org/10.5194/tc-13-2489-2019

140. Jackson RH, Nash JD, Kienholz C, Sutherland DA, Amundson JM, Motyka RJ, et al. Meltwater Intrusions Reveal Mechanisms for Rapid Submarine Melt at a Tidewater Glacier. Geophysical Research Letters. 2019; 47(2):2019GL085335–24. https://doi.org/10.1029/2019GL085335

141. Sutherland DA, Jackson RH, Kienholz C, Amundson JM, Dryer WP, Duncan D, et al. Direct observations of submarine melt and subsurface geometry at a tidewater glacier. Science. 2019; 365 (6451):369–374. https://doi.org/10.1126/science.aax3528 PMID: 31346063

142. Fried MJ, Catania GA, Bartholomaus TC, Duncan D, Davis M, Stearns LA, et al. Distributed subglacial discharge drives significant submarine melt at a Greenland tidewater glacier. Geophysical Research Letters. 2015; 42(21):9328–9336. https://doi.org/10.1002/2015GL065806

143. Rignot E, Fenty I, Xu Y, Cai C, Kemp C. Undercutting of marine–terminating glaciers in West Greenland. Geophysical Research Letters. 2015; 42(14):5909–5917. https://doi.org/10.1002/2015GL064236 PMID: 31031446

144. Podolskiy EA, Kanna N, Sugiyama S. Co-seismic eruption and intermittent turbulence of a subglacial discharge plume revealed by continuous subsurface observations in Greenland. Communications Earth & Environment. 2021; 2(1):66. https://doi.org/10.1038/s43247-021-00132-8

145. Jouvet G, Weidmann Y, Kneib M, Detert M, Seguinot J, Sakakibara D, et al. Short-lived ice speed-up and plume water flow captured by a VTOL UAV give insights into subglacial hydrological system of Bowdoin Glacier. Remote Sensing of Environment. 2018; 217:389–399. https://doi.org/10.1016/j.rse.2018.08.027

146. Pettit EC, Lee KM, Brann JP, Nystuen JA, Wilson PS, O'Neel S. Unusually loud ambient noise in tidewater glacier fjords: A signal of ice melt. Geophysical Research Letters. 2015; 42(7):2309–2316. https://doi.org/10.1002/2014GL062950

147. Xie S, Dixon TH, Holland DM, Voytenko D, Vaňková I. Rapid iceberg calving following removal of tightly packed pro-glacial mélange. Nature Communications. 2019; p. 1–15. https://doi.org/10.1038/s41467-019-10908-4 PMID: 31324756

148. Burton JC, Amundson JM, Cassotto R, Kuo CC, Dennin M. Quantifying flow and stress in ice mélange, the world's largest granular material. Proceedings of the National Academy of Sciences. 2018; 53 (20):201715136. https://doi.org/10.1073/pnas.1715136115 PMID: 29712869

149. Cassotto RK, Burton JC, Amundson JM, Fahnestock MA, Truffer M. Granular decoherence precedes ice mélange failure and glacier calving at Jakobshavn Isbræ. Nature Geoscience. 2021; 14(6):417–422. https://doi.org/10.1038/s41561-021-00754-9

150. Fried MJ, Catania GA, Stearns LA, Sutherland DA, Bartholomaus TC, Shroyer E, et al. Reconciling Drivers of Seasonal Terminus Advance and Retreat at 13 Central West Greenland Tidewater Glaciers. Journal of Geophysical Research: Earth Surface. 2018; 123(7):1590–1607. https://doi.org/10.1029/2018JF004628

151. Brinkerhoff D, Truffer M, Aschwanden A. Sediment transport drives tidewater glacier periodicity. Nature Communications. 2017; 8(1):91. https://doi.org/10.1038/s41467-017-00095-5 PMID: 28733603

152. Catania GA, Stearns LA, Sutherland DA, Fried MJ, Bartholomaus TC, Morlighem M, et al. Geometric controls on tidewater glacier retreat in central western Greenland. Journal of Geophysical Research: Earth Surface. 2018; 123(8):2024–2038. https://doi.org/10.1029/2017JF004499

153. Gilbert R, Nielsen N, Müller H, Desloges JR, Rasch M. Glacimarine sedimentation in Kangerdluk (Disko Fjord), West Greenland, in response to a surging glacier. Marine Geology. 2002; 191(1-2):1–18. https://doi.org/10.1016/S0025-3227(02)00543-1

154. Seifert M, Hoppema M, Burau C, Elmer C, Friedrichs A, Geuer JK, et al. Influence of Glacial Meltwater on Summer Biogeochemical Cycles in Scoresby Sund, East Greenland. Frontiers in Marine Science. 2019; 6. https://doi.org/10.3389/fmars.2019.00412

155. Streuff K, Ó Cofaigh C, Hogan K, Jennings A, Lloyd JM, Noormets R, et al. Seafloor geomorphology and glacimarine sedimentation associated with fast-flowing ice sheet outlet glaciers in Disko Bay, West Greenland. Quaternary Science Reviews. 2017; 169:206–230. https://doi.org/10.1016/j.quascirev.2017.05.021

156. Katlein C, Arndt S, Nicolaus M, Perovich DK, Jakuba MV, Suman S, et al. Influence of ice thickness and surface properties on light transmission through Arctic sea ice. Journal of Geophysical Research: Oceans. 2015; 120(9):5932–5944. https://doi.org/10.1002/2015JC010914 PMID: 27660738

157. Schmidt BE, Washam P, Davis PE, Nicholls KW, Holland DM, Lawrence JD, et al. Heterogeneous melting near the Thwaites Glacier grounding line. Nature. 2023; 614(7948):471–478. https://doi.org/10.1038/s41586-022-05691-0 PMID: 36792738

158. Machguth H, Thomsen HH, Weidick A, Ahlstrøm AP, Abermann J, Andersen ML, et al. Greenland surface mass-balance observations from the ice-sheet ablation area and local glaciers. Journal of Glaciology. 2016; 62(235):861–887. https://doi.org/10.1017/jog.2016.75

159. Schytt V. Glaciological investigations in the Thule Ramp area. vol. 28. Snow, Ice and Permafrost Research Establishment, Corps of Engineers, US Army; 1955.

160. Smeets PCJP, Munneke PK, van As D, van den Broeke MR, Boot W, Oerlemans H, et al. The K-transect in west Greenland: Automatic weather station data (1993-2016). Arctic, Antarctic, and Alpine Research. 2018; 50(1):S100002. https://doi.org/10.1080/15230430.2017.1420954

161. Vernon CL, Bamber JL, Box JE, Broeke MRvd, Fettweis X, Hanna E, et al. Surface mass balance model intercomparison for the Greenland ice sheet. The Cryosphere. 2013; 7(2):599–614. https://doi.org/10.5194/tc-7-599-2013

162. Shepherd A, Ivins E, Rignot E, Smith B, Broeke Mvd, Velicogna I, et al. Mass balance of the Greenland Ice Sheet from 1992 to 2018. Nature. 2020; 579(7798):233–239. https://doi.org/10.1038/s41586-019-1855-2

163. Noël B, van de Berg WJ, Lhermitte S, van den Broeke MR. Rapid ablation zone expansion amplifies north Greenland mass loss. Science Advances. 2019; 5(9):eaaw0123. https://doi.org/10.1126/sciadv.aaw0123 PMID: 31517042

164. Cogley JG, Hock R, Rasmussen LA, Arendt AA, Bauder A, Braithwaite RJ, et al. Glossary of glacier mass balance and related terms, IHP-VII technical documents in hydrology No. 86, IACS Contribution No. 2. International Hydrological Program. UNESCO, Paris.

165. Lister H, Taylor PF. Heat Balance and Ablation on an Arctic Glacier. Meddelelser om Grønland. C.A. Reitzel; 1961. Available from: https://books.google.co.uk/books?id=-zkTzwEACAAJ.

166. Box JE, Steffen K. Sublimation estimates for the Greenland ice sheet using automated weather station observations. Journal of Geophysical Research. 2001; 106(D24):33965–33982. https://doi.org/10.1029/2001JD900219

167. Lenaerts JTM, Smeets CJPP, Nishimura K, Eijkelboom M, Boot W, van den Broeke MR, et al. Drifting snow measurements on the Greenland Ice Sheet and their application for model evaluation. The Cryosphere. 2014; 8(2):801–814. https://doi.org/10.5194/tc-8-801-2014

168. Van As D, Andersen ML, Petersen D, Fettweis X, Van Angelen JH, Lenaerts JTM, et al. Increasing meltwater discharge from the Nuuk region of the Greenland ice sheet and implications for mass balance (1960–2012). Journal of Glaciology. 2014; 60(220):314–322. https://doi.org/10.3189/2014JoG13J065

169. Smith LC, Yang K, Pitcher LH, Overstreet BT, Chu VW, Rennermalm AK, et al. Direct measurements of meltwater runoff on the Greenland ice sheet surface. Proceedings of the National Academy of Sciences. 2017; 114(50):E10622–E10631. https://doi.org/10.1073/pnas.1707743114 PMID: 29208716

170. Mankoff KD, Noël BPY, Fettweis X, Ahlstrøm AP, Colgan W, Kondo K, et al. Greenland liquid water discharge from 1958 through 2019. Earth System Science Data. 2020; 12(4):2811–2841. https://doi.org/10.5194/essd-12-2811-2020

171. Tedesco M, Colosio P, Fettweis X, Cervone G. A computationally efficient statistically downscaled 100 m resolution Greenland product from the regional climate model MAR. The Cryosphere. 2023; 17 (12):5061–5074. https://doi.org/10.5194/tc-17-5061-2023

172. Reijmer CH, van den Broeke MR, Fettweis X, Ettema J, Stap LB. Refreezing on the Greenland ice sheet: a comparison of parameterizations. The Cryosphere. 2012; 6(4):743–762. https://doi.org/10.5194/tc-6-743-2012

173. Bales RC, Guo Q, Shen D, McConnell JR, Du G, Burkhart JF, et al. Annual accumulation for Greenland updated using ice core data developed during 2000–2006 and analysis of daily coastal meteorological data. Journal of Geophysical Research: Atmospheres. 2009; 114(D6). https://doi.org/10.1029/2008JD011208

174. Bales RC, McConnell JR, Mosley-Thompson E, Csatho B. Accumulation over the Greenland ice sheet from historical and recent records. Journal of Geophysical Research: Atmospheres. 2001; 106 (D24):33813–33825. https://doi.org/10.1029/2001JD900153

175. Larson KM, MacFerrin M, Nylen T. Brief Communication: Update on the GPS reflection technique for measuring snow accumulation in Greenland. The Cryosphere. 2020; 14(6):1985–1988. https://doi.org/10.5194/tc-14-1985-2020

176. van de Wal RSW, Greuell W, van den Broeke MR, Reijmer CH, Oerlemans J. Surface mass-balance observations and automatic weather station data along a transect near Kangerlussuaq, West Greenland. Annals of Glaciology. 2005; 42:311–316. https://doi.org/10.3189/172756405781812529

177. Koenig LS, Ivanoff A, Alexander PM, MacGregor JA, Fettweis X, Panzer B, et al. Annual Greenland accumulation rates (2009-2012) from airborne snow radar. The Cryosphere. 2016; 10(4):1739–1752. https://doi.org/10.5194/tc-10-1739-2016

178. Machguth H, MacFerrin M, van As D, Box JE, Charalampidis C, Colgan W, et al. Greenland meltwater storage in firn limited by near-surface ice formation. Nature Climate Change. 2016; 6(4):390–393. https://doi.org/10.1038/nclimate2899

179. Kanagaratnam P, Gogineni SP, Gundestrup N, Larsen L. High-resolution radar mapping of internal layers at the North Greenland Ice Core Project. Journal of Geophysical Research: Atmospheres. 2001; 106(D24):33799–33811. https://doi.org/10.1029/2001JD900191

180. Otosaka IN, Shepherd A, Ivins ER, Schlegel NJ, Amory C, van den Broeke MR, et al. Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020. Earth System Science Data. 2023; 15 (4):1597–1616. https://doi.org/10.5194/essd-15-1597-2023

181. Khan SA, Aschwanden A, Bjørk AA, Wahr JJ, Kjeldsen KK, Kjær KH. Greenland ice sheet mass balance: a review. Reports on Progress in Physics. 2015; 78(4):046801. https://doi.org/10.1088/0034-4885/78/4/046801 PMID: 25811969

182. van den Broeke MR, Bamber J, Ettema J, Rignot E, Schrama E, van de Berg WJ, et al. Partitioning Recent Greenland Mass Loss. Science. 2009; 326(5955):984–986. https://doi.org/10.1126/science.1178176 PMID: 19965509

183. Otosaka IN, Horwath M, Mottram R, Nowicki S. Mass Balances of the Antarctic and Greenland Ice Sheets Monitored from Space. Surveys in Geophysics. 2023. https://doi.org/10.1007/s10712-023-09795-8

184. Mankoff KD, Fettweis X, Langen PL, Stendel M, Kjeldsen KK, Karlsson NB, et al. Greenland ice sheet mass balance from 1840 through next week. Earth System Science Data. 2021; 13(10):5001–5025. https://doi.org/10.5194/essd-13-5001-2021

185. Ritz C, Edwards TL, Durand G, Payne AJ, Peyaud V, Hindmarsh RC. Potential sea-level rise from Antarctic ice-sheet instability constrained by observations. Nature. 2015; 528(7580):115–118. https://doi.org/10.1038/nature16147 PMID: 26580020

186. Cooper MA, Jordan TM, Schroeder DM, Siegert MJ, Williams CN, Bamber JL. Subglacial roughness of the Greenland Ice Sheet: relationship with contemporary ice velocity and geology. The Cryosphere. 2019; 13(11):3093–3115. https://doi.org/10.5194/tc-13-3093-2019

187. Law R, Christoffersen P, MacKie E, Cook S, Haseloff M, Gagliardini O. Complex motion of Greenland Ice Sheet outlet glaciers with basal temperate ice. Science Advances. 2023; 9(6):eabq5180. https://doi.org/10.1126/sciadv.abq5180 PMID: 36763651

188. Flowers GE. Hydrology and the future of the Greenland Ice Sheet. Nature Communications. 2018; 9 (1):1–4. https://doi.org/10.1038/s41467-018-05002-0 PMID: 30013134

189. Maier N, Gimbert F, Gillet-Chaulet F. Threshold response to melt drives large-scale bed weakening in Greenland. Nature. 2022; 607:714–720. https://doi.org/10.1038/s41586-022-04927-3 PMID: 35896647

190. Damsgaard A, Goren L, Suckale J. Water pressure fluctuations control variability in sediment flux and slip dynamics beneath glaciers and ice streams. Communications Earth & Environment. 2020; 1 (1):66. https://doi.org/10.1038/s43247-020-00074-7

191. Zoet LK, Iverson NR, Andrews L, Helanow C. Transient evolution of basal drag during glacier slip. Journal of Glaciology. 2022; 68(270):741–750. https://doi.org/10.1017/jog.2021.131

192. Ultee L, Felikson D, Minchew B, Stearns LA, Riel B. Helheim Glacier ice velocity variability responds to runoff and terminus position change at different timescales. Nature Communications. 2022; 13 (1):6022. https://doi.org/10.1038/s41467-022-33292-y PMID: 36224175

193. McCarthy C, Skarbek RM, Savage HM. Tidal modulation of ice streams: Effect of periodic sliding velocity on ice friction and healing. Frontiers in Earth Science. 2022; 10:719074. https://doi.org/10.3389/feart.2022.719074

194. Warburton KLP, Hewitt DR, Neufeld JA. Shear dilation of subglacial till results in time-dependent sliding laws. Proceedings of the Royal Society A. 2023; 479(2269):20220536. https://doi.org/10.1098/rspa.2022.0536

195. Harper JT, Humphrey NF, Meierbachtol TW, Graly JA, Fischer UH. Borehole measurements indicate hard bed conditions, Kangerlussuaq sector, western Greenland Ice Sheet. Journal of Geophysical Research: Earth Surface. 2017; 122(9):1605–1618. https://doi.org/10.1002/2017JF004201

196. Maier N, Humphrey N, Harper J, Meierbachtol T. Sliding dominates slow-flowing margin regions, Greenland Ice Sheet. Science Advances. 2019; 5:eaaw5406. https://doi.org/10.1126/sciadv.aaw5406 PMID: 31309154

197. Röösli C, Walter F, Husen S, Andrews LC, Lüthi MP, Catania GA, et al. Sustained seismic tremors and icequakes detected in the ablation zone of the Greenland ice sheet. Journal of Glaciology. 2014; 60 (221):563–575. https://doi.org/10.3189/2014JoG13J210

198. Walter F, Chaput J, Lüthi MP. Thick sediments beneath Greenland's ablation zone and their potential role in future ice sheet dynamics. Geology. 2014; 42(6). https://doi.org/10.1130/G35492.1

199. McBrearty IW, Zoet LK, Anandakrishnan S. Basal seismicity of the Northeast Greenland ice stream. Journal of Glaciology. 2020; 66(257):430–446. https://doi.org/10.1017/jog.2020.17

200. Podolskiy EA, Murai Y, Kanna N, Sugiyama S. Ocean-bottom and surface seismometers reveal continuous glacial tremor and slip. Nature communications. 2021; 12(1):3929. https://doi.org/10.1038/s41467-021-24142-4 PMID: 34168146

201. Iverson NR, Zoet LK. Experiments on the dynamics and sedimentary products of glacier slip. Geomorphology. 2015; 244:121–134. https://doi.org/10.1016/j.geomorph.2015.03.027

202. Stearns LA, Van der Veen CJ. Friction at the bed does not control fast glacier flow. Science. 2018; 361 (6399):273–277. https://doi.org/10.1126/science.aat2217 PMID: 29880724

203. Maier N, Gimbert F, Gillet-Chaulet F, Gilbert A. Basal traction mainly dictated by hard-bed physics over grounded regions of Greenland. The Cryosphere. 2021; 15(3):1435–1451. https://doi.org/10.5194/tc-15-1435-2021

204. Choi Y, Seroussi H, Gardner A, Schlegel NJ. Uncovering basal friction in northwest Greenland using an ice flow model and observations of the past decade. Journal of Geophysical Research: Earth Surface. 2022; 127(10):e2022JF006710. https://doi.org/10.1029/2022JF006710

205. Zoet LK, Iverson NR. A slip law for glaciers on deformable beds. Science. 2020; 368(6486):76–78. https://doi.org/10.1126/science.aaz1183 PMID: 32241945

206. Helanow C, Iverson NR, Woodard JB, Zoet LK. A slip law for hard-bedded glaciers derived from observed bed topography. Science Advances. 2021; 7(20):p.eabe7798. https://doi.org/10.1126/sciadv.abe7798 PMID: 33990323

207. Cowton T, Nienow P, Bartholomew I, Sole A, Mair D. Rapid erosion beneath the Greenland ice sheet. Geology. 2012; 40(4):343–346. https://doi.org/10.1130/G32687.1

208. Dowdeswell JA, Evans S. Investigations of the form and flow of ice sheets and glaciers using radio-echo sounding. Reports on Progress in Physics. 2004; 67(10):1821–1861. https://doi.org/10.1088/0034-4885/67/10/R03

209. Morlighem M, Rignot E, Mouginot J, Seroussi H, Larour E. High-resolution ice thickness mapping in south Greenland. Annals of Glaciology. 2014; 55(67):64–70. https://doi.org/10.3189/2014AoG67A088

210. Schroeder DM, Bingham RG, Blankenship DD, Christianson K, Eisen O, Flowers GE, et al. Five decades of radioglaciology. Annals of Glaciology. 2020; 61(81):1–13. https://doi.org/10.1017/aog.2020.11

211. Schroeder DM. Paths forward in radioglaciology. Annals of Glaciology. 2023; p. 1–5. https://doi.org/10.1017/aog.2023.3

212. Rodriguez-Morales F, Gogineni S, Leuschen CJ, Paden JD, Li J, Lewis CC, et al. Advanced multifrequency radar instrumentation for polar research. IEEE Transactions on Geoscience and Remote Sensing. 2013; 52(5):2824–2842. https://doi.org/10.1109/TGRS.2013.2266415

213. Paden J, Akins T, Dunson D, Allen C, Gogineni P. Ice-sheet bed 3-D tomography. Journal of Glaciology. 2010; 56(195):3–11. https://doi.org/10.3189/002214310791190811

214. Jezek K, Wu X, Gogineni P, Rodriguez E, Freeman A, Rodriguez-Morales F, et al. Radar images of the bed of the Greenland Ice Sheet. Geophysical Research Letters. 2011; 38(1). https://doi.org/10.1029/93GL03377

215. Franke S, Jansen D, Beyer S, Neckel N, Binder T, Paden J, et al. Complex basal conditions and their influence on ice flow at the onset of the Northeast Greenland Ice Stream. Journal of Geophysical Research: Earth Surface. 2021; 126(3):e2020JF005689. https://doi.org/10.1029/2020JF005689

216. Franke S, Bons PD, Westhoff J, Weikusat I, Binder T, Streng K, et al. Holocene ice-stream shutdown and drainage basin reconfiguration in northeast Greenland. Nature Geoscience. 2022; 15(12):995–1001. https://doi.org/10.1038/s41561-022-01082-2

217. Bentley CR, Koci BR. Drilling to the beds of the Greenland and Antarctic ice sheets: a review. Annals of glaciology. 2007; 47:1–9. https://doi.org/10.3189/172756407786857695

218. Talalay PG. Hot-Water Ice Drills. Thermal Ice Drilling Technology. 2020; p. 145–250. https://doi.org/10.1007/978-981-13-8848-4_3

219. Ryser C, Lüthi MP, Andrews LC, Hoffman MJ, Catania GA, Hawley RL, et al. Sustained high basal motion of the Greenland ice sheet revealed by borehole deformation. Journal of Glaciology. 2014; 60 (222):647–660. https://doi.org/10.3189/2014JoG13J196

220. Christ AJ, Bierman PR, Schaefer JM, Dahl-Jensen D, Steffensen JP, Corbett LB, et al. A multimillion-year-old record of Greenland vegetation and glacial history preserved in sediment beneath 1.4 km of ice at Camp Century. Proceedings of the National Academy of Sciences. 2021; 118(13): e2021442118. https://doi.org/10.1073/pnas.2021442118 PMID: 33723012

221. Robel AA, Sim SJ, Meyer C, Siegfried MR, Gustafson CD. Contemporary ice sheet thinning drives subglacial groundwater exfiltration with potential feedbacks on glacier flow. Science Advances. 2023; 9(33):eadh3693. https://doi.org/10.1126/sciadv.adh3693 PMID: 37595049

222. Voosen P. Greenland drilling campaign aims for bedrock to trace ice sheet's last disappearance. Science. 2020. https://doi.org/10.1126/science.abd6218

223. Aster RC, Winberry JP. Glacial seismology. Reports on Progress in Physics. 2017; 80(12):126801. https://doi.org/10.1088/1361-6633/aa8473 PMID: 28782729

224. Sheriff RE, Geldart LP. Exploration seismology. Cambridge university press. 1995.

225. Dow CF, Hubbard A, Booth AD, Doyle SH, Gusmeroli A, Kulessa B. Seismic evidence of mechanically weak sediments underlying Russell Glacier, West Greenland. Annals of Glaciology. 2013; 54 (64):135–141. https://doi.org/10.3189/2013AoG64A032

226. Christianson K, Peters LE, Alley RB, Anandakrishnan S Jacobel RW, Riverman KL, Muto A, et al. Dilatant till facilitates ice-stream flow in northeast Greenland. Earth and Planetary Science Letters. 2014; 401:57–59. https://doi.org/10.1016/j.epsl.2014.05.060

227. Booth AD, Christoffersen P, Schoonman C, Clarke A, Hubbard B, Law R, et al. Distributed acoustic sensing of seismic properties in a borehole drilled on a fast-flowing Greenlandic outlet glacier. Geophysical Research Letters. 2020; 47(13):e2020GL088148. https://doi.org/10.1029/2020GL088148

228. Booth AD, Christoffersen P, Pretorius A, Chapman J, Hubbard B, Smith EC, et al. Characterising sediment thickness beneath a Greenlandic outlet glacier using distributed acoustic sensing: preliminary observations and progress towards an efficient machine learning approach. Annals of Glaciology. 2023; p. 1–4. https://doi.org/10.1017/aog.2023.15

229. Schlegel R, Murray T, Smith AM, Brisbourne AM, Booth AD, King EC, et al. Radar derived subglacial properties and landforms beneath Rutford Ice Stream, West Antarctica. Journal of Geophysical Research: Earth Surface. 2022; 127(1):e2021JF006349. https://doi.org/10.1029/2021JF006349

230. Shoji H, Langway CC. Flow-law parameters of the Dye 3, Greenland, deep ice core. Annals of Glaciology. 1988; 10:146–150. https://doi.org/10.3189/S026030550000433X

231. Lüthi M, Funk M, Iken A, Gogineni S, Truffer M. Mechanisms of fast flow in Jakobshavn Isbræ, West Greenland: Part III. Measurements of ice deformation, temperature and cross-borehole conductivity in boreholes to the bedrock. Journal of Glaciology. 2002; 48(162):369–385. https://doi.org/10.3189/172756502781831322

232. Lüthi MP, Funk M, Iken A. Indication of active overthrust faulting along the Holocene-Wisconsin transition in the marginal zone of Jakobshavn Isbræ. Journal of Geophysical Research: Solid Earth. 2003; 108(B11). https://doi.org/10.1029/2003JB002505

233. Joughin I, Smith BE, Schoof CG. Regularized Coulomb friction laws for ice sheet sliding: Application to Pine Island Glacier, Antarctica. Geophysical research letters. 2019; 46(9):4764–4771. https://doi.org/10.1029/2019GL082526 PMID: 31244498

234. Meyer CR, Downey AS, Rempel AW. Freeze-on limits bed strength beneath sliding glaciers. Nature communications. 2018; 9(1):3242. https://doi.org/10.1038/s41467-018-05716-1 PMID: 30104640

235. Zoet LK, Carpenter B, Scuderi M, Alley RB, Anandakrishnan S, Marone C, et al. The effects of entrained debris on the basal sliding stability of a glacier. Journal of Geophysical Research: Earth Surface. 2013; 118(2):656–666. https://doi.org/10.1002/jgrf.20052

236. Lipovsky BP, Meyer CR, Zoet LK, McCarthy C, Hansen DD, Rempel AW, et al. Glacier sliding, seismicity and sediment entrainment. Annals of Glaciology. 2019; 60(79):182–192. https://doi.org/10.1017/aog.2019.24

237. Saltiel S, McCarthy C, Creyts TT, Savage HM. Experimental evidence of velocity-weakening friction during ice slip over frozen till: Implications for basal seismicity in fast moving, soft-bed glaciers and ice streams. Seismological Research Letters. 2021; 92(5):2793–2810. https://doi.org/10.1785/0220200480

238. Hansen DD, Zoet LK. Experimental constraints on subglacial rock friction. Annals of Glaciology. 2019; 60(80):37–48. https://doi.org/10.1017/aog.2019.47

239. Thompson AC, Iverson NR, Zoet LK. Controls on subglacial rock friction: Experiments with debris in temperate ice. Journal of Geophysical Research: Earth Surface. 2020; 125(10):e2020JF005718. https://doi.org/10.1029/2020JF005718

240. Ugelvig SV, Egholm DL. The influence of basal-ice debris on patterns and rates of glacial erosion. Earth and Planetary Science Letters. 2018; 490:110–121. https://doi.org/10.1016/j.epsl.2018.03.022

241. Hansen DD, Brooks JP, Zoet LK, Stevens NT, Smith L, Bate CE, et al. A power-based abrasion law for use in landscape evolution models. Geology. 2023; 51(3):273–277. https://doi.org/10.1130/G50673.1

242. Iverson NR, Helanow C, Zoet LK. Debris-bed friction during glacier sliding with ice–bed separation. Annals of Glaciology. 2019; 60(80):30–36. https://doi.org/10.1017/aog.2019.46

243. Moore PL. Deformation of debris-ice mixtures. Reviews of Geophysics. 2014; 52(3):435–467. https://doi.org/10.1002/2014RG000453

244. Law R, Christoffersen P, Hubbard B, Doyle SH, Chudley TR, Schoonman CM, et al. Thermodynamics of a fast-moving Greenlandic outlet glacier revealed by fiber-optic distributed temperature sensing. Science advances. 2021; 7(20):eabe7136. https://doi.org/10.1126/sciadv.abe7136 PMID: 33990322

245. Davison BJ, Sole AJ, Livingstone SJ, Cowton TR, Nienow PW. The Influence of Hydrology on the Dynamics of Land-Terminating Sectors of the Greenland Ice Sheet. Frontiers in Earth Science. 2019; 7:10. https://doi.org/10.3389/feart.2019.00010

246. Bartholomew I, Nienow P, Sole A, Mair D, Cowton T, King MA. Short-term variability in Greenland Ice Sheet motion forced by time-varying meltwater drainage: Implications for the relationship between subglacial drainage system behavior and ice velocity. Journal of Geophysical Research: Earth Surface. 2012; 117(F3). https://doi.org/10.1029/2011JF002220

247. Wal Rvd, Boot W, Broeke MRvd, Smeets CJPP, Reijmer CH, Donker JJA, et al. Large and Rapid Melt-Induced Velocity Changes in the Ablation Zone of the Greenland Ice Sheet. Science. 2008-07; 321 (5885):111–113. https://doi.org/10.1126/science.1158540 PMID: 18599784

248. Andrews LC, Catania GA, Hoffman MJ, Gulley JD, Lüthi MP, Ryser C, et al. Direct observations of evolving subglacial drainage beneath the Greenland Ice Sheet. Nature. 2014; 514(7520):80–83. https://doi.org/10.1038/nature13796 PMID: 25279921

249. Bowling J, Livingstone S, Sole A, Chu W. Distribution and dynamics of Greenland subglacial lakes. Nature communications. 2019; 10(1):2810. https://doi.org/10.1038/s41467-019-10821-w PMID: 31243282

250. Fan Y, Ke CQ, Shen X, Xiao Y, Livingstone SJ, Sole AJ. Subglacial lake activity beneath the ablation zone of the Greenland Ice Sheet. The Cryosphere. 2023; 17(4):1775–1786. https://doi.org/10.5194/tc-17-1775-2023

251. Straneo F, Hamilton GS, Sutherland DA, Stearns LA, Davidson F, Hammill MO, et al. Rapid circulation of warm subtropical waters in a major glacial fjord in East Greenland. Nature Geoscience. 2010; 3 (3):182. https://doi.org/10.1038/ngeo764

252. Nick FM, Van Der Veen CJ, Vieli A, Benn DI. A physically based calving model applied to marine outlet glaciers and implications for the glacier dynamics. Journal of Glaciology. 2010; 56(199):781–794. https://doi.org/10.3189/002214310794457344

253. Sutherland DA, Straneo F. Estimating ocean heat transports and submarine melt rates in Sermilik Fjord, Greenland, using lowered acoustic Doppler current profiler (LADCP) velocity profiles. Annals of Glaciology. 2012; 53(60):50–58. https://doi.org/10.3189/2012AoG60A050

254. Rignot E, Koppes M, Velicogna I. Rapid submarine melting of the calving faces of West Greenland glaciers. Nature Geoscience. 2010; 3(3):187–191. https://doi.org/10.1038/ngeo765

255. Straneo F, Heimbach P. North Atlantic warming and the retreat of Greenland's outlet glaciers. Nature. 2013; 504(7478):36–43. https://doi.org/10.1038/nature12854 PMID: 24305146

256. Willis J. Oceans Melting Greenland—Why is NASA in Greenland?; 2023. Available from: https://omg.jpl.nasa.gov/about/ [cited 25.08.2023].

257. Fenty I, Willis JK, Khazendar A, Dinardo S, Forsberg R, Fukumori I, et al. Oceans Melting Greenland: Early Results from NASA's Ocean-Ice Mission in Greenland. Oceanography. 2016; 29(4):72–83. https://doi.org/10.5670/oceanog.2016.100

258. Chudley TR, Howat IM, King MD, Negrete A. Atlantic water intrusion triggers rapid retreat and regime change at previously stable Greenland glacier. Nature Communications. 2023; 14(1):21–51. https://doi.org/10.1038/s41467-023-37764-7 PMID: 37076489

259. Mortensen J, Bendtsen J, Lennert K, Rysgaard S. Seasonal variability of the circulation system in a west Greenland tidewater outlet glacier fjord, Godthåbsfjord (64˚N). Journal of Geophysical Research: Earth Surface. 2014; 119.

260. Straneo F, Hamilton GS, Stearns LA, Sutherland DA. Connecting the Greenland Ice Sheet and the ocean: A case study of Helheim Glacier and Sermilik Fjord. Oceanography. 2016; 29(4):34–45. https://doi.org/10.5670/oceanog.2016.97

261. Snow T, Straneo F, Holte J, Grigsby S, Abdalati W, Scambos T. More than Skin Deep: Sea Surface Temperature as a Means of Inferring Atlantic Water Variability on the Southeast Greenland Continental Shelf Near Helheim Glacier. Journal of Geophysical Research: Oceans. 2021; 126(4): e2020JC016509. https://doi.org/10.1029/2020JC016509

262. Sutherland DA, Straneo F, Stenson GB, Davidson FJM, Hammill MO, Rosing-Asvid A. Atlantic water variability on the SE Greenland continental shelf and its relationship to SST and bathymetry. Journal of Geophysical Research Ocean. 2013; 118(2):847–855. https://doi.org/10.1029/2012JC008354

263. Heide-Jørgensen MP, Blackwell SB, Williams TM, Sinding MHS, Skovrind M, Tervo OM, et al. Some like it cold: Temperature-dependent habitat selection by narwhals. Ecology and Evolution. 2020; 10 (15):8073–8090. https://doi.org/10.1002/ece3.6464 PMID: 32788962

264. Nguyen AT, Pillar H, Ocaña V, Bigdeli A, Smith TA, Heimbach P. The Arctic Subpolar Gyre sTate Estimate: Description and Assessment of a Data-Constrained, Dynamically Consistent Ocean-Sea Ice Estimate for 2002–2017. Journal of Advances in Modeling Earth Systems. 2021; 13(5): e2020MS002398. https://doi.org/10.1029/2020MS002398

265. Killick R. EN4.2.2 Product User Guide; 2021.

266. Stammer D, Wunsch C, Giering R, Eckert C, Heimbach P, Marotzke J, et al. Global ocean circulation during 1992–1997, estimated from ocean observations and a general circulation model. Journal of Geophysical Research: Oceans. 2002; 107(C9):1–1–1–27. https://doi.org/10.1029/2001JC000888

267. Straneo F, Heimbach P, Sergienko O, Hamilton G, Catania G, Griffies S, et al. Challenges to Understanding the Dynamic Response of Greenland's Marine Terminating Glaciers to Oceanic and Atmospheric Forcing. Bulletin of the American Meteorological Society. 2013; 94(8):1131–1144. https://doi.org/10.1175/BAMS-D-12-00100.1

268. Kochtitzky W, Copland L, King M, Hugonnet R, Jiskoot H, Morlighem M, et al. Closing Greenland's Mass Balance: Frontal Ablation of Every Greenlandic Glacier From 2000 to 2020. Geophysical Research Letters. 2023; 50(17):e2023GL104095. https://doi.org/10.1029/2023GL104095

269. Mortensen J, Rysgaard S, Arendt KE, Juul-Pedersen T, Søgaard DH, Bendtsen J, et al. Local Coastal Water Masses Control Heat Levels in a West Greenland Tidewater Outlet Glacier Fjord. Journal of Geophysical Research: Oceans. 2018; 123(11):8068–8083. https://doi.org/10.1029/2018JC014549

270. Jackson RH, Straneo F. Heat, Salt, and Freshwater Budgets for a Glacial Fjord in Greenland. Journal of Physical Oceanography. 2016; 46(9):2735–2768. https://doi.org/10.1175/JPO-D-15-0134.1

271. Wagner TJW, Straneo F, Richards CG, Slater DA, Stevens LA, Das SB, et al. Large spatial variations in the flux balance along the front of a Greenland tidewater glacier. The Cryosphere. 2019; 13(3):911–925. https://doi.org/10.5194/tc-13-911-2019

272. Slater DA, Straneo F, Das SB, Richards CG, Wagner TJW, Nienow PW. Localized Plumes Drive Front-Wide Ocean Melting of A Greenlandic Tidewater Glacier. Geophysical Research Letters. 2018; 45(22):12,312–350,358. https://doi.org/10.1029/2018GL080763

273. Serreze MC, Francis JA. The Arctic Amplification Debate. Climatic Change. 2006; 76(3):241–264. https://doi.org/10.1007/s10584-005-9017-y

274. Serreze MC, Barrett AP, Stroeve JC, Kindig DN, Holland MM. The emergence of surface-based Arctic amplification. The Cryosphere. 2009; 3(1):11–19. https://doi.org/10.5194/tc-3-11-2009

275. Jensen CD. Weather Observations from Greenland 1958- 2021—Observational Data with Description. Danish Meteorological Institute (DMI); 2022. Available from: https://www.dmi.dk/fileadmin/Rapporter/2022/DMIRep22-08.pdf.

276. Cappelen J. Greenland-DMI Historical Climate Data Collection 1784-2019. Danish Meteorological Institute; 2020.

277. Aoki T, Matoba S, Uetake J, Takeuchi N, Motoyama H. Field activities of the "Snow Impurity and Glacial Microbe effects on abrupt warming in the Arctic"(SIGMA) Project in Greenland in 2011-2013. Bulletin of Glaciological Research. 2014; 32:3–20. https://doi.org/10.5331/bgr.32.3

278. Government of Greenland. Research—the road to progress. Greenland's national Research Strategy 2022–2030. Ministry of Education Culture, Sports and Church; 2022.

279. Easterling WE. Dear Colleague Letter: Update on NSF's Efforts to Improve the Inclusion of Local and Indigenous Voices in Arctic Research. National Science Foundation; 2021.

280. Mercer JL, Nymand J, Culler LE, Lynge R, Lund S, Gregersen B, et al. Bilateral collaboration between the Greenland (Kalaallit Nunaat) and United States Research Communities–from a vision to everyday practice. Polar Record. 2022; 58:e42. https://doi.org/10.1017/S0032247422000298

281. NNA Working Group. Navigating the New Arctic (NNA)—Program Solicitation. National Science Foundation; 2016.

282. Holm L, Grenoble L, Virginia R. A praxis for ethical research and scientific conduct in Greenland. Etudes/Inuit/Studies. 2011; 35(1-2):187–200. https://doi.org/10.7202/1012841ar

283. Minor K, Lund-Jensen M, Hamilton L, Bendixen M, Lassen DD, Rosing M. Experience Exceeds Awareness of Anthropogenic Climate Change in Greenland. Research Square. 2022. https://doi.org/10.21203/rs.3.rs-2304659/v1

284. Culler LE, Lund S, Nymand J, Virginia RA. Facilitating increased engagement between the research communities of Greenland and the U.S. Institute for Arctic Studies Dartmouth, Greenland Research Council, Government of Greenland; 2018.

285. Petersburg High School. LeConte Glacier 1983-present; 2023. Available from: https://sites.google.com/pcsd.us/leconte-glacier/home?authuser=0 [cited 07.09.2023].

286. Culler LE, Busk K, Demant-Poort L, Jørgensen R, Lennert M, Wallstrom E, et al. The Joint Science Education Project (JSEP): a Co-designed Arctic Science Program for a Cross-Cultural Field Classroom in Greenland. In: AGU Fall Meeting Abstracts. vol. 2022; 2022. p. ED53A–03.

287. Karplus MS, Young TJ, Anandakrishnan S, Bassis JN, Case EH, Crawford AJ, et al. Strategies to build a positive and inclusive Antarctic field work environment. Annals of Glaciology. 2023; p. 1–7. https://doi.org/10.1017/aog.2023.32

288. Nelson RG, Rutherford JN, Hinde K, Clancy KBH. Signaling Safety: Characterizing Fieldwork Experiences and Their Implications for Career Trajectories. American Anthropologist. 2017; 119(4):710–722. https://doi.org/10.1111/aman.12929