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Progress toward globally complete frontal ablation estimates of marine-terminating glaciers

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Abstract

Knowledge of frontal ablation from marine-terminating glaciers (i.e., mass lost at the calving face) is critical for constraining glacier mass balance, improving projections of mass change, and identifying the processes that govern frontal mass loss. Here, we discuss the challenges involved in computing frontal ablation and the unique issues pertaining to both glaciers and ice sheets. Frontal ablation estimates require numerous datasets, including glacier terminus area change, thickness, surface velocity, density, and climatic mass balance. Observations and models of these variables have improved over the past decade, but significant gaps and regional discrepancies remain, and better quantification of temporal variability in frontal ablation is needed. Despite major advances in satellite-derived large-scale datasets, large uncertainties remain with respect to ice thickness, depth-averaged velocities, and the bulk density of glacier ice close to calving termini or grounding lines. We suggest ways in which we can move toward globally complete frontal ablation estimates, highlighting areas where we need improved datasets and increased collaboration.

1. Introduction

Frontal ablation of water-terminating glaciers is defined as the mass lost at the near-vertical calving front and includes calving, subaerial melting, sublimation, and subaqueous melting (Cogley and others, 2011). The sum of frontal ablation and climatic-basal balance make up the total mass balance of a glacier or ice sheet (Cogley and others, 2011), although only the mass lost above flotation will contribute to sea level rise. Accurate quantification of frontal ablation and its separate components is needed to inform mass balance estimates and associated contributions to sea level and characterize the relative importance of the processes involved (e.g., Huss and Hock, 2015; Rignot and others, 2016; Moon and others, 2020). Frontal ablation is currently an important component of the mass budget of glaciers and ice sheets, and is thus essential for models and process understanding of glacier evolution (e.g. Rignot and others, 2016; Aschwanden and others, 2019; Catania and others, 2020), and other applications such as assessing risks to marine activities from icebergs (Obisesan and Sriramula, 2018; Lee and Park, 2021), fresh water inputs to the ocean (e.g., Flexas and others, 2022) and changes in marine ecosystems (Ingels and others, 2021). Thus, we need methodologically consistent and globally complete estimates of frontal ablation of glaciers and ice sheets.

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At present, frontal ablation estimates for entire glacier regions are available for Alaska (McNabb and others, 2015), Patagonia (Minowa and others, 2021), two subantarctic islands (King George Island (Osmanoğlu and others, 2013) and Livingston Island (Osmanoğlu and others, 2014)). Recently, Kochtitzky and others (2022, In Review) computed frontal ablation for all glaciers in the Northern Hemisphere and found a loss of 522 ± 17 Gt a^{-1} from 2000 to 2010, increasing to 559 ± 13 Gt a^{-1} from 2010 to 2020, with ∼90% originating from the Greenland Ice Sheet (Fig. 1). This is greater than the combined net mass loss rate of 224 Gt a^{-1} for Northern Hemisphere glaciers (outside the Greenland Ice Sheet) from 2000–2020 (Hugonnet and others, 2021) and 290 Gt a^{-1} for the Greenland Ice Sheet from 2010–2018 (Mouginot and others, 2019) over these periods, indicating that the climatic-basal mass balance of all Northern Hemisphere land ice masses was positive. In other words, if no frontal ablation had occurred there would have been a mass gain.

Here we outline current challenges in quantifying past frontal ablation for glaciers and ice sheets from observations, highlight datasets that need improvement, and describe the most immediate steps needed to globally complete frontal ablation estimates, including all glaciers and ice sheets. We further emphasize areas where increased collaboration is needed across geographies and methodologies.

2. Current challenges in frontal ablation estimates

Measuring frontal ablation is difficult because the glacier terminus is the most dynamic part of marine-terminating glaciers. Thus, quantifying individually all four physical processes – calving, subaerial melting, subaqueous melting, and subaerial sublimation (Cogley and others, 2011) – at the calving face has not been completed by any study to date. However, several studies have quantified the important role of submarine melt in total frontal ablation at grounded marine-terminating termini. For example, Motyka and others (2003) found that more than half of the estimated total mass loss at the calving front of LeConte glacier in Alaska occurred by melt with the remainder from calving, which was later corroborated with multibeam sonar surveys (Sutherland and others, 2019). However, most studies (e.g., Osmanoğlu and others, 2013; King and others, 2018, 2020; Mankoff and others, 2020; Minowa and others, 2021; Kochtitzky and others, 2022) rely on a flux gate approach, computing the ice discharge through an arbitrary cross-section some distance upstream of the terminus or at the grounding line, based on estimates of ice surface velocity and ice thickness.

The flux-gate approach requires the calculation of two components of frontal ablation ($\dot{A}_f$; Eqn (1); Kochtitzky and others, 2022): (1) ice discharge ($\dot{D}_{ice}$) due to ice motion (computed through a flux gate near the terminus; Eqn (2)) and (2) mass change due to retreat or advance of the terminus ($\dot{M}_{term}$) during the considered period (Δt; Eqn (3)). For the first component we need flux gate length (d_n), depth-averaged ice velocity perpendicular to the fluxgate (V_n), ice density (ρ), and ice thickness (H_n) at points n along the flux gate. For the second component we need the total area lost or gained (ΔS_{term}) over Δt and its average thickness ($\bar{H}$) and density. To partition the mass flux properly, both components also need to be corrected for mass change due to the climatic-basal mass balance ($\dot{B}$) over the area down-glacier from the most retreated flux gate (S_f; component 1) and the area that may have been lost or gained (ΔS_{term}; component 2).

$$\dot{A}_f = \dot{D}_{ice} + \dot{M}_{term} \tag{1}$$

$$\dot{D}_{ice} = \left(\rho\left(\sum_{n=1}^{N}(V_n \cdot H_n \cdot d_n)\right) - (S_f \cdot \dot{B})\right) \tag{2}$$

$$\dot{M}_{term} = \left(\rho \cdot \frac{\Delta S_{term}}{\Delta t} \cdot \bar{H} + \Delta S_{term}/2 \cdot \dot{B}\right) \tag{3}$$

While some frontal ablation studies have neglected the mass change due to calving front variations (e.g., Van Wychen and others, 2014; King and others, 2018; Mankoff and others, 2020; Bollen and others, 2022), recent studies of glaciers and the Greenland Ice Sheet quantify both components separately (Minowa and others, 2021; Kochtitzky and others, 2022, In Review). However, all these studies neglect basal melt down-glacier of the flux gate, which is a reasonable assumption for grounded marine-terminating glaciers but could be problematic for the few remaining ice shelves or floating glacier tongues in the Arctic (Dowdeswell and Jeffries, 2017), and is very problematic for large Antarctic ice shelves with high basal melt rates that account for more mass loss than from calving (Depoorter and others, 2013; Rignot and others, 2013). Whereas many datasets included in frontal ablation calculations have improved in recent years, there are still large knowledge gaps we need to address to improve and complete global frontal ablation estimates. Below we highlight each component of frontal ablation and the steps needed to improve the datasets used in these calculations.

2.1 Glacier inventory

Glacier inventories form the basis of large-scale observational and modeling studies. Inventories give us a common basis to identify and describe glaciers to ensure that studies are consistent with each other and seperate glaciers by type (e.g., attached or not to an ice sheet). Frontal ablation studies rely on accurate mapping and attribution of marine-terminating glaciers to inform glacier identification, terminus changes, flux gate placement, area calculations, and more. In this section, we outline current shortcomings of glacier inventories and suggest improvements, specifically in the ways in which they inform frontal ablation studies.

The Randolph Glacier Inventory (RGI) provides the best global inventory of glacier outlines outside the ice sheets, and its compilation involved a monumental and ongoing community effort (Pfeffer and others, 2014; RGI Consortium, 2017). RGI prioritizes outlines that are as close to the year 2000 as possible to improve the temporal consistency across the dataset, although this is not always possible (Pfeffer and others, 2014). Version 6.0 of the RGI was released in July 2017, and Version 7.0 is in preparation as of April 2023.

The RGI needs further improvement, particularly in improving the consistency of outlines across regions (Fig. 2). For example, Kochtitzky and others (2022) found 126 marine-terminating glaciers in RGI v6.0 in the Northern Hemisphere that have one outline, and thus one ID, but with at least two distinct termini, which typically originate from different accumulation zones (example in Fig. 2a). In the Russian Arctic and the Antarctic periphery, some ice caps with radial flow have subdivided basins while others do not (Figs 2b and 2c). Other glaciers, such as those in northern Greenland (Fig. 2d), have significant inaccuracies in geometry, which can be corrected with available imagery (e.g., see Ochwat and others, 2022). The RGI v6.0 does not correctly identify all marine-terminating glaciers (both false positives and false negatives), although this can be improved by incorporating recent datasets such as Kochtitzky and Copland

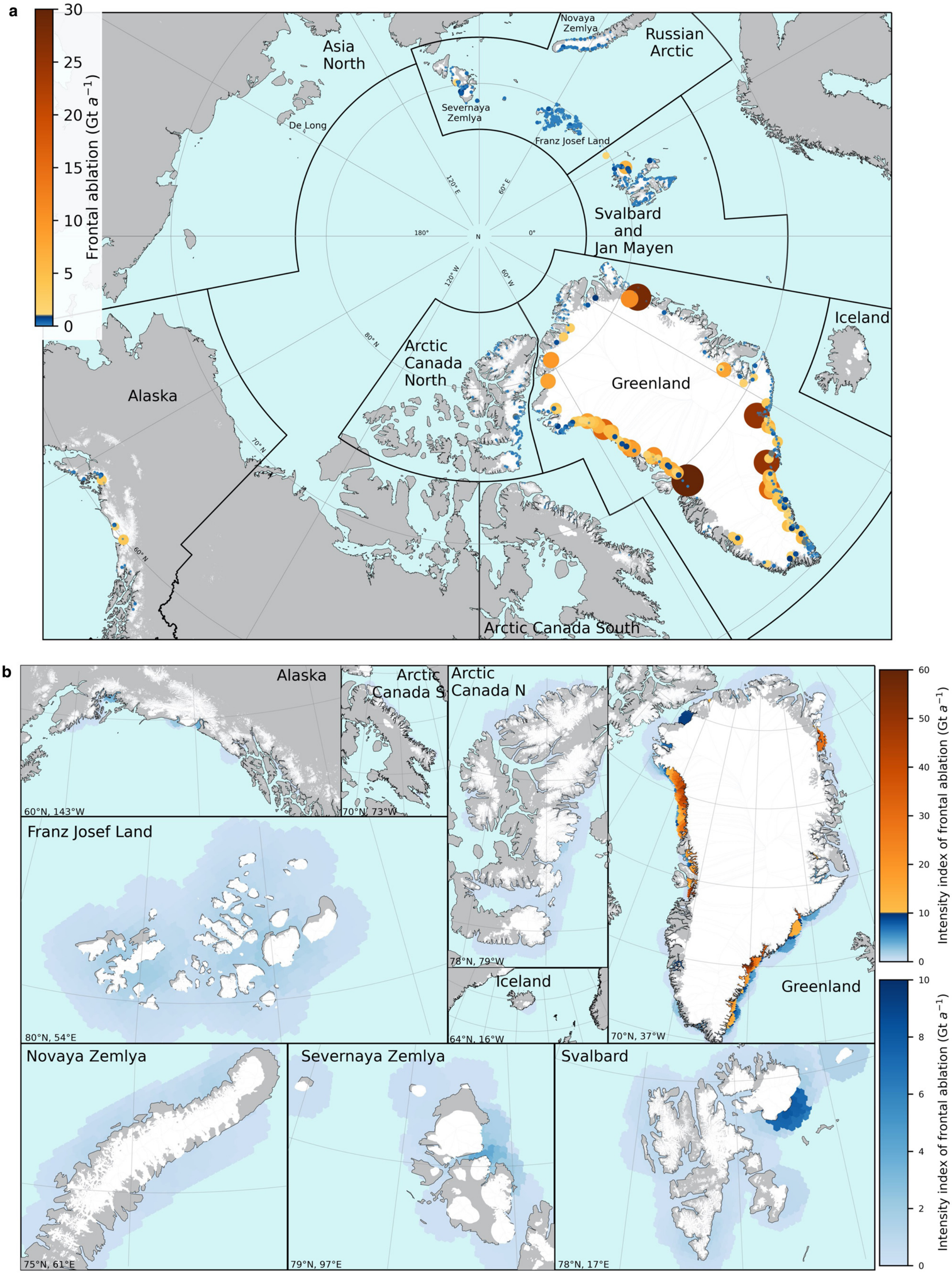

Figure 1. (a) Frontal ablation of all marine-terminating glaciers in the Northern Hemisphere for 2010-2020. Each point shows the location of one glacier. Glaciers with frontal ablation rates <1 Gt a^{-1} are shown in blue, with larger contributions shown as yellow to red. The size of each circle corresponds to the total frontal ablation. (b) Frontal ablation intensity index along the coastline of each region. We define the frontal ablation intensity index as the sum of frontal ablation from all glaciers within 80 km (Greenland) and 50 km (everywhere else) of a given location. This highlights parts of the ocean that receive the most frontal ablation. Data from Kochtitzky and others (2022, In Review).

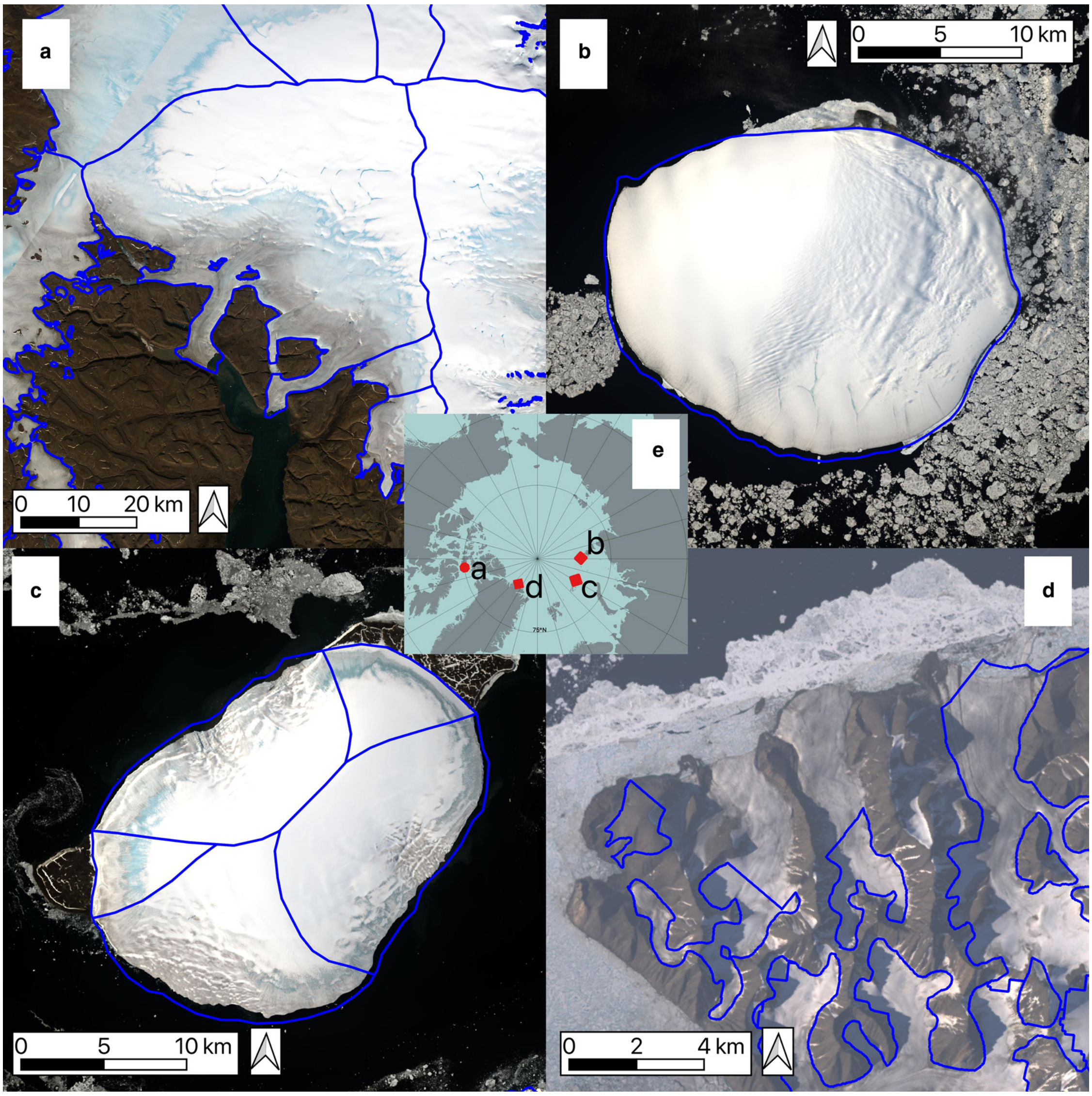

Figure 2. Examples of inconsistencies in RGI v6.0. (a) Two glaciers with one RGI ID (RGI60-03.02489) with Landsat 8 imagery from 15 August 2019 on Devon Island, Canada. (b) Ice cap on Severnaya Zemlya, Russia without subdivisions with Landsat 8 imagery from 29 July 2019. (c) Ice cap with subdivisions in Franz Josef Land, Russia with Landsat 8 imagery from 20 July 2019. (d) Errors in Greenland showing incomplete glacier outlines with Landsat 8 imagery from 8 August 2018. (e) Locations of Figs 2a–d with land areas in gray.

(2022). There have also been significant variations (typically retreat) of marine-terminating glaciers since the year 2000 (Kochtitzky and Copland, 2022), but these are not reflected in the RGI. Improving the accuracy and consistency of RGI outlines across the globe for fixed dates (i.e., 2000, and more recently) in future versions should therefore be a priority, although it will take a massive collective effort to achieve a more accurate and consistent dataset. While GLIMS provides guidelines for submitting glacier polygons to the database, details about including and subdividing glacier geometries could help to standardize and improve these inventories.

Seperating ice sheet and periphery glacier mass loss is important to ensure consistency across studies. Glacier inventories for the ice sheets are generally more accurate, as glacier basins are typically larger and have simpler geometries, and there are relatively few ice sheet basins. Most recent discharge or frontal ablation estimates for ice sheets have relied on Mouginot and Rignot (2019; Greenland) and Rignot and others (2019; Antarctica). While Rastner and others (2012) provided a first attempt to separate the hydrologic connectivity of Greenlandic periphery and ice sheet outlets, there is no similar inventory for Antarctica. For example, in Antarctica, some islands have glaciers that are surrounded by an ice shelf and feed into it, which are currently included in RGI v6.0. At the moment, there is no clear indication of which glaciers should be included or excluded in ice sheet and periphery glacier inventories, making studies inconsistent at best and at times inaccurate. Thus, a priority for the ice sheet and glacier communities in the coming years should be to clearly define how this seperation should occur, and which glaciers are connected to the ice sheets and which are excluded, so that global studies are complete and consistent.

2.2 Flux gate placement and terminus area change

Ideally, flux gates should be positioned as close as possible to the calving front to minimize the corrections needed due to melt and sublimation processes down-glacier of the flux gate. Often, they are placed a minimum of a few hundred meters up-glacier from the calving face to ensure that velocity data are reliable and that the flux gate is above the most retreated position of the calving front during the considered period. When appropriate, ice sheet studies typically place the flux gate at the grounding line, which

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can be tens, if not hundreds, of kilometers up-glacier from the calving face (Gardner and others, 2019; Rignot and others, 2019). While some automated gate placement methods exist (Mankoff and others, 2020), these methods introduce other uncertainties and are more reliant on existing glacier geometries/masks than manual procedures. Flux gate placements, except at the grounding line, and terminus area change quantifications both rely heavily on optical satellite imagery.

Dense records of optical imagery are important for robust gate placement (by ensuring that termini do not retreat behind the gates, even temporarily) and for measuring terminus area changes. Several satellite missions, with Landsat contributing the most, have collected imagery since the 1970s to inform flux gate creation and terminus area change measurements, but many data gaps exist in space and time. Data gaps exist at high latitudes because satellites (e.g., ASTER and Landsat) simply did not cover these areas, such as far northern Greenland and northern Ellesmere Island. Even though some of these sensors have been operating since the 1970s, many of them, particularly the older ones, did not collect data on every pass of the satellite, leaving numerous and large temporal and spatial gaps.

Gaps in the historical optical satellite record can be filled with synthetic aperture radar (SAR) data, from satellites such as Radarsat-1 and ALOS PALSAR, although this imagery is often of lower spatial resolution and is more difficult to interpret termini from than optical imagery, which is the case for ∼2000 and ∼2010 in northern Greenland and Ellesmere Island. Many polar locations have frequent cloud cover, leaving gaps of several years in the medium-resolution optical satellite image record, a real challenge for studies requiring higher temporal resolution for terminus area change measurements in the past. SAR, including Sentinel-1, may be useful in delineating glaciers in these areas (Rastner and others, 2017), but can also be more challenging to work with.

Recently, a new set of national-program optical satellites have been launched, comprising Landsat 8 (2013) and Landsat 9 (2021), and Sentinel 2a (2015) and Sentinel 2b (2017). Together, these provide high temporal repeat imaging and coverage to all latitudes where marine-terminating glaciers are found, and moreover are a part of an open data-access program by their agencies (Wulder and others, 2019; Zhu and others, 2019). These satellites are now collecting without spatial data gaps, and often with short intervals between acquisitions (<1 to 3 days, depending on latitude). With sometimes multiple images a day to choose from, choice of optical imagery is rarely a limitation in this part of frontal ablation calculations. Numerous commercial optical satellites have also been launched in the past two decades (e.g., WorldView, Planet, SkySat, SPOT 6 and 7), and in some cases abundant and accessible imagery is available from these sensors at no cost for researchers (e.g., through the European Space Agency's Third Party Missions Programme, and Planet Education and Research Program), at higher temporal and spatial resolutions than is possible from national-program satellites. We now face the challenge of picking the best imagery for the task and ensuring that datasets are consistent across satellite platforms.

To date, the only frontal ablation studies that have included terminus area changes have done so by using manual digitization of front positions and have, consequently, primarily relied on Landsat imagery (McNabb and others, 2015; Kochtitzky and others, 2022). Manual delineation is partially necessary to ensure accuracy, for example when quantifying only the area that changed from ocean to land or vice versa. Using tools, such as GEEDiT (Lea, 2018) to digitize glacier fronts can make the work more efficient. Recent work in automatically mapping glacier termini (e.g. Liu and others, 2021; Goliber and others, 2022) represent a large dataset that, if incorporated properly, could greatly enhance the temporal resolution of frontal ablation observations and allow for quantification of seasonal variability.

Ice sheet grounding zones, mostly in Antarctica, are commonly mapped using either Differential Satellite Radar Interferometry (DInSAR; Rignot and others, 2011) or laser altimetry (e.g., Li and others, 2020). These methods map the line along which ice transitions from resting on the bed to floating, based on where tidal motion is seen. Grounding zones can be more than 2.5 km wide, such as that of Thwaites Glacier (Milillo and others, 2019), making identification of the location for the flux gate challenging. While marine-terminating glaciers without a grounding zone are more easily mapped with optical imagery, SAR imagery and laser altimetry are effective for these large glaciers, where the moderate resolution of SAR or the gaps between altimetry orbits are not problematic.

2.3 Velocity observations

Large-scale multi-temporal velocity mapping efforts, particularly the ITS_LIVE project (Gardner and others, 2019), make it possible, along with all the other required datasets, to estimate temporal variations in frontal ablation. However, there are data gaps and limitations in space and time, particularly in the early versions of this velocity data archive, mostly associated with the challenges of using optical imagery as described in section 2.2 (e.g., lack of far northern coverage). SAR datasets are also commonly used to map velocity for both glaciers (Friedl and others, 2021) and ice sheets (Rignot and others, 2017; Joughin, 2022), and complement optical records. While velocity datasets have greatly improved in recent years, there are still many challenges.

One limitation with current velocity observations from high latitude regions is that they are determined from imagery collected at different times of the year: typically, in the spring-summer-fall for optical imagery due to the need for daylight (Gardner and others, 2019), and winter for SAR imagery due to the need for a frozen dry surface (Van Wychen and others, 2014; Strozzi and others, 2022). Because the datasets can be temporally and spatially scarce, one must combine multiple datasets when estimating frontal ablation. Although systematic analyses are limited, marine-terminating glaciers can undergo significant seasonal velocity variations of >10%, with large differences between and within regions (Van Wychen and others, 2014, 2016; Strozzi and others, 2022; Yang and others, 2022).

Only a few studies have considered seasonal and annual variations in their frontal ablation or discharge estimates, such as in Greenland (King and others, 2018; Mankoff and others, 2020), Alaska (McNabb and others, 2015) and the Subantarctic (Osmanoğlu and others, 2014). Better integration of optical and SAR observations, both spatially (regional) and temporally (winter and summer), will be important to improve frontal ablation estimates. Since frontal ablation rates are highest when ice velocities peak, accurate regional information as to how glacier velocity varies seasonally and annually is necessary to inform frontal ablation estimates and allow comparisons between different glaciers and regions.

Recent efforts to map glacier velocities globally (Gardner and others, 2019; Friedl and others, 2021) are a huge step forward, and with ice sheet specific datasets (Rignot and others, 2017; Joughin, 2022) provide most of the velocity data needed for frontal ablation estimates, although some key gaps exist, mainly for mountain glaciers. Although recent efforts greatly improve velocity estimates from SAR imagery in the eastern Arctic for the 1990s to present (Strozzi and others, 2022), we still need better temporal resolution and geographic/temporal coverage of velocity observations in many parts of Arctic Russia, northern Canada, and northernmost Greenland. While small glaciers make up a very small percentage of total frontal ablation, they

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often have the lowest spatial resolution and least accurate velocity data available, such as those in Jan Mayen, and may be good candidates for InSAR observations.

A major assumption in frontal ablation estimates is that depth-averaged velocity is a fixed fraction of surface velocity (Cuffey and Paterson, 2010). Since the depth-averaged velocity term multiplies with the frontal ablation (eq. 2), it can have a large impact of frontal ablation estimates. At present, studies outside the ice sheets typically assume that depth-averaged glacier velocity is less than 100% of the surface velocity, e.g., 90% (McNabb and others, 2015), 94% (Minowa and others, 2021), and 95% (Kochtitzky and others, 2022). Ice sheet studies often assume that depth-averaged velocity is equal to the surface velocity, e.g., in Greenland (King and others, 2018, 2020; Mankoff and others, 2020; Kochtitzky and others, in review), and in Antarctica (Gardner and others, 2018). However, there are almost no in situ measurements available to confirm this assumption, and the ratio of surface velocity to depth-averaged velocity likely varies based on factors such as ice thickness, the relative importance of basal sliding vs internal deformation (Brinkerhoff and others, 2021), and ice temperature, all of which can vary temporally and spatially, particularly for mountain glaciers. The few studies that have looked at bed vs surface velocity have found that ice velocity at the bed can be between ~70% (Raymond, 1971; Willis and others, 2003) and 99% (Seroussi and others, 2011) that of the surface velocity. Thus, assumptions about depth-averaged velocity are almost certainly incorrect and significantly impact frontal ablation estimates, but the glaciology community currently lacks the data to define any better numbers to use instead. Future efforts to better measure depth-averaged velocity, particularly for the ice sheets, and to model it for each glacier, would improve frontal ablation estimates.

2.4 Glacier thickness

While the glaciology community has put considerable effort into collecting (MacGregor and others, 2021) and compiling (GlaThiDa Consortium, 2019; Welty and others, 2020) glacier thickness measurements, many glaciers still lack any observations. Kochtitzky and others (2022) found that the glaciers that together contributed 69% of Northern Hemisphere frontal ablation have at least one thickness observation along their flux gates, although this makes up only 18% of marine-terminating glaciers by count. Glacier and ice sheet models (Morlighem and others, 2017, 2020; Farinotti and others, 2019; Millan and others, 2022) are therefore critical to fill gaps, especially in glaciers lacking measurements. However, these models still struggle to estimate marine-terminating glacier thickness near termini, as few inversion studies account for frontal ablation when estimating ice thickness (e.g., Recinos and others, 2019). For example, Kochtitzky and others (2022) found an average 135 m bias (modeled ice thickness was too high) between observations and model estimates from Millan and others (2022) along flux gates used in frontal ablation estimates; this is more than 100% of the average glacier thickness of ~120 m. More observations and improving ice thickness models, particularly near the calving face, are therefore important for improving frontal ablation estimates in the future.

Because glacier thickness measurements are typically derived from surface elevations that are available at much coarser temporal resolution than velocities, we need rates of elevation change to correct glacier thickness to match the time of the velocity observations. Globally complete surface-elevation-change-based estimates of glacier mass balance, at high resolution, are available outside the ice sheets (Hugonnet and others, 2021), and for the ice sheets (e.g. Smith and others, 2020; Khan and others, 2022), for the period 2000 to 2020. However, all these datasets report mass balance changes on annual to decadal time scales, and none report elevation changes on seasonal time scales that would match the temporal resolution of current velocity datasets. Repeat thickness observations of glaciers that produce most of the frontal ablation, are regionally important, and/or are changing rapidly would ensure accurate thickness estimates in these calculations. Recent and future campaigns, such as Operation IceBridge (MacGregor and others, 2021), to collect more glacier thickness observations and water depth at the calving front will continue to improve this dataset. Glaciers without thickness measurements, but which have high frontal ablation rates should be a priority, such as those in the Russian Arctic (Kochtitzky and others, 2022; Fig. 1).

Ice thickness data over the ice sheets is more comprehensive, although the spatial scale of the ice sheets allows them to benefit from relatively coarse (~1 km) ice thickness interpolations, a scale that would not be useful for most mountain glaciers. Significant community-wide efforts have managed to compile high-quality radar profile data for both the major ice sheets (e.g., Bamber and others, 2013; Fretwell and others, 2013) as well as Patagonia (Millan and others, 2019). Building on these compilations, an approach based on the conservation of mass combines ice thickness observations, surface velocity, surface elevation changes, and surface mass balance to provide the best mapping of ice thickness in between radar measurements (Huss and Farinotti, 2014; Morlighem and others, 2017, 2020). We suggest community-based efforts to collect and compile radar ice thickness data for glaciers and ice sheets where information is currently lacking, such as for smaller outlet glaciers and regions with limited coverage such as the Russian Arctic.

2.5 Climatic mass balance down-glacier of a flux gate

To allow proper partitioning of total glacier-wide mass change into frontal ablation and climatic-basal mass balance, ice discharge through the flux gate needs to be corrected to account for the climatic mass balance that occurs down-glacier of the flux gate, a process which is impossible to measure on large scales with existing methods. Kochtitzky and others (2022) found that accounting for the climatic mass balance lowered discharge estimates by 20% and terminus mass change by 9%. Given that the location of the glacier terminus changes over time, this correction is needed for both the discharge component and retreat/advance component of frontal ablation. To approximate the climatic mass balance between the flux gate and calving face, we rely on glacier models (Hock and others, 2019; Marzeion and others, 2020; Rounce and others, 2020) or climate models (Noël and others, 2018; van Wessem and others, 2018). Glacier models are typically forced with air temperature and precipitation data from reanalysis products (e.g., ERA5; Hersbach and others, 2020) and use temperature-index models to estimate surface melt. Since model outputs are only needed for a small portion of the glacier close to the terminus, results can be highly sensitive to uncertainties in the climate forcing and elevation-dependent model parameters and thus prone to errors, which hampers proper partitioning of the mass balance components down-glacier of the flux gate. Thus, modeled climatic balances must be carefully evaluated prior to deriving frontal ablation, but are critical to ensure accurate frontal ablation estimates.

2.6 Submarine, subaqueous frontal, and basal melt

Submarine melt is the sum of subaqueous frontal melting, which occurs along the submerged base of an approximately vertical calving front, and basal melt, which occurs along the underside of ice shelves and floating glacier tongues. In this context, only subaqueous frontal melt is a component of frontal ablation (Cogley and others, 2011). However, in much of the literature the terms submarine melt and subaqueous melt are used interchangeably and include melt processes at the ice-water interface along both the front and the base of marine-terminating glaciers and ice shelves (Truffer and Motyka, 2016).

To date, all estimates of frontal ablation include basal melting (down-glacier of the flux gate) in their estimates, although they all claim it is negligible (Osmanoğlu and others, 2013, 2014; Minowa and others, 2021; Kochtitzky and others, 2022, In Review). Estimates of Antarctic discharge at grounding lines typically include estimates of submarine melting as it accounts for over half the mass that passes through the flux gate (Rignot and others, 2013).

No direct measurements of submarine melt exist, although multibeam sonar surveys have quantified submarine melt and calving (Sutherland and others, 2019), and altimetry observations infer melt from ice shelf height changes (Adusumilli and others, 2018). Most field and satellite observations use a budget method, including residual thinning (Rignot and Jacobs, 2002; Pritchard and others, 2012; Enderlin and Howat, 2013); balance methods relying on oceanographic measurements of temperature, salinity, and water flux, or chemical tracers (Truffer and Motyka, 2016; Huhn and others, 2021); and observations and models of upwelling fresh water plumes (Jenkins, 2011; Cowton and others, 2019; Jackson and others, 2022). Other work has focused on parametrizing subglacial melt (Cowton and others, 2015; Jackson and others, 2022; Slater and Straneo, 2022). Parameterizations of plume-driven submarine melt rate use the product of total subglacial meltwater discharge at the calving front (sum of surface melting and subglacial frictional melting) and ocean thermal forcing (difference between ocean temperature and freezing point). These parameterizations may not provide the correct absolute values, but the relative changes in melt rate are well captured. These models are limited by assumptions about how meltwater enters fjords, meltwater quantity, and a lack of observationally based ocean temperature and bathymetry data (Slater and Straneo, 2022).

Submarine melt measured from ocean observations in front of two tidewater glaciers in Alaska accounted for ∼50–65% of their frontal ablation (Motyka and others, 2003, 2013; Bartholomaus and others, 2013; Jackson and others, 2022), while only 20% for a glacier in west Greenland (Xu and others, 2013). Submarine melt under Antarctic ice shelves has been estimated to exceed ice sheet-wide calving flux by 30%, and locally by ∼50% (Rignot and others, 2013). The relative contribution of submarine melt is variable over time and space (Adusumilli and others, 2018; Fried and others, 2019) but maximum rates occur where ocean thermal forcing is high and where ocean waters have access to grounding lines through deep troughs (Rignot and Jacobs, 2002; Motyka and others, 2011; Pritchard and others, 2012).

Measurements or coupled ocean-ice sheet models that would enhance our understanding of the contribution and variability of submarine melt should include water column temperature and salinity stratification and upwelling, wind forcing, ice-proximal and subglacial bathymetry, subglacial discharge and melt plume behavior and changes in sea ice (Pritchard and others, 2012; Bintanja and others, 2013; Beckmann and others, 2019; Cowton and others, 2019; Wagner and others, 2019; Slater and Straneo, 2022). Recent advances include an ice-sheet wide inventory of Greenland meltwater plumes in the context of fjord depth and discharge rates (Slater and others, 2022). At regional and local scales, accurate ice thickness measurements are needed in addition to repeat high-resolution measurements of thinning of ice shelves and tidewater termini from satellite or airborne altimetry measurements (e.g., IceSat-2: Taubenberger and others, 2022; Operation IceBridge: MacGregor and others, 2021).

2.7 Ice density

The density of snow and ice on a glacier can range from ∼10 to over 917 kg m^{-3} (i.e., fresh snow to dense bottom ice; Cogley and others, 2011). At present, frontal ablation studies outside the ice sheets typically assume that ice density is 900 kg m^{-3} (Cuffey and Paterson, 2010; Kochtitzky and others, 2022), while recent discharge studies on the Greenland Ice Sheet have typically assumed an ice density of 917 kg m^{-3} (King and others, 2018, 2020; Mankoff and others, 2020). Work in Antarctica uses firn models for density (e.g., Stevens and others, 2020; Medley and others, 2022). In geodetic mass balance studies of valley glaciers, 850 kg m^{-3} is commonly used (Huss, 2013). Since density is a direct multiplier on mass change, using a value of 900 kg m^{-3} instead of 917 kg m^{-3} results in a 1.9% reduction in the estimated frontal ablation. There is essentially no field data available to know what the density of an entire ice mass is, especially at low elevations. While ice cores can provide density estimates (e.g., Gow and others, 1997), they are commonly extracted at high elevations for their climate record, and rarely taken at low elevations where density observations are needed for converting the ice flux into a mass flux. Crevasses, moulins and sub-, en-, and supraglacial channels will alter the depth-density average of marine-terminating glaciers and thus directly impact the depth-averaged density. While current assumptions used in estimates of frontal ablation are certainly inaccurate, we lack field data to better inform this choice. Given the challenges of collecting observations close to the termini of glaciers, we need to develop models that can estimate this value from indirect or remote measurements, in frontal ablation calculations.

3. Conclusion

Frontal ablation is a critical component of global glacier mass loss, yet we still lack globally consistent estimates, primarily due to incomplete estimates from the periphery of the Antarctic Ice Sheet. In addition, estimates of the Antarctic Ice Sheet generally refer to grounding line ice discharge rather than frontal ablation at the calving front. Of course, improving underlying datasets globally, including glacier outlines, terminus changes, surface and depth-averaged velocity, glacier thickness, ice density, and basal-climatic balance, will reduce uncertainties in future work and make the estimates more accurate. Further field campaigns to collect thickness observations will improve past and future frontal ablation estimates. It is only practical to measure glacier velocities from space for inclusion in frontal ablation estimates and with the recent dramatic increase in the number of optical and other Earth observing satellites, velocity datasets will continue to improve. Furthering our understanding of glacier velocity variability will also refine modeling of ice thickness and increase the accuracy of frontal ablation estimates. Isolating the component of frontal ablation due to subaqueous frontal melting vs calving could enable models to account for the impact that changes in ocean temperatures have on marine-terminating glaciers and the relationship between subglacial discharge and frontal ablation. Furthermore, working together to improve methods of spatio-temporal estimation and error analysis, in ice thickness, velocity, and other variables, will have far reaching benefits beyond frontal ablation work.

Future work in calculating frontal ablation should focus on annual and seasonal estimates, especially in Greenland and Antarctica, where most frontal ablation occurs, but also in Svalbard and Arctic Russia, which dominates the frontal ablation of glaciers outside the ice sheets. In many glacier regions frontal ablation is both spatially heterogeneous and temporally variable. Glacier surges can strongly influence frontal ablation rates and may bias multi-year averages, which can be better understood with annual or seasonal estimates. However, it is also going to be challenging to work across a variety of spatio-temporal scales to estimate the frontal ablation of surge-type glaciers. While glacier velocity and terminus position observations are attainable on a weekly to monthly basis for many glaciers, other needed inputs, like thickness, are not as readily available at these time scales.

Frontal ablation and ice discharge studies to date have made different assumptions and have inconsistent mapping across regions. Future work would benefit from collaboration across these studies to increase consistency and close gaps. For example, the mountain glacier and ice sheet communities should mutually agree upon glacier inventories and which ice bodies belong as part of, or separate from, the ice sheets. More work on bulk ice density and deriving depth-averaged velocity from surface velocity, which is currently treated differently across glacier types, is equally critical, but will be a much harder problem to solve. Enhanced collaboration across glacier and ice sheet communities on methods, locations, and spatial scales can yield new insights into processes across the cryosphere. This can include better synthesis between existing networks such as the Global Terrestrial Network for Glaciers (GTN-G) and the Ice Sheet Model Intercomparison Project (ISMIP), or proposed initiatives such as the Greenland Ice Sheet-Ocean Observing System (GrIOOS: Straneo and others, 2019), together with community building and coordination through agencies such as the American Geophysical Union (AGU), International Association of Cryospheric Sciences (IACS) and national funding agencies (e.g. Catania and others, 2020).

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