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Progress and challenges to understanding iceberg calving around the Greenland Ice Sheet

Timothy C. Bartholomaus[1] and Jeremy N. Bassis[2]

[1]University of Texas at Austin
[2]University of Michigan

Mass loss from the Greenland Ice Sheet is a key component of sea level rise and contributes significantly to the freshwater flux entering the ocean, thereby affecting global climate change. The Greenland Ice Sheet is surrounded by glaciers that terminate in near-vertical ice cliffs partially submerged in the ocean (called tidewater glaciers) and glaciers where the terminus separates from the bed and floats freely in the ocean (called ice tongues). Observations show that it is these marine margins that are most susceptible to rapid change and radically increased mass loss (Schenk and Csathó 2012). Moreover, mass loss from the fronts of Greenland's glaciers is presently responsible for as much as half of the ice sheet mass loss and is driving the spatial patterns of ice sheet thinning (Harig and Simons 2012; Enderlin et al. 2014).

Mass loss in marine terminating regions of the Greenland Ice Sheet is dominated by (1) warm seawater's gradual erosion of ice by frontal melting and (2) the sudden, sporadic detachment of blocks of ice in a process called iceberg calving. Mass loss associated with abrupt increases in iceberg calving rate can be extremely rapid. For example, between 1998 and 2002, the floating ice tongue that protruded from Jakobshavn Isbræ, one of Greenland's largest outlet glaciers, completely disintegrated, and the increased ice discharge that followed continues to this day (Joughin et al. 2012). Interannual and spatial variability in calving rate and terminus retreat is often complicated. For example, glaciers throughout southeast Greenland retreated during the mid-2000s, but these rates subsequently decreased. In some locations, adjacent glaciers exhibit opposite trends, with one glacier advancing and another retreating in a neighboring fjord (Moon and Joughin 2008). This observation is inconsistent with a view in which mass loss at glacier termini is tied purely to some broader environmental forcing, such as regional climate or regional ocean temperatures, and suggests some degree of local control associated with individual glaciers. In Alaska, historical observations, combined with glacial and marine geology, have shown that these glaciers have a complex cycle of slow advance and rapid retreat that is also only weakly related to climate (Post et al. 2011). This cycle is often attributed to instabilities driven by feedbacks between near-terminus sediment transport, calving behavior, and ice flow dynamics (Motyka et al. 2006; Pfeffer 2007). Because data on the centennial-scale positions of Greenland's tidewater outlets or from the bottoms of Greenland's fjords is sparse, it is unknown whether these theories are appropriate for Greenland's glaciers.

At present, the broad causes of terminus retreat and the processes responsible for iceberg calving remain poorly understood, much less accurately represented in ice sheet models. This lack of understanding casts doubt on the predictive skill of ice sheet models and potentially introduces large uncertainties into sea level rise projections in the coming decades and centuries. We outline below some of the challenges associated with a better understanding of iceberg calving and the frontiers on which progress in its quantification and predictions are being made.

The calving menagerie

Iceberg calving is ultimately related to the mechanical failure of ice. However, predicting mass loss from calving events remains challenging because calving takes on different forms under different conditions. For example, large tabular icebergs sporadically detach from freely floating ice tongues with many years of quiescence between major calving events. This type of calving regime is exemplified by the 2010 and 2012 Petermann Glacier calving events during which the glacier shed icebergs larger than the size of Manhattan (Falkner et al. 2011). In the presence of ample surface melt, hydro-fracturing can fragment ice shelves so completely that they disintegrate into plumes of needle shaped icebergs, as occurred in the spectacular collapse of the Larsen B ice shelf over 6 weeks in 2002 (Scambos et al. 2003). This type of catastrophic failure event has yet to be observed in Greenland, but remains a possibility for floating ice tongues in regions with sustained increases in surface melt. Grounded glaciers, in contrast, calve more frequent, smaller icebergs than floating glaciers. The simplest of these events may be termed a serac failure, when an ice block (10 – 100 m scale) breaks free either above or below the water line. These types of events occur at all tidewater glaciers. Where thicker glaciers (>~800 m) flow into the ocean, larger, more intact icebergs can separate from the terminus 100s of meters back from the glacier front. These large slabs (1000 m scale) are buoyantly unstable and frequently capsize after detachment. Slab rotations, which in Greenland occur only at the largest 15 or so tidewater glaciers (Veitch and Nettles 2012), are accompanied by innumerable smaller serac failures (Walter et al. 2012). In some fjords, accumulated iceberg debris bound together by sea ice is found seasonally near the termini of Greenland's calving glaciers. The presence of this material, termed *ice mélange*, potentially limits the occurrence of slab rotation calving (Amundson et al. 2010). This diversity in calving regimes has prompted some to question whether fundamentally different processes control calving in disparate environments, or if the same processes operate in all regimes with changes in the style and vigor of calving resulting from a smooth change in controlling parameters (Bassis and Jacobs 2013).

Quantifying iceberg calving

A glacier terminus will advance when the rate of ice flow at the glacier terminus exceeds the combined rates of calving and frontal melting (Fig. 1):

$$\frac{dL}{dt} = u_t - u_c - u_m, \qquad (1)$$

where each term is averaged over the cross-sectional area of the glacier terminus and over a time interval that is long compared to the recurrence interval between calving events. Here dL/dt is the rate of advance (or retreat) of the calving front, u_t is the terminus velocity, u_c is the calving rate (length of glacier lost due to iceberg calving per unit time), and u_m is the length lost due to frontal melting at the terminus per unit time. The calving rate represents an average of discrete iceberg calving events, the timing and size of which have a stochastic component that makes individual events impossible to forecast. The calving rate thus provides a description of glacier dynamics akin to a "climatology" of calving whereas individual calving events represent the "weather" of the glacier system.

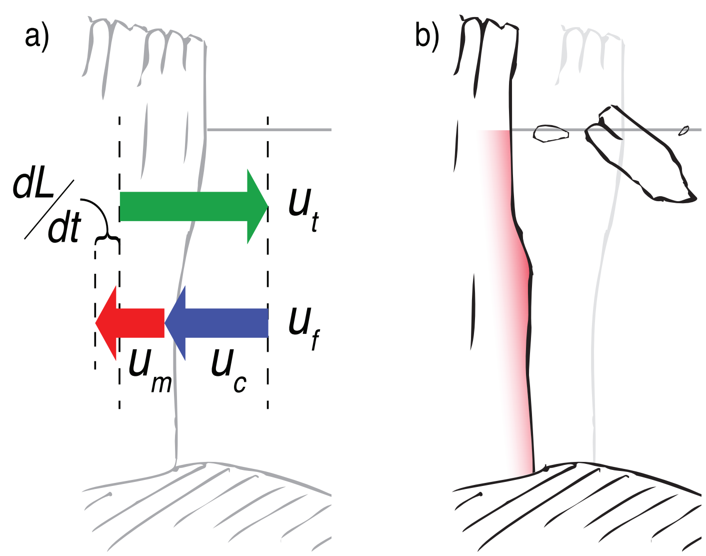

Fig. 1 Processes acting at the terminus of a marine-terminating glacier. Cross-sectional view. (a) The components of Equation 1, the terminus velocity u_t and frontal ablation rate u_f, made up of calving u_c and melt u_m. The relative magnitudes of these components dictate how quickly a terminus will advance or retreat *dL/dt*. (b) Cartoon showing each of the terminus processes at work during a given time period. Ice flow at the terminus has the potential to move the terminus forward (light gray). However, iceberg calving and submarine melt of the glacier terminus lead to a net retreat.

Of the four terms encompassed by Equation (1), it is straightforward to measure the rate of change in glacier terminus position (dL/dt) and geodetic and remote sensing techniques can provide the surface velocity at the terminus. Hence, dL/dt and u_t can be used to infer the combination of iceberg calving and submarine melt. Glaciological studies historically conflated iceberg calving and frontal melting by either ignoring submarine melt altogether or lumping the two mass loss processes into a single term loosely referred to as the *effective calving rate*. This can introduce significant confusion as recent measurements show that melting can be comparable to or even exceed calving when fjord seawater is warm (Bartholomaus et al. 2013; Motyka et al. 2013). Recently, a more precise term has come into use; the *frontal ablation* rate is the sum of the calving and frontal melting rates $u_f = u_c + u_m$. While frontal ablation, $u_f = u_t - dL/dt$, is comparatively easy to measure, it is the independent components u_c and u_m that must be identified if we seek process-based models of calving and melt.

The relative contributions of submarine melt and iceberg calving likely vary from location to location (Enderlin and Howat 2013). On one end of the spectrum, the Alaska Coastal Current transports water with summer temperatures in excess of 10°C into Alaska's glacierized fjords. There, melt rates are sufficient to pace the rate of iceberg calving by melting the foundations of subaerial seracs (Bartholomaus et al. 2013). In contrast, in northern Greenland fjords, where water temperatures are colder and runoff is less, calving is often the dominant frontal ablation process. However, frontal melting and iceberg calving are not necessarily independent and it remains unclear if it is possible – or even desirable – to fully separate our understanding of these two processes. In the sections that follow, we examine different approaches used to include calving in ice flow models.

Empirical calving laws

The earliest attempts to understand glacier retreat focused on seeking empirical relationships between frontal ablation rate and a suite of external and internal variables. This type of relationship is often called a 'calving law', although calving parameterization may be a more accurate description. These studies revealed various correlations between frontal ablation and water depth (Brown et al. 1982) or terminus position and some terminus height above the threshold at which the terminus would begin to float (Meier and Post 1987; C.J. van der Veen 2002). These empirical relationships are consistent with the general observation that glaciers terminating in deep water or that rest on beds sloping down into the interior are unstable. However, subsequent observations have cast doubt on the validity of these empirically based calving laws, suggesting that many of the correlations are spurious and do not reflect causal relationships (C. J. van der Veen 2002; Bassis and Walker 2012; Bassis and Jacobs 2013). Moreover, empirical calving laws proposed to date do not allow glaciers to form floating termini, a severe setback in Greenland where many glaciers form seasonal floating ice tongues. This experience hints that we need to be cautious in seeking statistical correlations to establish causative relationships. Fortunately, if empirical relationships are sought going forward, larger datasets that span a wide variety of calving regimes and environmental conditions are becoming available to develop and test improved calving laws.

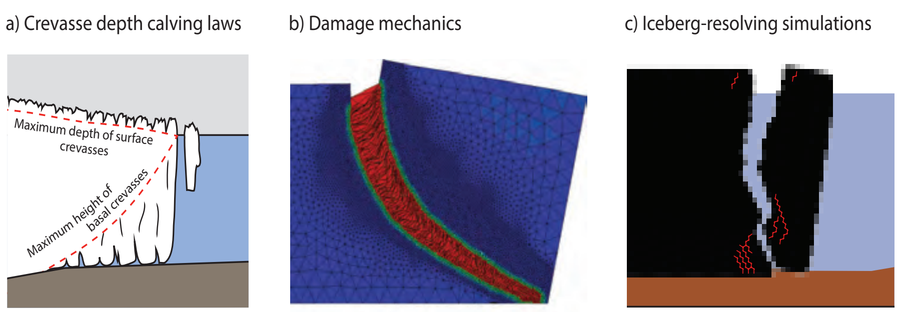

Fig. 2 Cross-sectional illustrations of three leading models for understanding and predicting iceberg calving. (a) The crevasse depth model assumes that surface and basal crevasses are formed in response to longitudinal stresses (Nick et al. 2010). Calving occurs where surface and basal crevasses intersect to penetrate the entire thickness of the glacier terminus (illustration by Sophie Gilbert). (b) Damage mechanics treats microfractures within the glacier as a bulk material property, described by a continuously defined state variable. Calving occurs when this "damage variable" exceeds some threshold (figure from Duddu and Waisman 2013). (c) Iceberg-resolving simulations model the forces between discrete elements of ice elastically, with some finite strength (figure from Bassis and Jacobs 2013). Calving occurs when the bonds connecting a mass of ice "boulders" to the glacier are broken.

Crevasse-depth calving laws

A second type of calving law relies on the understanding of iceberg calving as a fracturing process, and frames calving as an extension of the crevassing that is ubiquitous near the fronts of nearly every calving glacier. This calving law predicts that the terminus is located where the combination of surface and basal crevasses at the glacier front exceed a threshold penetration, ostensibly intersecting to form separate icebergs (Fig. 2a; Benn et al. 2007; Nick et al. 2010). Crevasses form when the stress within a glacier exceeds the strength of ice. This model is, in principle at least, appropriate for floating and grounded ice and has been successful in reproducing trends of advance and retreat of several major Greenland outlet glaciers, including those with floating ice tongues (Nick et al. 2012; 2013). A number of complications, however, remain. For example, instead of allowing crevasses to initiate and advect from up-glacier of the terminus, researchers tend to assume that crevasses only form in response to the local stress field. Furthermore, researchers typically use a heuristic formulation in which the lateral extent of crevasses along with any time history is ignored. These simplifications likely contribute to the most severe deficiency of this approach: the prediction that crevasses only penetrate the entire ice thickness when surface crevasses are filled with melt water. Melt water is used as a poorly constrained tuning knob to force models to agree with observations, limiting confidence in predictions. Further work is needed to refine our understanding of the fracture process within ice and reconcile it with observed glacier behavior, but it is encouraging that first-order agreement between models and observations is, to some extent, now possible.

Damage mechanics based calving laws

An alternative approach seeks to model the bulk failure of ice, without explicitly resolving individual fractures, an approach that is frequently called damage mechanics (Fig. 2b; Pralong and Funk 2005). Continuum versions of this phenomenological approach have been applied to study the failure of hanging glaciers, accumulation of damage in floating ice shelves, and surface crevasse penetration (Pralong and Funk 2005; Albrecht and Levermann 2012; Borstad et al. 2012; Duddu et al. 2013). These flavors of damage mechanics can easily be incorporated into continuum ice sheet models. However, evolution of damage is controlled by an (as of yet) heuristic law, and this law is tuned to match limited laboratory observations or sparse field measurements. The lack of observations that span relevant fracture regimes of glacier ice makes it difficult to deconvolve damage (i.e., fracture) from other processes, like recrystallization. Damage has yet to be fully integrated into ice sheet models, but it provides a promising avenue of future research.

Iceberg resolving models

A third productive direction for iceberg calving literature has been the simulation of individual calving events using discontinuous damage mechanics or discrete element models (Fig. 2c). These models idealize glacier ice as a granular material, with adjacent ice "boulders" bound together by cohesive and frictional forces, acting under the influence of gravity and buoyancy. These models are able to qualitatively reproduce the observed styles of iceberg calving events (Åström et al. 2013; Bassis and Jacobs 2013). The computational expense of these seconds-to-minutes-scale simulations of "iceberg weather" is too great for inclusion in century to millennial-scale ice flow simulations. However, the success of these conceptual process models thus far indicates that scientists are beginning to understand some of the essential physics of iceberg calving.

Outlook and opportunities for further progress

Further progress in understanding iceberg calving is likely to be substantially interdisciplinary. Studies simultaneously drawing on glaciological and oceanographic methods have the potential to disentangle calving and submarine melt contributions to frontal ablation. Remote sensing data can inform modeling results, while field data temporally "fill the gaps" between satellite scenes. Field data also allow for the observation of individual calving events as they occur, coincident with other environmental data such as the passage of ocean waves and air temperatures. Crucially, neither satellite nor field observations are currently able to constrain key parameters needed for models. For example, we have very limited ability to measure the extent to which crevasses are water filled and have little knowledge of the location and geometry of fractures within the ice that are ultimately responsible for calving events.

We expect that significant improvements in our understanding of ice loss from glacier termini in Greenland and elsewhere will come from disentangling the two components of frontal ablation: iceberg calving and frontal melting. At present it is unclear how or even if this can be done in general settings; modeling studies have come to conflicting conclusions as to whether submarine melt may sufficiently alter the stress field within an unfractured glacier front to modulate calving rates (O'Leary and Christoffersen 2013; Cook et al. 2013). In extremely warm fjord environments with massive front melting, observations demonstrate that summer iceberg calving rates can be paced by rates of submarine melt – thus calving and melt components are practically inseparable (Bartholomaus et al. 2013). However, examining glaciers in cold ocean settings where frontal melting is negligible provides a window into calving that may be uncontaminated by melting. Although, remote sensing offers a coarse, if easily attainable picture of frontal ablation rates, studies of the individual submarine melt and calving components often require expensive, labor-intensive fieldwork. Heat and salt budget methods, combined with subglacial discharge estimates or fjord current speeds, allow for the quantification of submarine melt within seawater (Straneo et al. 2011; Motyka et al. 2013), but methods that allow for the direct measurement of iceberg calving fluxes are in their infancy. Focused, high-rate, ground-based observations of glacier termini using either seismic methods or ground-based interferometric radar are likely to yield new insights (Fig. 3). Innovative field experiments are essential as scientists disentangle the calving and submarine melt components of frontal ablation.

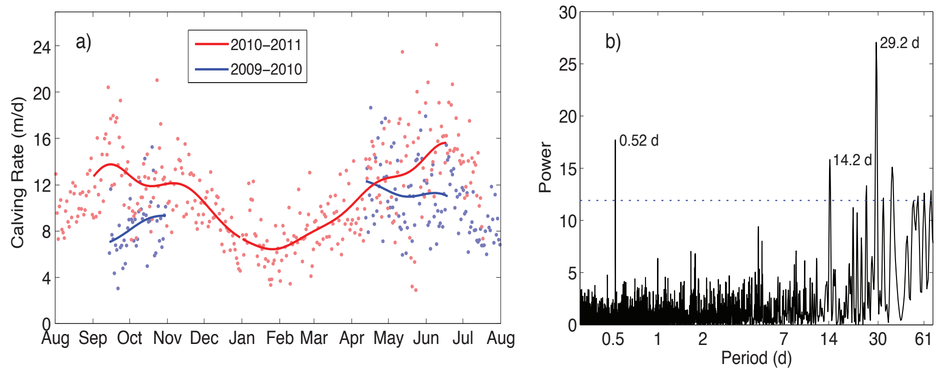

Fig. 3 Views of interannual, seasonal, daily, and tidal calving variability at tidewater Yahtse Glacier, Alaska (Bartholomaus 2013). The calving rate is estimated seismically, using the properties of "icequakes" produced when icebergs impact the sea surface. (a) The daily calving rate is lowest during the winter, and varies amongst years and from day to day. (b) Periodogram showing the strength of variations in calving rate at a range of different timescales. Strong peaks in power are present at semi-diurnal, fortnightly, and monthly periods – all important tidal timescales at Yahtse Glacier. Units are arbitrary; dotted line shows the 95% confidence interval on the peaks.

Iceberg calving is an emerging, unsettled field and the broad spectrum of temporal and spatial scales has thwarted attempts to develop convenient parameterizations. Nonetheless, observational work has shown that frontal ablation (and calving) varies at a number of timescales, including seasonally and tidally (Schild and Hamilton 2013; Bartholomaus 2013). Additional field observations combined with improved process-based models may allow us to better understand the processes and conditions that occur during individual iceberg calving events, but history suggests we should be cautious generalizing results to other glaciers, even those nearby. Alternatively, bulk parameterizations of the climatology of calving are easier to observe and more directly ingestible into numerical models. However, models based on bulk parameterizations are necessarily more heuristic, less tightly constrained by fundamental physics, and risk breaking down when extrapolated to future conditions. A consequence is that creation and validation of process physics based models and even empirical parameterization requires detailed – daily or better – resolution of local meteorological, oceanographic, and glaciological variables for a large suite of glaciers that surround the Greenland Ice Sheet. We anticipate this will require new observational platforms that complement existing methods to propel understanding forward.

Conclusions

Despite challenges, understanding of calving and frontal ablation has developed significantly over recent decades. Observational work reveals that iceberg calving is not steady, and, in addition to interannual and decadal variability, calving varies seasonally and tidally. Numerical models are beginning to reproduce this behavior while providing insight into the essential character of calving. We anticipate that progress will continue as new observations and models add to our understanding. However, rapid progress requires a concerted effort to use observations to discriminate between models so that we can begin to whittle down the complex ecology inherent within proposed calving laws. Finally, we must be sure to look beyond traditional disciplinary boundaries, as breaching these barriers is the most direct route to significant progress and understanding.

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Greenland Ice Sheet Workshop Report

Download the report from the International Workshop on Understanding the Response of Greenland's Marine-Terminating Glaciers to Oceanic and Atmospheric Forcing. The report provides a prioritized set of recommendations for interdisciplinary and internationally coordinated observations, data access, and process studies to improve understanding of physical process and their representation in climate models. Investment in these priorities over the next decade will provide more reliable, physically based projections of freshwater flux from the Greenland Ice Sheet and its contributions to changes to sea level, the North Atlantic circulation, and related climate changes. The workshop was sponsored by US CLIVAR agency contributions from NASA, NOAA, NSF, and DoE, and the NSF Office of Polar Programs.