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**Article:**

Schild, K. M., Renshaw, C. E., Benn, D. I. et al. (7 more authors) (2018) Glacier Calving Rates Due to Subglacial Discharge, Fjord Circulation, and Free Convection. *Journal of Geophysical Research: Earth Surface*. pp. 2189-2204. ISSN 2169-8961

<https://doi.org/10.1029/2017JF004520>

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## RESEARCH ARTICLE

10.1029/2017JF004520

## Glacier Calving Rates Due to Subglacial Discharge, Fjord Circulation, and Free Convection

## Key Points:

- We partition calving rate due to submarine melt into calving due to free convection, horizontal fjord circulation, and meltwater discharge
- The calving rate due to meltwater discharge is up to an order of magnitude larger than fjord circulation and free convection calving rates
- A given flux of meltwater has a greater impact on calving rate at the end of the melt season than in the early melt season

K. M. Schild<sup>1,2</sup> , C. E. Renshaw<sup>1</sup> , D. I. Benn<sup>3</sup> , A. Luckman<sup>4,5</sup> , R. L. Hawley<sup>1</sup> , P. How<sup>6,7</sup> , L. Trusel<sup>8</sup>, F. R. Cottier<sup>9,10</sup> , A. Pramanik<sup>11</sup>, and N. R. J. Hulton<sup>7</sup>

<sup>1</sup>Department of Earth Sciences, Dartmouth College, Hanover, NH, USA, <sup>2</sup>Department of Earth Sciences, Now at University of Oregon, Eugene, OR, USA, <sup>3</sup>School of Geography and Geosciences, University of St Andrews, Saint Andrews, UK, <sup>4</sup>Department of Geography, Swansea University, Swansea, UK, <sup>5</sup>Arctic Geophysics, University Centre in Svalbard, Longyearbyen, Svalbard, <sup>6</sup>School of GeoSciences, University of Edinburgh, Edinburgh, UK, <sup>7</sup>Arctic Geology, University Centre in Svalbard, Longyearbyen, Svalbard, <sup>8</sup>Department of Geology, Rowan University, Glassboro, NJ, USA, <sup>9</sup>Scottish Association for Marine Science, Oban, UK, <sup>10</sup>Department of Arctic and Marine Biology, UiT The Arctic University of Norway, Tromsø, Norway, <sup>11</sup>Norwegian Polar Institute, Tromsø, Norway

## Correspondence to:

K. M. Schild,  
schild.km@gmail.com

## Citation:

Schild, K. M., Renshaw, C. E., Benn, D. I., Luckman, A., Hawley, R. L., How, P., et al. (2018). Glacier calving rates due to subglacial discharge, fjord circulation, and free convection. *Journal of Geophysical Research: Earth Surface*, 123, 2189–2204. <https://doi.org/10.1029/2017JF004520>

Received 12 OCT 2017

Accepted 2 AUG 2018

Accepted article online 22 AUG 2018

Published online 15 SEP 2018

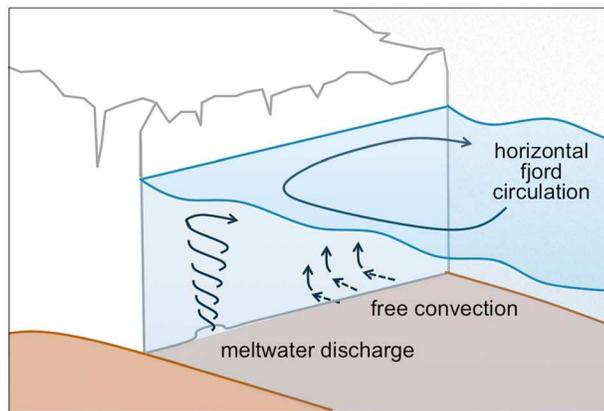
**Abstract** Tidewater glacier calving provides the most direct mechanism of ice transfer from land to the ocean. However, the physical melt processes influencing calving remain challenging to constrain. In this study we focus on calving rates at Kongsbreen, a tidewater glacier in Svalbard, due to three mechanisms of submarine melt: (1) free convection, (2) horizontal fjord circulation, and (3) meltwater discharge. To calculate an overall calving rate, we measure glacier velocity and terminus change using Sentinel imagery. We calculate free convection, fjord circulation, and meltwater discharge calving using mooring data for mid-fjord ocean temperature (30–80 m depth), reanalysis results for meltwater runoff, and georectified time-lapse imagery to track icebergs and infer surface circulation. Results show that the total glacier calving rate is highly correlated with ocean temperature during the 2016 melt season. When runoff was present, we found that subglacial discharge accounted for calving rates an order of magnitude greater than the maximum calving rates assigned to the other two melting mechanisms combined. Further, subglacial discharge at Kongsbreen was more efficient in inducing calving later in the season than earlier in the season, implying that the increase in ocean temperatures, the timing of meltwater discharge within a melt season, and/or the development of discrete meltwater exit channels are critical components to calving rates. As the recent atmospheric warming trend and subsequent increase in meltwater discharge is expected to continue, it is essential to understand the processes contributing to an increase in glacier calving and incorporate these processes into predictive models.

## 1. Introduction

Tidewater glaciers transport mass directly from land to the ocean through frontal ablation: the combined result of iceberg calving and submarine melting of the terminus face. Since mass loss from these glaciers has an immediate impact on sea level, understanding the processes central to the rate of tidewater glacier frontal ablation is critical to accurately predicting the cryospheric contribution to global sea level rise in a warming climate. The recent coincident timing of Arctic tidewater glacier acceleration, increased calving, and atmospheric and oceanic warming suggests that one or more processes acting at the ice-ocean boundary may be a controlling mechanism on tidewater glacier frontal ablation, particularly those relating to ocean temperature (Holland et al., 2008; Howat et al., 2007; Luckman et al., 2015; Nick et al., 2009; Straneo & Heimbach, 2013; van den Broeke et al., 2009) and to the development of subglacial meltwater channels (Slater et al., 2016). Submarine melting, specifically melt undercutting, often facilitates calving (e.g., Benn et al., 2017; O'Leary & Christoffersen, 2013; Slater et al., 2017), and therefore quantifying submarine melt processes is central to understanding the mechanisms operating at the ice-ocean interface. However, progress towards understanding and quantifying the controls on frontal ablation has been hindered by the challenges associated with collecting in situ measurements in this environment. Most notably, processes linking melt to calving have rarely been quantified. Here we propose a new partitioning of the total glacier calving rate into the calving rates due to three simplified mechanisms of submarine melt, and apply this partitioning at a Svalbard tidewater glacier. In attributing calving rates to specific processes at the ice-ocean interface, our results allow for more accurate characterization and prediction of glacier behavior.

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**Figure 1.** Three broad mechanisms of submarine melting as they are partitioned in this study. Melting mechanisms include: (1) free convection, (2) horizontal fjord circulation, and (3) meltwater discharge. Arrows indicate possible directions of water movement.

## 2. Background

Tidewater glacier calving style and calving rate are influenced by several environmental factors, including glacier and fjord geometry (Enderlin et al., 2013; Schild & Hamilton, 2013), the presence or strength of a buttressing mélange (Amundson et al., 2010; Christoffersen et al., 2012; Vieli & Nick, 2011), the bathymetry of the fjord (Nick et al., 2013; Rignot et al., 2016), and ocean temperature and circulation (Holland et al., 2008; Luckman et al., 2015; Straneo & Heimbach, 2013). Calving style (e.g., tabular, flakes, and rotating icebergs) is largely controlled by internal glacier processes, including glacier velocity and strain rates (Bassis & Jacobs, 2013; Benn et al., 2007), with individual calving events influenced by processes at the ice-ocean interface, including crevasse fracture propagation, submarine melting, and glacier bending at the grounding line (Benn et al., 2007, 2017). Recent modeling studies have pointed to two distinct calving styles resulting from melt undercut: small calving events only impacting ice directly above the melt undercut region (no amplification; Benn et al., 2017) and large calving events incorporating ice beyond the melt under-

cut region (with amplification). The second scenario includes the melting of larger portions of the supporting ice below the waterline, creating ice weaknesses, which propagate upglacier and intensify calving (Benn et al., 2017; O'Leary & Christoffersen, 2013). Based upon these two different scenarios, the calving rate due to submarine melting would be dependent upon the degree of submarine melting prior to a calving event. Recent studies in Svalbard have shown that submarine melting, specifically small-scale melt undercut, is likely a dominant driver of calving at grounded Svalbard tidewater glaciers (Benn et al., 2017; How et al., 2017) and that the overall calving rate is highly correlated with the ocean temperature (Luckman et al., 2015).

Oceanographic studies estimating submarine melt rates have used field measurements of conductivity, temperature, and depth (CTD) collected from boats, helicopters, or moorings to quantify up-fjord heat transport. Ship and helicopter-based CTD casts (e.g., Cottier et al., 2005; Holland et al., 2008; Straneo et al., 2010; Sutherland & Straneo, 2012) serve as point measurements, but are seasonally biased, as the location of the CTD cast and the timing of these deployments are dictated by variables such as mélange and sea ice cover, thereby limiting studies to predominantly summer months (May–September). Additionally, the seasonal or long-term melt rates are harder to extrapolate from point measurements alone, as these measurements represent a temporal snapshot of a dynamic system (e.g., Jackson et al., 2014; Jackson & Straneo, 2016; Straneo et al., 2010). Instrumented remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) have successfully measured temperature and salinity close to an actively calving terminus (e.g., Mankoff et al., 2016; Stevens et al., 2016), but require an open path for travel and are therefore susceptible to the limitations listed above. Permanent moorings can provide a full seasonal record (e.g., Cottier et al., 2005; Inall et al., 2014; Jackson et al., 2014; Luckman et al., 2015; Straneo et al., 2010), however they must be placed a safe distance away from the terminus and any passing icebergs. As such they are generally deployed down-fjord or in protected coves, well away from the calving glacier terminus. Nevertheless, successful mooring deployments and retrievals have occurred closer to the glacier terminus in fjords with smaller icebergs (e.g., Cottier et al., 2005).

The degree of submarine melt is dependent upon the temperature of the ocean water and the movement of water within the fjord. Fjord circulation is driven by local density gradients between ocean water and fresh water, as well as mechanical forcing from subglacial discharge plumes or the wind. While fjord circulation involves a series of complex relationships between the ocean water, freshwater, and the melting of ice, three broad mechanisms of submarine melting have been identified through models and field campaigns: (1) free convection (e.g., Chauché et al., 2014; El-Tahan et al., 1987; Magorrian & Wells, 2016), (2) horizontal fjord circulation (Cowton et al., 2015), and (3) meltwater discharge (e.g., Carroll et al., 2016; Cenedese & Linden, 2014; Chauché et al., 2014; Christoffersen et al., 2012; Kimura et al., 2014; Motyka et al., 2013; Slater et al., 2016; Xu et al., 2012; Figure 1).

The first mechanism of submarine melt, free convection (also referred to as melt-driven convection), occurs when ocean water comes in contact with the glacier terminus, melting the glacier ice, and

thereby introducing freshwater to the system. This freshwater initiates a density-driven circulation, or free convection, with freshwater moving buoyantly up the ice face displacing ocean water (e.g., El-Tahan et al., 1987; Josberger, 1977; Magorrian & Wells, 2016). Free convection drives only weak fjord circulation, which might easily be overwhelmed by the other two circulation processes.

In the second form of submarine melting, horizontal fjord circulation, melting occurs as ocean water is moved horizontally along the terminus. While this horizontal surface circulation may potentially have a larger impact on submarine melting than free convection due to the forced movement of water, there have been no direct measurements of this process. Preliminary model results suggest that melting due to horizontal surface fjord circulation external to a meltwater discharge plume is minimal (Cowton et al., 2015). However, the spatial resolution of the model (200 m) may be too coarse to sufficiently resolve near ice circulation. Additionally, this model has so far only included surface circulation as initiated by subglacial meltwater discharge, and therefore does not include other potential drivers of circulation, such as wind or tides, and consequently may underestimate the melting.

The third mechanism of submarine melt, meltwater discharge, has a dominant control on along-fjord circulation (Xu et al., 2012). As meltwater exits the subglacial environment, it begins to rise buoyantly towards the surface, entraining warm ocean water in the process. This water mixture flows vertically against the terminus until it reaches the surface or entrains enough ocean water for the density of the buoyant plume to equilibrate with the ambient fjord water, melting the terminus in the process. In systems with prominent subglacial meltwater discharge locations, this submarine melt is localized and results in melt undercutting and calving immediately above the discharge location, locally accelerating calving and generating an embayment within the ice face (Fried et al., 2015; Slater et al., 2015). However, in systems with multiple discharge locations, the number of exit points and distance between them is important to the overall impact of submarine melting. If two large plumes are close together, the plumes can coalesce (Cenedese & Linden, 2014; Kimura et al., 2014) and the overall melt decreases when compared with two independent plumes, however if the terminus is scattered with subglacial discharge locations, the combined melting of all the discharge locations can be larger than one single location (Fried et al., 2015; Slater et al., 2015).

O'Leary and Christoffersen (2013) represented the relationship between submarine melt rate and calving rate in terms of the total glacier calving rate (ice loss per time),  $\dot{c}_{total}$ , such that

$$\dot{c}_{total} = \dot{c}_d + \dot{c}_{sub}, \quad (1)$$

and

$$\dot{c}_{sub} = \omega \dot{m}_{sub}. \quad (2)$$

Here  $\dot{c}_d$  is the dry calving rate, or the calving rate of the glacier without the influence of submarine melt, relating to ice temperature, strain rate, and predominant crevasse separation. The calving rate due to all mechanisms of submarine melt,  $\dot{c}_{sub}$ , is the product of the amplification factor,  $\omega$ , and the terminus melt rate encompassing all mechanisms of submarine melt,  $\dot{m}_{sub}$ . Localized melting induces structural weakness which results in brittle failure (calving) of the glacier terminus. Thus, the total mass loss due to submarine melting may be greater than just the mass loss due to melting, and an amplification factor must be introduced. O'Leary and Christoffersen (2013) proposed that the degree of amplification ( $\omega \approx 1-6$ ) is based upon glacier geometry, closeness to flotation, and the nature of the crevasse pattern.

In this study, we use a combination of in situ ocean temperature data and in situ and remotely sensed imagery to quantify free convection calving, develop a new methodology to quantify fjord circulation calving rates, use calving style to quantify the dry calving rate, and attribute the remainder of the total glacier calving rate to meltwater discharge calving. We demonstrate this methodology by calculating the contribution from each of the three submarine melt mechanisms over the 2016 melt season for Kongsbreen, a tidewater glacier in Svalbard.

### 3. Methods

#### 3.1. Study Location

Kongsbreen (78.96°N, 12.61°E, 378 km<sup>2</sup>) is located on the west coast of Spitsbergen, the largest island in the Svalbard archipelago and shares a fjord with the research base and town of Ny-Ålesund (Figure 2a). The Svalbard archipelago is ~60,000 km<sup>2</sup> and located midway between mainland Norway and the North Pole. We choose Kongsbreen for this study largely due to its accessibility, mélange-free terminus during the summer months, availability of time-lapse camera and satellite imagery, and richness of in situ measurements. The overlap of these remote sensing and in situ measurements defines the study period as 10 April to 7 October (day 101–281) 2016. Kongsbreen has a nunatak dividing the terminus into two branches (Figure 2a), the northern branch (Figure 2b) drains into Kongsfjorden, which is ~140 m deep at the terminus (2007 position; Schellenberger et al., 2015), while the southern branch is much slower and partially land-terminating. We therefore focus our study on the northern branch, as it is also one of the fastest flowing, non-surging tidewater glaciers in Svalbard (Błaszczuk et al., 2009; Schellenberger et al., 2015). Between 1990 and 2007, the terminus of Kongsbreen's northern branch, hereafter referred to as Kongsbreen, was at a stable position. Since 2007, it has retreated and accelerated, reaching a peak flow speed of 2.7 m/day in 2013 (Schellenberger et al., 2015). Kongsbreen has one prominent subglacial discharge location across the width of its terminus (Figure 2b, red triangle), where a spatially static but variably sized sediment plume, visible at the fjord surface, is present during the summer months.

#### 3.2. Partitioning the Calving Rate

We partition the calving rate due to submarine melt ( $\dot{c}_{sub}$  in equation (1)) to quantify the individual calving rates due to free convection, fjord circulation, and meltwater discharge. Specifically, we modify equation (2) to separate calving rates into these simplified mechanisms of submarine melt and expand equation (1) to become:

$$\dot{c}_{total} = \dot{c}_d + \dot{c}_{free} + \dot{c}_{circ} + \dot{c}_{MW}, \quad (3)$$

where  $\dot{c}_{free}$  is the calving rate due to free convection,  $\dot{c}_{circ}$  is the calving rate due to horizontal fjord circulation, and  $\dot{c}_{MW}$  is the calving rate due to meltwater discharge. These calving rates are defined as

$$\dot{c}_{free} = \omega_f \dot{m}_{free}, \quad (4)$$

$$\dot{c}_{circ} = \omega_f \dot{m}_{circ}, \quad (5)$$

and

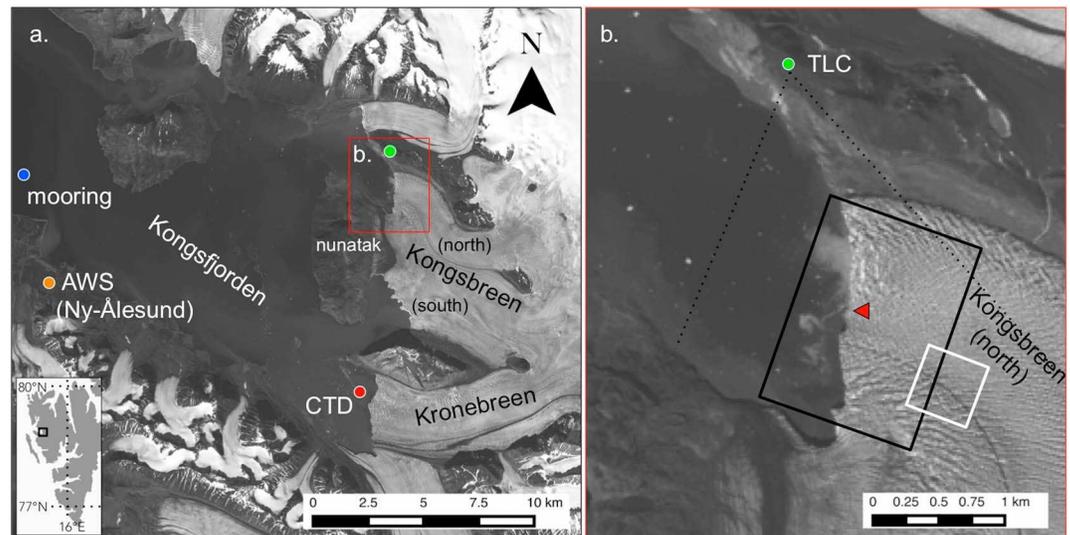
$$\dot{c}_{MW} = \omega_{MW} \dot{m}_{MW}. \quad (6)$$

Here  $\omega_f$  remains the wet calving multiplier for both the melt rate due to free convection ( $\dot{m}_{free}$ ) and fjord circulation ( $\dot{m}_{circ}$ ). The calving rate due to meltwater discharge ( $\dot{c}_{MW}$ ) uses a potentially different calving multiplier,  $\omega_{MW}$ . We justify the use of separate amplification factors for free convection and fjord circulation ( $\omega_f$ ) versus meltwater discharge ( $\omega_{MW}$ ) on the basis that melting due to free convection and fjord circulation act across the entire width of the terminus, while direct melting due to meltwater discharge is likely spatially localized due to the single prominent discharge location at Kongsbreen. Additionally, melting at one prominent location can result in a similarly localized stress field, and a modification of the overall terminus shape. During peak meltwater discharge, focused calving results in an indent of the terminus at the prominent discharge location. This behavior is in contrast to the more spatially uniform stress field created by melting across the entire terminus width, as with free convection and fjord circulation.

#### 3.3. Calculating Glacier Velocity and the Total Glacier Calving Rate ( $\dot{c}_{total}$ )

As in Benn et al. (2007), we determine the total glacier calving rate by measuring the difference between glacier velocity ( $v_g$ ) at the terminus and change in glacier terminus position over a period of time ( $dp/dt$ ):

$$\dot{c}_{total} = v_g - \frac{dp}{dt}. \quad (7)$$



**Figure 2.** Location map of Kongsbreen, Svalbard (inset), showing the northern and southern branches (a) and an enlarged map of the northern branch (b). The prominent subglacial discharge location (b, red triangle) is labeled, as well as the time-lapse camera (TLC; a, b, green circle), automatic weather station (AWS; a, orange circle), mooring (a, blue circle), CTD cast (a, red circle), and areas of the glacier and fjord used to calculate iceberg velocity (b, black box), calving rate (b, black box), and glacier velocity (b, white box). Background Landsat-8 image (a, b) was collected on 2 July 2016.

We use Sentinel-1a synthetic aperture radar (SAR) imagery to measure the change in terminus position and calculate glacier velocities. Sentinel is a European Space Agency constellation composed of several satellites, with Sentinel-1a and Sentinel-1b carrying identical C-band (5.405 GHz) SAR instruments operating in four different modes. In this study, we use the interferometric wide swath (IW) mode with  $\sim 5 \times 20$  m (range  $\times$  azimuth) spatial resolution. Sentinel-1a has a 12-day orbit and, because it is an active radar sensor, polar darkness and cloud cover do not hinder image collection. We use 11 Sentinel-1a images of Kongsbreen during the time-lapse camera image acquisition (30 April to 15 September) and an additional four images to bookend this period (two on each end).

To calculate the change in terminus position, we follow the methods of Moon and Joughin (2008), first digitizing the glacier terminus position, and then measuring the area upglacier of the terminus within a projected standardized box (Figure 2b, black box). We divide the upglacier area by the width of the standardized box (1,336 m), resulting in a normalized terminus position ( $P$ ; as in Schild & Hamilton, 2013). Using the width-averaged method, the location of area loss, whether focused at a meltwater discharge location or spread across the width of the terminus, will be indistinguishable. Therefore, we use this method in combination with the manually digitized terminus positions to identify locations of increased calving activity throughout the melt season.

To derive glacier velocity, we apply feature tracking to sequential Sentinel-1a imagery (Joughin et al., 2010; Luckman et al., 2015). The ground-range aspect ratio of the single-look data is  $\sim 1:5$ , so the correlation window size of  $500 \times 100$  pixels covers a ground area of  $\sim 1 \times 1$  km. Velocity is sampled every  $\sim 100$  m in ground range ( $50 \times 10$  pixels). Surface crevasses are the most likely features to exhibit useful correlations between images, while speckle is probably rarely correlated over 12 days at this location because of highly variable temperatures and relatively high flow rates. To characterize the terminus speed at Kongsbreen, we calculate the median speed within a  $500 \times 500$  m region (Figure 2b, white square) just upglacier of the terminus and equidistant from the fjord walls.

### 3.4. Constraining the Dry Calving Rate

As noted in previous studies, there is not a straightforward division between submarine melt driven calving and any other type of calving (Benn et al., 2017; O'Leary & Christoffersen, 2013; Seale et al., 2011). Here we use the same distinction of *dry* (melt-free) versus *wet* (melt-driven) calving as in O'Leary and Christoffersen (2013).

Observationally, it is difficult to measure the calving behavior of the glacier without the ubiquitous presence of frontal melting, and we therefore exploit the seasonal hydrologic cycle to constrain the dry calving rate. To quantify the dry calving rate, we select a time period when glacier runoff is minimal ( $\dot{m}_{MW} \approx 0$ ) and the terminus is also free to calve (no buttressing due to the wintertime sea ice). We use a reanalysis runoff time series for Kongsbreen in combination with the timing of Sentinel-1a image acquisition and define the early melt season as 10 April to 16 May (day 101–137). During this period glacier runoff is zero, therefore we set  $\dot{c}_{MW} = 0$  and equation (3) simplifies to  $\dot{c}_{total} = \dot{c}_d + \dot{c}_{free} + \dot{c}_{circ}$ . In using equations (4) and (5), this equation expands to become  $\dot{c}_{total} = \dot{c}_d + \omega_f(\dot{m}_{free} + \dot{m}_{circ})$ .

To constrain the calving amplification factor,  $\omega_f$ , we focus on the calving style of Kongsbreen during the early melt season period. Previous work proposed that small flake calving events likely result from no amplification, whereas large calving events result from large undercuts with calving amplification (Benn et al., 2017). During the early melt season, we find the calving events to be frequent ( $\sim 1$  event every 5 hr) and small, representative of calving with little to no amplification (Benn et al., 2017). Therefore, we set  $\omega_f = 1$  (i.e., no amplification) to compute  $\dot{c}_{free}$  and  $\dot{c}_{circ}$  and then solve for the dry calving rate. We find the dry calving rate to be 0.18 m/day, and hold it constant throughout the melt season (as in O’Leary & Christoffersen, 2013).

### 3.5. Calculating Submarine Melt Rates

#### 3.5.1. Free Convection Melt Rate ( $\dot{m}_{free}$ )

We quantify the free convection melt rate,  $\dot{m}_{free}$  (m/day), using a modified version of the empirical expression of El-Tahan et al. (1987; as in Kubat et al., 2005; Moon et al., 2017):

$$\dot{m}_{free} = 7.62 \times 10^{-3} T_d + 1.3 \times 10^{-3} T_d^2, \quad (8)$$

where the thermal driving temperature,  $T_d$  (°C), is calculated as the difference between ocean temperature and the freezing point of ocean water (Josberger, 1977). For ocean temperature, we use subsurface fjord temperature data collected from a mooring in Kongsfjorden (78.96°N, 11.80°E; Figure 2a, blue circle)  $\sim 16$  km from the Kongsbreen glacier terminus in an  $\sim 200$  m deep fjord (as used by Luckman et al., 2015). The mooring supported 10 temperature sensors spanning the 200 m depth, with approximately six sensors between 30 and 80 m, spaced at 10-m intervals. We choose a maximum depth of 80 m based upon the probable water mass exchange between the inner (glacier terminus) and outer (mooring location) fjord, as a 50 m sill stands between the mooring and the terminus of Kongsbreen (MacLachlan et al., 2016). Ocean temperature was measured throughout the duration of the 2016 melt season, with the exception of a 12-day gap (day 233–244) for instrument maintenance and data recovery. We use the mean daily ocean temperature, with a precision better than 0.1 °C after calibration (described by Cottier et al., 2005), and then average these daily temperatures to calculate the mean ocean temperature between Sentinel image acquisition dates. We calculate the average freezing temperature ( $\bar{T}_{fp}$ ) of the ocean water by averaging the local freezing point,  $T_{fp}$ , between 30 and 80 m depth, using the equation:

$$T_{fp} = \lambda_1 S + \lambda_2 + \lambda_3 z_b, \quad (9)$$

where  $S$  is the ambient salinity,  $z_b$  is the ambient pressure (dbar), and  $\lambda_1$  ( $-5.73 \times 10^{-2}$  °C/psu),  $\lambda_2$  ( $8.32 \times 10^{-2}$  °C), and  $\lambda_3$  ( $-7.61 \times 10^{-4}$  °C/dbar) are constants. For the ambient salinity,  $S$ , we use in situ measurements of salinity between 30 and 80 m (average of 34.5 PSU), collected in Kongsfjorden from a ship-based CTD cast on 23 August 2016 (Figure 2a, red circle), and calculate  $\bar{T}_{fp}$  to be  $-1.93$  °C. Based upon the average freezing temperature, we then calculate the thermal driving temperature,  $T_d$ , for each 12-day period between the 2016 Sentinel images, and determined the corresponding free convection melt rate using equation (8).

#### 3.5.2. Fjord Circulation Melt Rate ( $\dot{m}_{circ}$ )

To calculate the melt rate due to horizontal fjord circulation ( $\dot{m}_{circ}$ ), we use the simplified version of the three equation formulation for melt due to turbulent water motion (e.g., Hellmer & Olbers, 2004; Holland & Jenkins, 1999) proposed by McPhee (1992) and subsequently used by Jenkins (2011). For this calculation, we assume that water is moving horizontally along the terminus rather than vertically up the face as in plume models.

$$\dot{m}_{circ}L_i + \dot{m}_{circ}c_i(\bar{T}_{fp} - T_i) = c_w C_d^{1/2} \Gamma_{TS} \vartheta_w T_d, \quad (10)$$

and  $L_i$  ( $3.35 \times 10^5$  J/kg) is the latent heat of fusion of ice,  $c_i$  (2009 J/(kg °C)) and  $c_w$  (3974 J/(kg °C)) are the specific heat capacities of ice and ocean water,  $T_i$  is the ice temperature ( $-2$  °C) based on full-thickness temperature profiles collected at nearby glaciers (Björnsson et al., 1996),  $C_d^{1/2} \Gamma_{TS}$  is the Stanton number ( $5.9 \times 10^{-4}$ ; Jenkins et al., 2010),  $\vartheta_w$  is the water velocity relative to the glacier terminus (m/s), and  $T_\infty$  is the far field temperature measurement (°C). We modify the original conservation of heat equation by replacing  $T_\infty$  with  $T_d$  (°C) to include salinity (as in Moon et al., 2017).

In lieu of deploying instruments with a high likelihood of failure due to mélange, sea ice, and iceberg movement, we quantify the velocity of near-terminus fjord surface circulation ( $\vartheta_w$ ) by measuring the movement of natural trackers (icebergs) using time-lapse imagery. We installed a time-lapse camera at  $\sim 325$  m above sea level on the north side of the fjord (Figure 2b, green circle), which acquired photographs at a temporal resolution of 30 min from 30 April to 15 September 2016 (day 121–259). This time frame spans the disintegration of the wintertime mélange and sea ice in the spring, through the peak of the melt season in summer, to the development of the wintertime mélange in early fall. To postprocess the time-lapse imagery, we use a MATLAB georectification package (available at [https://gitlasso.uqar.ca/bourda02/g\\_rect](https://gitlasso.uqar.ca/bourda02/g_rect)) specifically designed to georectify oblique terrestrial imagery. We first stabilize the time-lapse images using foreground and distant bedrock for image alignment, which accounts for any slight movements or change in the camera's position caused by wind or camera servicing during image collection. We then orthorectify the imagery using ground-control points (GCPs) of known bedrock and terminus position coordinates visible in simultaneous ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer; 15 m) and time-lapse camera imagery (Figures 3a and 3b). Next we reproject the orthorectified images onto a 2-m grid in UTM coordinates, thus enabling analysis of iceberg movement as if viewed from nadir (Figure 3c). We use additional ASTER satellite imagery to validate the initial georectification and use ASTER and Landsat-8 imagery throughout the time series to validate iceberg identification and terminus position. Lastly, we use the MATLAB image georectification and feature tracking toolbox, ImGRAFT (Messerli & Grinsted, 2015), to calculate the movement of small icebergs within 50 m of the glacier terminus and within the center  $\sim 1.3$  km of the fjord (Figure 2b, black box) to avoid any boundary effects from the fjord walls. The errors associated with using ImGRAFT to calculate iceberg velocity are based upon uncertainties in the template matching, pixel coordinates of features, and resolution of the digital elevation model (DEM). For this study, we did not reproject the imagery onto a DEM as we were solely concerned with the fjord region, which is not susceptible to large variations in surface topography. We also have strongly constrained viewing geometry, therefore the errors resulting from feature tracking are due solely to template matching. We calculate this error by computing the velocity of a stationary area of bedrock over a 24-hr period (48 image pairs), thereby including any tracking errors due to illumination. We find the average velocity of the stationary bedrock to be  $2.56 \times 10^{-4}$  m/s, and thus also the error associated with iceberg velocity.

To derive water velocity from iceberg movement and remove the influence of wind, we apply the 2% rule where the movement of small icebergs due to the wind is approximately 2% of the wind velocity, relative to the ocean currents (e.g., Garrett, 1985; Smith, 1993; Wagner et al., 2017). To justify the use of this approximation, the icebergs must fall into the *small* category ( $l \times w \times h$  defined as  $< 100 \times 67 \times 67$  m; Bigg et al., 1997). To confirm Kongsbreen's icebergs meet this requirement, we determine a characteristic iceberg shape and volume using two WorldView-2 DEMs (2 m) collected at the peak of the 2015 melt season (3 July and 30 July). We first digitize the perimeter of 20 icebergs in open water, near the glacier terminus, and using the freeboard, calculate the volume of each iceberg using a density of  $1,026$  kg/m<sup>3</sup> for the ocean water (Svendsen et al., 2002) and an ice density of  $900$  kg/m<sup>3</sup> (Enderlin & Hamilton, 2014). The characteristic Kongsbreen iceberg has a mass of  $\sim 2.9 \times 10^8$  kg, and average surface dimensions of  $\sim 34 \times 34$  m, with a depth of 64 m based on a cylinder geometry. Kongsbreen icebergs therefore fall within the small category supporting the use of the 2% rule. However, 2% of the median recorded wind speed (2.7 m/s, 2% = 0.0054 m/s), measured at the Ny-Ålesund automatic weather station (AWS; 78.92°N, 11.93°E, 15 m above sea level; Figure 2a, orange circle), fell within our range of measured iceberg velocities (discussed in section 4.3) and we therefore consider  $\vartheta_i = \vartheta_w$  in all subsequent calculations (i.e., we assume the water velocity is equal to the velocity of the tracked iceberg).



**Figure 3.** Corresponding Kongsbreen ground control points (GCPs) in the ASTER image (a, blue circles, 26 July 2016 12:30) and time-lapse camera image (TLC; b, red crosses, 26 July 2016 12:33) used to orthorectify the time-lapse imagery for the 2016 summer season. The georectified time-lapse image (c) shows the ASTER GCP coordinates (blue circles) lining up with the corresponding time-lapse camera GCP positions (red crosses), indicating a well-constrained georectification.

### 3.5.3. Meltwater Discharge Melt Rate ( $\dot{m}_{MW}$ )

To calculate the meltwater discharge melt rate ( $\dot{m}_{MW}$ ), we use a modified version of the relationships established in Slater et al. (2016) for meltwater discharge from a distributed subglacial hydrology network:

$$\dot{m}_{MW(dist.)} = \frac{A_1[1 + A_2(T_{ocean} - T_{MW})]Q_{AVG}^{1/3}h}{l}, \quad (11)$$

and from a channelized subglacial network:

$$\dot{m}_{MW(channel.)} = \frac{A_3[1 + A_4(T_{ocean} - T_{MW})]Q_{AVG}^{1/3}h^{5/3}}{l}. \quad (12)$$

Here  $T_{MW}$  is the calculated pressure melting point temperature of meltwater discharging from under the glacier ( $-0.147^\circ\text{C}$ , equation in Cuffey & Paterson, 2010),  $Q_{AVG}$  is the average subglacial discharge ( $\text{m}^3/\text{s}$ ) between Sentinel images,  $h$  is the height of the terminus under water (140 m), and  $l$  is the terminus length experiencing melting (m). For the distributed case,  $l = 1,336$  m, and for the channelized case,  $l = 200$  m, based upon previous observations of submarine channel size (Jackson et al., 2017). The constants  $A_1$ ,  $A_2$ ,  $A_3$ , and  $A_4$  are from Slater et al. (2016) with values of  $1.56 \times 10^{-5} \text{s}^{-2/3}$ ,  $0.84/^\circ\text{C}$ ,  $4.05 \times 10^{-6} \text{m}^{1/3} \text{s}^{-2/3}$ , and  $0.75/^\circ\text{C}$ , respectively.

To calculate  $Q$ , we use a reanalysis model which simulates runoff from the entire Kongsfjorden basin using an energy balance model coupled with a subsurface snow model (Van Pelt and Kohler, 2015). We derive the individual catchment around Kongsfjorden with a topographically controlled flow algorithm (Schwanghart & Kuhn, 2010) and determine the tidewater glacier catchment with hydraulic head calculations. The surface energy balance model computes melt by considering all the energy fluxes present in the Kongsbreen glacier environment. We use local air temperature, air pressure, relative humidity, and cloud cover from the Ny-Ålesund AWS (Figure 2a, orange circle, AWS), and precipitation from downscaled ERA-Interim reanalysis (Østby et al., 2017) to force the model. Meltwater produced at the surface enters the snowpack where it is allowed to refreeze or be stored as irreducible water depending upon the density, temperature, and available pore spaces of each of the 100 vertical layers. All residual meltwater, which has penetrated the entirety of the vertical layers and has reached the interface between snow and ice, is able to penetrate the remainder of the ice through crevasses, and therefore is considered subglacial meltwater runoff. We assume that there is no subglacial storage of water and that all water reaches the terminus by traveling along the steepest slope and without significant delay on a daily scale.

**Table 1**

Calculated Calving Rates, Melt Rates, and Velocities for the 2016 Melt Season at Kongsbreen With the Sentinel Image Pairs (Column 1) Determining Wach Sampling Period

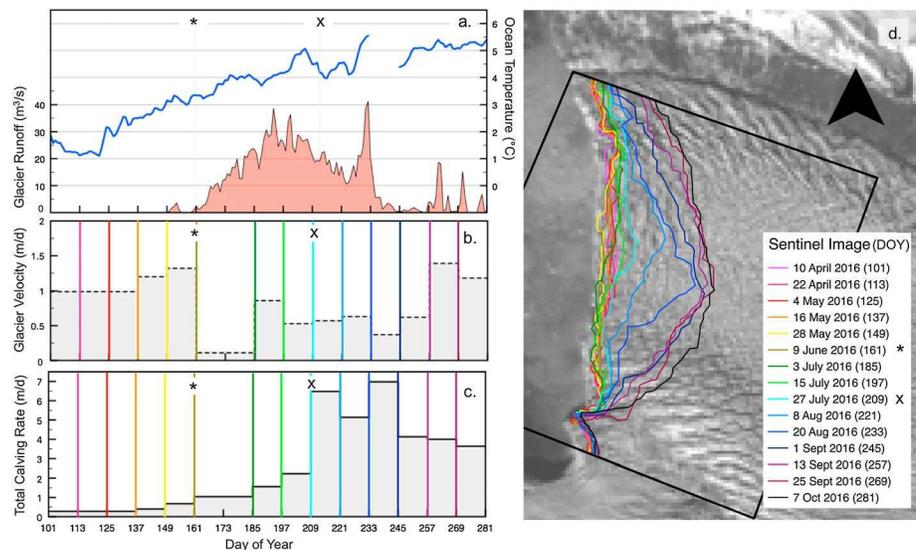
Image pairs (day of year)	$\vartheta_g$ (m/day)	$\frac{dP}{dt}$ (m/day)	$\dot{c}_{total}$ (m/day)	$T_{ocean}$ (°C)	$T_d$ (°C)	$Q_{avg}$ (m <sup>2</sup> /s)	$\dot{m}_{free}$ (m/day)	$\dot{m}_{circ}$ (m/day)	$\dot{c}_f$ (m/day)	$\dot{m}_{MW(200)}$ (m/day)	$\dot{m}_{MW(1336)}$ (m/day)	$\dot{c}_{resid}$ (m/day)
101–137	0.99	+0.71	0.28	1.69	3.62	0	0.04	0.06	0.10	0	0	0
137–149	1.20	+0.80	0.40	2.73	4.66	0.01	0.06	0.07	0.13	0.10	0.10	0.09
149–161	1.32	+0.65	0.67	3.19	5.12	0.97	0.07	0.08	0.15	0.52	0.53	0.34
161–185	0.11	−0.93	1.04	3.73	5.66	12.24	0.08	0.09	0.17	1.35	1.39	0.69
185–197	0.86	−0.70	1.56	3.97	5.90	26.67	0.09	0.09	0.18	1.82	1.88	1.20
197–209	0.53	−1.70	2.23	4.64	6.57	26.73	0.11	0.10	0.21	2.05	2.12	1.84
209–221	0.57	−5.91	6.48	4.31	6.24	18.42	0.10	0.10	0.20	1.71	1.77	6.10
221–233	0.63	−4.51	5.14	4.76	6.69	20.26	0.11	0.11	0.22	1.91	1.97	4.74
233–245	0.37	−6.61	6.98	4.86	6.32	4.94	0.10	0.10	0.20	1.21	1.25	6.60
245–257	0.62	−3.51	4.13	4.85	6.78	1.01	0.11	0.11	0.22	0.71	0.74	3.73
257–269	1.39	−2.61	4.00	5.17	7.10	4.71	0.12	0.11	0.23	1.25	1.29	3.59
269–281	1.18	−2.46	3.64	5.23	7.17	2.87	0.12	0.11	0.23	1.07	1.11	3.23

Note. Days of Sentinel imagery (column 1) are used to calculate glacier velocity (column 2), the change in terminus position (column 3), and the total calving rate (column 4). Ocean temperatures collected at a mooring (column 5), adjusted ocean temperatures calculated using measurements from a CTD cast (column 6), and glacier runoff (column 7) are used to calculate melt rates due to free convection (column 8) and fjord circulation (calculated with average observed ocean velocities, column 9). The combined calving rate due to free convection and fjord circulation (column 10) assumes an amplification factor ( $\omega_f$ ) of 1, and the residual calving rate (column 13) is calculated by subtracting the calving due to free convection and fjord circulation (column 10) and the dry calving rate (0.18 m/day) from the total calving rate (column 4). Melt rates due to meltwater discharge are calculated for a focused channel (column 11) assuming all discharge emerges from the central 200 m of the glacier terminus and a distributed subglacial hydrology network (column 12) assuming discharge is emerging across the entire 1,336 m of the glacier terminus.

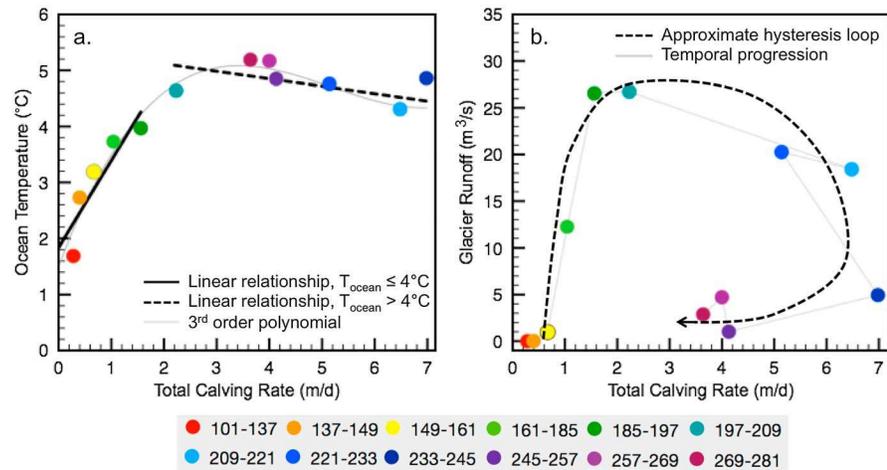
## 4. Results

### 4.1. Glacier Velocity and Calving Rates

Applying feature tracking to the Sentinel imagery, we found glacier velocities ranged from 0.11 to 1.39 m/day (Table 1), which, combined with terminus position changes in equation (7), corresponds to a total calving rate ( $\dot{c}_{total}$ ) between 0.28 and 6.98 m/day (Table 1). We solved equation (3) for each time period, where  $\dot{c}_d = 0.18\text{m/day}$ ,  $\omega_f = 1$ , and equations (8) and (10) are used to calculate the melt rate due to free convection



**Figure 4.** Plot of the daily average ocean temperature between 30 and 80 m depth (a, blue line) and glacier runoff (a, pink fill), in comparison with glacier velocity (b) and total calving rate (c) between sequential Sentinel images over the 2016 melt season. Colors of vertical lines (b and c) correspond to digitized terminus position on the Kongsbreen image map (d). The asterisks represents a decrease in glacier velocities, and the cross represents a jump in the calving rate due to meltwater discharge and a transition to calving focused at the meltwater discharge location.



**Figure 5.** Average ocean temperature (from a depth of 30 to 80 m; a) and average glacier runoff (b) between sequential Sentinel images (colored circles) plotted against the total calving rate. Linear (a, black lines) and third-order polynomial (a, solid gray line) lines show the strongest relationship between the total calving rate and the ocean temperature. The hysteresis loop (b, dashed black line) suggests a variable calving response to glacier runoff, which is temporally dependent. The transition to calving focused at the prominent meltwater discharge location occurs on day 209, the same time the relationship between the total calving rate and glacier runoff transitions from linear to a hysteresis loop.

and fjord circulation, respectively. The contribution to total glacier calving rate from free convection and fjord circulation ( $\dot{c}_f$ ) ranged from 0.10 to 0.23 m/day. The remainder of the total calving rate, 0–6.60 m/day (residual calving rate,  $\dot{c}_{\text{resid}}$ ), we attribute to meltwater discharge calving ( $\dot{c}_{\text{MW}}$ ). At the peak of calving, the calving rates attributed to meltwater discharge was an order of magnitude greater than the calving rate attributed to free convection and fjord circulation calving combined. Flake icebergs ( $<1,000 \text{ m}^2$ , average  $\sim 250 \text{ m}^2$ ) dominate calving early in the melt season, and a combination of flakes and larger icebergs ( $\sim 450 \text{ m}^2$ ) are produced as the predominant area of iceberg calving transitions to the subglacial discharge location in the late-season (July–August, Figure 4d).

#### 4.2. Total Calving Rate Versus Ocean Temperature and Glacier Runoff

In comparing the total glacier calving rate (0.28–6.98 m/day) to concurrent average ocean temperatures from 30 to 80 m depth (1.69–5.23 °C), we find an approximately linear relationship between these variables with a break at  $\sim 4^\circ\text{C}$  (Figure 5a). Data points with an ocean temperature less than  $4^\circ\text{C}$  have a slope of  $\sim 1.5$  ( $R^2 = 0.80$ ), similar to nearby Kronebreen (Luckman et al., 2015), and data points with an ocean temperature greater than  $4^\circ\text{C}$  have a slightly negative slope ( $R^2 = 0.38$ ). If we fit a third order polynomial to these data instead of two linear trend lines, we find a strong correlation ( $R^2 = 0.95$ , Figure 5a, solid gray line), however, a polynomial fit is nonsensical outside the range of observations, so we therefore use ocean temperature to divide the linear relationships. When comparing the total glacier calving rate with modeled glacier runoff results (Figure 5b), we find no consistent relationship, but a temporally distinct hysteresis loop (Figure 5b, dashed black line) where the same rate of glacier runoff late in the season has a larger associated calving rate than early in the melt season. The amplified calving late in the season also coincides with the highest ocean temperatures recorded during the study period (Figure 4a) and a shift from calving occurring across the terminus width to focused calving at the submarine discharge location (Figure 4d). These concurrent changes suggest that the meltwater discharge melt rate, timing of meltwater discharge, and the temperature of the ocean are critical parameters to the total glacier calving rate.

#### 4.3. Water Velocities From Iceberg Motion

To quantify water flow direction and speed, we measure iceberg motion close to the terminus of Kongsbreen. Using the iceberg feature tracking results from the georectified time-lapse camera imagery, we identify four prominent states of iceberg movement, and therefore water flow, in the near-terminus region:

1. Along-fjord flow: characterized by surface water moving either up-fjord or down-fjord as a collective unit. Such flow is generally related to large calving or wind events, and on very few occasions is coincident with the subdiurnal tide.
2. Isolated along-terminus flow: characterized by surface water moving parallel to the glacier terminus on a local scale (less than the full terminus width). Such flow generally occurred at locations adjacent to calved icebergs or sites of subglacial discharge and immediately following a calving event or subglacial discharge pulse.
3. U-turn flow: characterized by surface water moving toward the glacier on one side of the fjord, contacting the glacier, redirecting to flow parallel to the terminus, impacting the opposite fjord wall, and flowing toward the ocean on the opposite side of the fjord. The along-terminus flow occupied the entire width of the fjord, and the entry and exit sides were variable.
4. Eddy circulation: characterized by closed-loop circulation of surface waters in a clockwise or counterclockwise orientation adjacent to the terminus. The spatial and temporal variability ranges from 10s of meters in diameter lasting minutes to hours, to full-fjord-width circulation lasting several hours.

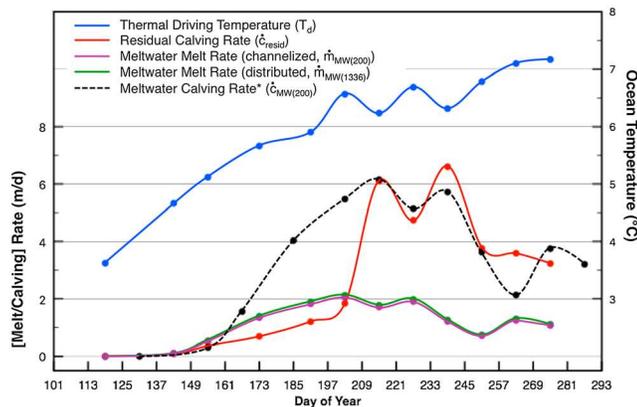
For the remainder of this paper, we use velocities adjacent to the terminus calculated only during eddy circulation events (iceberg movement state 4), occupying the full-fjord width, and consider this range of velocities as characteristic of all fjord circulation velocities present throughout the melt season. We choose this circulation pattern as it encompasses all of the prominent states of iceberg movement (e.g., flow along-terminus, into the terminus, away from the terminus, and circulation back toward the terminus) and therefore is an appropriate representation of average fjord circulation. The eddy circulation events lasted between 3.5 and 15 hr, with an average iceberg velocity of  $2.6 \times 10^{-2} \pm 2.56 \times 10^{-4}$  m/s (range of  $1.6 \times 10^{-2}$  to  $3.6 \times 10^{-2}$  m/s). While the water velocity is variable throughout a melt season and likely with depth, we apply this range of water velocities across the entire study period and with fjord depth to establish a maximum melt rate and terminus undercutting due to fjord circulation.

## 5. Discussion

### 5.1. Calculating Meltwater Discharge Calving Rate ( $\dot{c}_{MW}$ )

To calculate the calving rate due to meltwater discharge, we quantify the melt rate due to meltwater discharge ( $\dot{m}_{MW}$ ) and constrain the calving amplification factor ( $\omega_{MW}$ ). We use the relationships established in equations (11) and (12) to first calculate the meltwater discharge melt rate (Figure 6, solid green and purple lines) and compare this melt rate to the residual calving rate (Figure 6, solid red line). We find a stark difference between the meltwater discharge melt rates and the residual calving rate before and after day 209 (Figure 6). After day 209, the meltwater discharge melt rates (Figure 6, solid green and purple lines) are drastically lower than the residual calving rate (Figure 6, solid red line), therefore calving amplification is likely occurring and  $\omega_{MW} \neq 1$ . A calving amplification physically represents ice loss extending beyond the submarine melt undercut. The calving record supports this implication, as larger icebergs calve as soon as calving becomes focused at the meltwater discharge location.

For Kongsbreen, we found the highest correspondence between the residual calving rate and the computed meltwater discharge calving rate when  $\omega_{MW(200)} = 3$ , and we shifted the meltwater calving rate forward by 12 days (accounting for a proposed temporal lag of 12 days; modification indicated by asterisks in Figure 6). While this shift and calving amplification may more closely characterize the residual calving rate than no shift or calving amplification, the modification still overestimates the early season calving and underestimates the late season calving (Figure 6, black dashed line). This misrepresentation could be, in part, due to the hysteresis relationship between glacier runoff and total glacier calving rate (Figure 5b). Early in the melt season, the lag between an increase in meltwater runoff and calving response may represent the time needed for the submarine undercut notch to develop (e.g., Fried et al., 2015; Rignot et al., 2015; Slater et al., 2017). However, in both the distributed and channelized subglacial discharge configurations used to calculate the meltwater calving rates, an overestimation of calving early in the melt season is observed. Processes not driven by submarine melting could be contributing to the late season offset, such as calving resulting from destabilized terminus geometry (e.g., from focused calving). However, the complex relationship between meltwater discharge melt rates, ocean temperatures, and meltwater discharge calving rates is also likely not fully represented in this simplified amplification



**Figure 6.** Melt rate (green and purple solid lines) and potential calving rate trend (black dashed line) due to meltwater discharge and thermal driving temperature of the ocean (blue line). While both calving rate trends closely follow one another, the green line assumes discharge across the entire width of the glacier (1,336 m) and an amplification factor dependent on the differential ocean temperature ( $T_d$ ), while the purple line assumes all discharge is focused at one opening (200 m wide) and a constant amplification factor independent of ocean temperature. The calving rate is shifted forward by 12 days (indicated by asterisks) to better correspond with the residual calving rate (red line) trend.

factor. Nevertheless, this calving response justifies the partitioning of the calving rate into free convection, fjord circulation, and meltwater discharge.

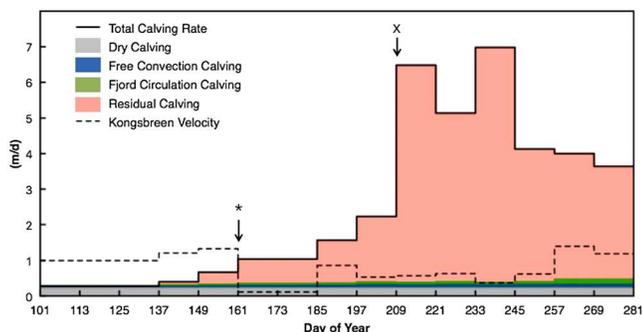
### 5.2. Calving Rates and Environmental Controls

In comparing the records of partitioned calving rates and glacier velocity (Figure 7), there are two distinct transitions in the synthesis of these time series. The first is the significant drop in glacier velocity (day 161), which also marks the transition from fairly consistent winter-time velocities to variable summer velocities. This occurred 35 days after the breakup of the wintertime sea ice (day 126, 5 May 2016) and between 12 and 24 days after the total glacier calving rate transitioned from being dominated by free convection and fjord circulation calving to residual (meltwater) calving (day 161, asterisk, Figures 4 and 7; Table 1). The combination of increased meltwater calving and decreased glacier velocities could signify the transition between a distributed subglacial configuration to a more connected, efficient, subglacial network (as observed by Nienow et al., 1998). The second transition occurs when the residual calving rate spikes, and calving begins to focus at the meltwater discharge location (day 209, cross, Figures 4 and 7).

### 5.3. Caveats and Uncertainties

The methods developed and successfully used here are easily generalized to other tidewater glaciers; however, the dynamics they reveal may vary from glacier to glacier. Kongsbreen has one dominant discharge location, and therefore the majority of meltwater is likely routed to this central location amplifying the single impact of meltwater discharge on terminus geometry. However, if Kongsbreen had multiple dominant discharge locations, meltwater discharge would still influence terminus shape as localized melting would continue, but the overall impact of each individual discharge location would be dampened and a single focused calving location, as observed here, likely would not occur.

The shallow depth of Kongsbreen's fjord (~140 m) likely allows subglacial meltwater to rise more frequently to the surface, thereby melting the entire height of the terminus face during the meltwater transit. In deeper fjords, the meltwater has a greater vertical distance to travel before reaching the surface, so the probability of meltwater equilibrating at depth is greater, thus only allowing terminus melt for a portion of the terminus thickness (e.g., Carroll et al., 2016; Chauché et al., 2014). Meltwater equilibration at depth is also one of the proposed mechanisms for development of subsurface layers, which would also encourage equilibration (Sciascia et al., 2013; Sole et al., 2011; Straneo et al., 2011). Therefore, it may be that the meltwater discharge amplification factor ( $\omega_{MW}$ ) decreases with increasing fjord depth. Conversely, tidewater glaciers draining into deeper fjords may also have a larger catchment basin, such as those in Greenland, and therefore greater meltwater discharge; this would enable a more expedient development of a submarine notch and allow meltwater to impact the glacier for a longer portion of the melt season. In this case, increased meltwater discharge would encourage more efficient terminus melting and subsequent calving (Luckman et al., 2015; Motyka et al., 2013).



**Figure 7.** Kongsbreen velocity (m/day, dashed black line) and total calving rate (m/day, solid black line) for the 2016 summer melt season derived from Sentinel-1a imagery. Colored bars indicate the partitioning of the total calving rate into the dry calving rate (gray bar), and the calving rates of free convection (blue bar), fjord circulation (green bar), and residual (pink bar), attributed largely to meltwater discharge calving. The asterisk represents a large decrease in glacier velocity, while the cross notes a large spike in the residual (meltwater) calving rate (as shown in Figure 5).

Several assumptions were made in parameterizing melt rates, specifically those associated with fjord circulation. Many of the assumptions were made to establish the maximum contribution of fjord circulation melt on total glacier calving rate. These assumptions include the full-submerged thickness of the glacier terminus experiencing the same along-terminus flow as at the surface, the water velocities associated with full-fjord-width circulation events representing the average circulation along the terminus,

and the calculated water velocities occurring throughout the entire melt season. All of these assumptions are unlikely to be entirely justified due to the subglacial discharge and fjord mixing present at Kongsbreen, and thus these calculations likely overestimate fjord melting. Nevertheless, even as an overestimate, fjord melting still remains a relatively small contributor to the total glacier calving rate.

Lastly, while we attempted to present a conservative estimate of calving due to meltwater discharge by maximizing calving rates due to fjord circulation, we only include the three simplified mechanisms of submarine melting and terminus undercutting. We therefore recognize that the residual calving rate may likely include yet unidentified forms of submarine melt mechanisms in addition to meltwater discharge calving, such as tides. However, we saw very few instances of coincident iceberg movement with tidal phase in the time-lapse camera time series and therefore rule it out as a dominant control at Kongsbreen. We note that, for simplicity, several other relationships of potential importance have been ignored, such as the interplay between the three mechanisms of submarine melting, specifically meltwater discharge-driven horizontal fjord circulation, as well as changes in the dry calving rate of the glacier resulting from glacier thinning or crevasses filling with water. The inclusion of these additional mechanisms or changes in the glacier surface would decrease the residual calving rate, and subsequently the calving rate due to meltwater discharge. Additionally, the melt rate calculations presented here currently rely on parameterizations not very well tested observationally and/or only derived in numerical models. More in situ studies and laboratory experiments are needed to physically support these equations.

## 6. Conclusions

During this study we partitioned total glacier calving rate into calving resulting from three forms of submarine melting: free convection, horizontal fjord circulation, and meltwater discharge. We used a variety of in situ and remote sensing data to quantify submarine melt rates including time-lapse camera and Sentinel imagery collected during the 2016 melt season at Kongsbreen, Svalbard, as well as mooring data for mid-fjord ocean temperature (30–80 m depth), a CTD cast, and reanalysis runoff results. To calculate water velocity, we used the time-lapse imagery to capture icebergs moving along the terminus. We orthorectified and geolocated the time-lapse imagery and, through the 30-min temporal resolution, were able to track iceberg movement near the terminus corresponding to water velocities between  $1.6 \times 10^{-2}$  and  $3.6 \times 10^{-2} \pm 2.56 \times 10^{-4}$  m/s. We used full-fjord width (eddy) circulation events as a benchmark for persistent along-terminus flow, and found fjord circulation accounts for a maximum of 0.06–0.11 m/day of terminus undercutting with the melt rate due to fjord circulation of comparable magnitude to free convection melt rates (0.10–0.22 m/day). In quantifying the calving rate due to free convection and fjord circulation (0.10–0.23 m/day), we isolated the residual calving rate, due largely to meltwater discharge, finding this calving rate to be 0–6.60 m/day, or up to an order of magnitude larger than the combined calving rate due to free convection and fjord circulation. We calculated the melt rates due to meltwater discharge in a channelized and distributed subglacial hydrology configuration, finding melt rates between 0 and 2.05 m/day when focused across 200 m (channelized) or 0 and 2.12 m/day when discharging across the entire 1,336 m width of the terminus (distributed).

In this study, we observed an increase in the contribution of meltwater discharge calving to overall calving rate in parallel with an increase in meltwater discharge and ocean temperature (Figures 4 and 7), which supports our hypothesis, and ideas previously proposed by others, that meltwater discharge is a dominant control on terminus shape and retreat (e.g., Fried et al., 2015; Motyka et al., 2013; Rignot et al., 2015; Truffer & Motyka, 2016). Due to the variable relationship between meltwater discharge melt rate and the residual calving rate, we propose an amplification factor of 3 and a temporal lag of 12 days (Figure 6). However, we were still unable to completely fit the meltwater discharge calving rate to the residual calving rate, likely due to the hysteresis relationship between glacier runoff and total glacier calving rate (Figure 5b). Therefore, lacking an ideal correspondence between melt rate and calving rate, using calving rates to assess the impact of meltwater discharge on glacier terminus stability could provide a more fruitful alternative to directly calculating melt rates. Due to the influence of meltwater on terminus position and shape, and the dominant control meltwater discharge and ocean temperatures have on total glacier calving rates, continued investigations into the controls on submarine melting are critical. Additionally, incorporation of these relationships into models is essential to accurately predicting the future of glaciers as atmospheric and oceanic temperatures, and thus meltwater discharge, continue to rise.

## Acknowledgments

We would like to thank the New Hampshire Space Grant Consortium (award # NNX15AH79H) for the training grant to fund KMS; the ConocoPhillips-Ludín Northern Area Program (under the CRIOS project) and the Dartmouth Graduate Studies Travel fund for their financial support to conduct fieldwork and travel for data dissemination; the Polar Geospatial Center for arranging access to the WorldView-2 imagery; the UK Natural Environmental Research Council (NERC) Oceans 2025 and Northern Sea Program for mooring work support, with further support from the Research Council of Norway (NFR) projects: Circa (214271), Cleopatra (178766), Cleopatra II (216537), and Marine Night (226471); Alex Hart and the GeoSciences Mechanical Workshop at the University of Edinburgh for manufacturing the time-lapse camera enclosure that was used in this study; Colin Griffiths (SAMS) and Jørgen Berge (UiT) for overseeing the collection of mooring data in Kongsfjorden since 2002; ESA for processing the Copernicus Sentinel data (2016). A video of the Sentinel imagery used in this study (doi:10.18739/A2NZ80P8K), as well as the raw time-lapse imagery (doi:10.18739/A2SQ8QH3F), mooring ocean temperature data, and CTD cast measurements (doi:10.18739/A2XG9F97K) are all available at the Arctic Data Center. Lastly, we would like to thank Bryn Hubbard and the four anonymous reviewers for their very helpful and thorough reviews.

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