Spatiotemporal Distributions of Icebergs in a Temperate Fjord: Columbia Fjord, Alaska

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Abstract. Much of the world's ice enters the ocean via outlet glaciers terminating in fjords. Inside fjords, icebergs may affect glacier-ocean interactions by cooling incoming ocean waters, enhancing vertical mixing, or by providing back stress on the terminus. However, relatively few studies have been performed on iceberg dynamics inside fjords, particularly outside of Greenland. We examine icebergs calved from Columbia Glacier, Alaska, over eight months spanning late winter to mid-fall using 0.5-meter resolution satellite imagery, identifying icebergs based on pixel brightness. Iceberg sizes fit a power-law distribution with an overall power-law exponent, *m*, of -1.26 ± 0.05. Seasonal variations in the power-law exponent indicate that brittle fracture of icebergs is more prevalent in the summer months. Combining our results with those from previous studies of iceberg distributions, we find that iceberg calving rate, rather than water temperature, appears to be the major control on the exponent value. We also examine iceberg spatial distribution inside the fjord and find that large icebergs (10,000 m^2 – 100,000 m^2 cross-sectional area) have low spatial correlation with icebergs of smaller sizes due to their tendency to ground on the shallows. We estimate the surface area of icebergs in contact with incoming seawater to be $3.0 \pm 0.63 \times 10^4$ m^2. Given the much larger surface area of the terminus, $9.7 \pm 3.7 \times 10^5$ m^2, ocean interactions with the terminus should have a larger impact on ocean heat content than interactions with icebergs.

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1 Introduction

In recent decades, fjord-terminating glaciers have been rapidly losing mass (Larsen et al., 2007; Pritchard et al., 2009), contributing significantly to eustatic sea level rise (Gardner et al., 2013; McNabb and Hock, 2014). High volumes of ice discharge due to iceberg calving and submarine melt have been attributed to contact with relatively warm and salty fjord waters (Bartholomaus et al., 2013; Motyka et al., 2003). Current fjord circulation models do not take icebergs into account, though icebergs may modify warm, dense waters entering the fjord by enhancing vertical mixing and by extracting heat through iceberg melt (Carroll et al., 2015; Klinck et al., 1981; Mortensen et al., 2018; Motyka et al., 2003; Rignot et al., 2010). Various studies have examined the iceberg calving process (Bahr, 1995; Chapuis and Tetzlaff, 2014; Hughes, 2002; O'Neel et al., 2003; Warren et al., 2001), as well as the transport and evolution of icebergs in the open ocean (Bigg et al.,

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1997; Dowdeswell and Forsberg, 1992; Gladstone et al., 2001; Kubat et al., 2007), but comparably little is known about iceberg transformation occurring inside the fjords where they originate.

Recent studies of icebergs have focused on icebergs calved from Greenland or Antarctic glaciers, however in this study we provide insight into the size and location of icebergs in a major Alaskan fjord using high-resolution satellite imagery. We examine the differences in iceberg populations over a span of eight months in 2013 to gain insights into the seasonal influence on iceberg size and distribution. We also investigate how icebergs of varying sizes evolve along the fjord to better understand where iceberg meltwater is introduced in vertical and horizontal dimensions.

Our analyses focus on the fjord of Columbia Glacier, which connects with Prince William Sound, Alaska. Columbia Glacier is the single largest contributor to ice loss from Alaskan glaciers, accounting for ~6-17% of annual land ice loss from this region (Gardner et al., 2013; Pfeffer, 2015; Rasmussen et al., 2011). Columbia Glacier is also one of the best-studied glaciers in the world. The United States Geologic Survey (USGS) has been instrumenting Columbia Glacier since the 1970's, and the first time-lapse cameras used to study glacier movement and iceberg calving were implemented in 1978 (Meier and Post, 1978; Pfeffer, 2012). From 2012 to 2015, the Prince William Sound Regional Citizen's Advisory Council (PWSRCAC) commissioned a study of Columbia Glacier, which included several field campaigns and geophysical tools, with the aim of better predicting the future behavior of the glacier. PWSRCAC was particularly interested in understanding iceberg discharge, as icebergs that exit Columbia Fjord later intrude on the shipping lanes into and out of the Port of Valdez (Pfeffer, 2012, 2013a, 2013b, 2014a, 2014b, 2015).

Columbia Glacier has a total surface area of around 910 km^2 (McNabb et al., 2012a), and is located in central Alaska in the Chugach Mountains (Fig. 1). From 1794 – when the terminus of Columbia Glacier was first mapped by Captain George Vancouver – to 1980, the terminus of the glacier was in a stable location, terminating at the northern end of Heather Island (Meier and Post, 1978; Post, 1975). From 1980 to 2013, the year when the satellite images used in this project were acquired, the glacier retreated approximately 20 km. This retreat revealed a fjord extending north-south, roughly 5 km in width and 20 km in length. At the entrance to the fjord is a submarine end moraine – which shall be referred to as "Heather Moraine" – built by the glacier when it was in its extended Neoglacial position (Meier and Post, 1978). An oceanographic survey of Columbia Fjord completed in 1983 determined that the water column over Heather Moraine was shallow – less than 20 m below Mean Lower Low Water (the average height of the lowest tide over the National Tidal Datum Epoch, as defined by the National Oceanographic and Atmospheric Administration [NOAA]) – and partially exposed (Pfeffer, 2013a; Walters et al., 1988). Pfeffer (2013a) examined more recent bathymetric surveys of Heather Moraine and found that the bathymetry did not change significantly between 1977 and 2005, indicating that very little erosion has occurred. The mean tidal fluctuation in nearby Valdez, as measured by NOAA, is ~3m, with maximum fluctuations up to 5-6m, indicating the maximum water depth above Heather Moraine to be ~25m. Behind Heather Moraine, fjord bathymetry descends to 200 m b.s.l. (Walters et al., 1988). Iceberg calving rates increased following the initiation of glacial retreat, and reached a maximum of over 10 km^3 yr^{-1} in 1999-2000 (Pfeffer, 2013b) – 8.5 km^3 yr^{-1} averaged over 1996-2007 (Rasmussen et al., 2011). Calving rates at Columbia Glacier have since been decreasing (Pfeffer, 2013b). Between

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2010 and 2013 the average ice flux into the fjord was measured at 2.23 km^3 yr^{-1} (Pfeffer, 2013b), most of which came from the main branch of the glacier. Between 2011 and 2014 the average mass flux from the main branch of Columbia Glacier was measured to be 1.18 ± 0.30 Gt yr^{-1} (~1.29 km^3 yr^{-1}) (Vijay and Braun, 2017).

2 Methods

2.1 Image Processing

To determine the spatial distribution of icebergs, we obtained 0.5 m-resolution, 8-bit, grayscale imagery of Columbia Fjord from the Polar Geospatial Center at the University of Minnesota. The images were taken by the WorldView satellites 1 and 2 during 2013, and georeferenced by the Polar Geospatial Center (image details shown in Table 1). Although the WorldView 2 satellite offered multispectral bands, we only used the higher-resolution panchromatic bands from both satellites (WorldView 1 spectrum spanned wavelengths 400 – 900 nm, and WorldView 2 spectrum spanned wavelengths 450 – 800 nm). The spread of nine dates provides seasonal coverage of the fjord, from late winter to the middle of the fall: March 13, May 6, June 10, July 11, July 12, and November 19. Note that we use the oceanographic definitions of seasons, such that winter is January-February-March, and so on in 3-month increments. To image large swaths, the WorldView satellites capture multiple overlapping images at once. We mosaiced these overlapping images taken simultaneously or within hundredths of a second to provide complete coverage of the fjord, with the exception of July 11 and May 06b. For several of the dates a second set of images were taken one minute later, for the purposes of stereo imagery. We distinguish between the two sets of images by labelling the first image mosaic 'a' and the second 'b'. Because the icebergs likely remain unchanged between these sets of images, the differences in iceberg identification between 'a' and 'b' images potentially result from changes in reflectivity of the open ocean due to the two distinct satellite viewing angles. Changing the angle at which we view the ocean changes the reflectivity of the ocean, which could therefore affect which pixels were identified as ice versus water. Additionally, we use these pairs of images to constrain the error on our iceberg identification method. We consider the fjord to be the area bounded by the shores of the fjord, the glacier termini, and Heather Moraine (covering a total area of ~87 km^2 [8.7 x10^7 m^2]). Because of the shallow water depths above Heather Moraine, it is a natural barrier separating Columbia Fjord from Prince William Sound. In addition, the shallow depths cause large icebergs to run aground, allowing for easy identification of the submarine moraine in the satellite imagery.

To identify and locate icebergs in each image we created a thresholding algorithm using the MATLAB image processing toolbox that identified potential iceberg areas based on pixel intensity value. Icebergs had higher pixel brightness values than the darker fjord waters, thus we set a threshold brightness value above which pixels were classified as icebergs and below which they were classified as water. Because frequency histograms of pixel brightness did not reveal a bimodal pattern, we therefore chose a threshold value of 41 out of 255, which corresponded with the highest pixel value for open ocean identified through visual inspection. The automatic iceberg recognition algorithm performance was impacted when the icebergs were surrounded by ice mélange, tiny chunks of ice derived from icebergs or the glacier terminus floating on top

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In addition to defining the pixel intensity threshold, we set upper and lower bounds on the iceberg area, with the lower bound corresponding to the smallest group of pixels we could visually identify as an iceberg (20 pixels, or 5 m^2) and the upper bound corresponding to the number of pixels in the largest iceberg we found visually (112,000 pixels). We set an upper bound on iceberg size to prevent large areas of ice mélange being identified as a single iceberg. The term 'iceberg' in this study refers to icebergs (>15m across as defined by the Canadian Ice Service, or >3000 ft^2 [278 m^2] in area as defined by the US National Ice Service), as well as growlers and bergy bits (glacially-derived ice in the ocean that is smaller than an iceberg).

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To quantify the error on iceberg identification, we compared the results of the manual and automatic iceberg identification. We divided each mosaic into a test grid, with each test cell being 250 by 250 pixels (~125m x 125m, or roughly half the area of the largest iceberg). We then randomly selected test cells on each of the mosaics and counted the number of icebergs by eye and using the thresholding code. After examining a total of 107 grid cells, we found that the algorithm identified 95 ± 4 % of the icebergs identified by an observer. Occasionally, when icebergs were close together, the algorithm would categorize them as a single iceberg, leading to the under-identification of the number of icebergs. To verify if we had counted enough cells, we divided the cumulative number of icebergs identified by the algorithm in cells 1 through N (where N is the number of test cells counted) by the cumulative number of icebergs identified manually (cells 1 through N), and plotted this versus N (Fig. 2a). The slope of the line plateaued around N=44. We used the mean and the standard deviation of the line between N=44 and N=107 as our estimate of iceberg identification error. Error in automatic iceberg identification was greater in mélange-covered areas than open ocean. We found that the algorithm identified 67 ± 6 % of the icebergs in the areas of ice mélange. To assess the amount of mélange present in Columbia Fjord, we examined the pixels identified as ice, but not counted as icebergs. The area of the fjord covered by mélange ranged from 1.1 ± 0.12 to 9.9 ± 0.79 % (Table 4).

In addition to quantifying the error in the number of icebergs identified, we estimated the error on the area of the icebergs by comparing the total area of icebergs calculated by the algorithm. For June 10a and June 10b, the difference in total iceberg area amounted to less than 8% of the total calculated iceberg area for each image. For July 12a and July 12b, that difference amounted to less than 4%.

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2.2 Overall Iceberg Distributions

To examine the spatial distribution of icebergs inside the fjord, we created a time-integrated map of iceberg density. We did this by dividing the fjord into 500 m x 500 m squares and counting the number of icebergs whose centroids were present within each square. Overlaying the results from March 13, June 10a, July 12a, and November 19, we created a map which depicted the locations of all the icebergs identified during our study (Fig. 4a). We created a similar map of cumulative area of icebergs whose centroids resided in each square (Fig. 4b).

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2.3 Along Fjord Iceberg Distributions

To examine the variation in spatial distribution of icebergs between scenes, we divided the fjord longitudinally into evenly spaced sections roughly one kilometer in length starting from the terminus to Heather Moraine. The icebergs were binned into those sections based on the location of their centroids. In some of our analyses, we needed a larger sample size of icebergs, so we also divided the fjord into three geographic sections (Fig. 1), which are based on fjord geometry. The "Proximal Zone" spans from the terminus of the glacier to the first major constriction, the "Mid-Fjord Zone" spans from the constriction to the inlet on the east side of the fjord, roughly two-thirds of the way downfjord, and the "Distal Zone" spans from the inlet to Heather Moraine.

Following the methodology established in prior similar studies, we fit a power-law equation of the form $Pr(A > a) = bA^m$ to iceberg areas in each of the three zones to determine the iceberg size-distribution (Kirkham et al., 2017; Sulak et al., 2017; Tournadre et al., 2016). $Pr(A > a)$ represents the number of icebergs whose waterline cross-sectional area, A, is greater than a. b and m are the constants which are constrained by data fitting. We chose values of a to be multiples of 1000 from 0 to 100,000 m^2, increasing the resolution of a between 0 and 1000 m^2 to include: 10, 25, 50, 75, 100, 250, 500, and 750 m^2. To determine the goodness of fit of the power-law we performed a Kolmogorov-Smirnov test. To obtain a fit with 95% confidence we had to remove the largest icebergs, which deviate from the power-law size distribution followed by smaller icebergs. There is often difficulty fitting the tail of the distribution due to the number of samples being too low, and removing the largest icebergs to fit the distribution has been done in other similar recent studies (e.g. Sulak et al., 2017). An example of our power-law fit is shown in Fig. 3.

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To test whether icebergs of various sizes co-vary spatially within Columbia Fjord, we separated the iceberg population into five class sizes based on their waterline cross-sectional area, which we define as the area of the icebergs visible from satellite imagery. The class size bins were spaced logarithmically (0-10 m^2, 10-100 m^2, 100-1,000 m^2, 1,000-10,000 m^2, and 10,000-100,000 m^2) with Class 1 representing the smallest icebergs and Class 5 representing the largest. For each one-kilometer bin along the fjord we compared the evolution of the different classes down the fjord by plotting the different class sizes against each other and calculating the Pearson correlation coefficient using the equation:

$$P_{C_a C_b} = \frac{cov(C_a, C_b)}{\sigma_{C_a}\sigma_{C_b}} \qquad \text{Eq. (1)}$$

where cov is the covariance, σ is the standard deviation, and C_a and C_b represent the two class sizes being compared. The limits of the 95% confidence interval were used as the upper and lower bounds of the error. We calculated the Pearson correlation coefficient using the icebergs from all scenes combined. In addition to calculating the correlation of the different size classes, we plotted the exact locations of the large icebergs (Classes 3-5) inside the fjord for each date to better understand where the large icebergs were located inside the fjord.

2.4 Iceberg Characteristics

We use the waterline cross-sectional area of the icebergs (A) to calculate iceberg volume. We estimate iceberg volume using two previously proposed scaling laws. For the first approach we use the equation for iceberg volume (V) derived by Sulak et al. (2017):

$$V = 6.0A^{1.30} \qquad \text{Eq. (2)}$$

For the second approach we assume the icebergs to be rectangular prisms and use the proportions used by Bigg et al. (1997) where the ratio of iceberg length to width is equal to 1.5:1, the draught to the width ratio equal to 1:1, and the draught to freeboard ratio equal to 5:1. The equation relating area to volume using these dimensions is:

$$V = 0.98A^{1.5} \qquad \text{Eq. (3)}$$

We also use the dimensions outlined in Bigg et al. (1997) to estimate keel depth (k) and underwater surface area (SA) of the icebergs:

$$k = 0.67A^{0.5} \qquad \text{Eq. (4)}$$

$$SA = \frac{11}{3}A \qquad \text{Eq. (5)}$$

We calculated the relative increase in the fjord albedo due to the presence of ice for each scene by assigning an albedo of 0.60 for each pixel identified as ice (Zeng et al., 1984) and 0.060 for the remaining pixels representing ocean surface. In this way, icebergs as well as mélange were taken into account. The selected albedo of fjord water is the monthly averaged albedo for ocean water surface for the months of April, May, June, August, and September for the latitude of Columbia Fjord (Payne, 1972). We calculated albedo using this method to avoid problems with atmospheric influence on albedo calculations made from satellite imagery as well as to ignore the influence of solar angle on the ocean albedo whilst illustrating the impact of ice in the fjord on fjord albedo.

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3 Results

3.1 Overall Iceberg Distributions

During 2013, the majority of icebergs were found within the first 5 km of the terminus, corresponding to the area of the fjord prior to where the fjord coastline pinches in and forms a constriction (Fig. 4a). Beyond the constriction, the number of icebergs drop steeply (Fig. 4a). Iceberg area followed a similar pattern, with the majority of iceberg area in the first 5 km from the terminus, followed by a rapid decline in total iceberg area on the other side of the constriction (Fig. 4b and Fig. 5).

All scenes show a peak in the total iceberg area not directly adjacent to the terminus, but 2 to 5 kilometers away. Most icebergs were small; over 95% of all the icebergs identified in this study had a waterline cross-sectional area of 100 m^2 or less (Classes 1 and 2). The mélange coverage in the spring and fall months was similar ($2.8 \pm 1.8 \times 10^6$ m^2), whereas the mélange coverage in the summer months was $9.1 \pm 0.8 \times 10^6$ m^2.

3.2 Along Fjord Iceberg Distributions

The exponents from the power-law equations fit to the iceberg size distributions indicate a pattern in both the spatial and seasonal size distributions of icebergs inside the fjord (Fig. 6). The power exponent represents the relative abundance of large versus small icebergs, with more negative power exponent values indicating a higher proportion of small icebergs. The power exponents for the spring and fall months were similar, whereas the power exponents were more negative for the summer scenes. The power exponent for the spring and fall months ranged from -1.22 ± 0.03 to -0.91 ± 0.02 with a mean of -1.08. In the summer scenes, the power exponent ranged from -1.54 ± 0.03 to -1.12 ± 0.07 with a mean of -1.35. Every scene showed a decrease in the power-law exponent from the Proximal Zone to the Mid-Fjord Zone – indicating a decrease in the proportion of large icebergs with distance from the glacier terminus – and a subsequent increase in the power-law exponent from the Mid-Fjord Zone to the Distal Zone indicating an increase in the proportion of large icebergs near Heather Moraine. The average decrease in the power exponent from the Proximal-Fjord to the Mid-Fjord Zone was 0.16, and the average increase from the Mid-Fjord Zone to the Distal Zone was 0.24.

We calculated the spatial correlation of the different iceberg size classes along the fjord to reveal similarities and differences in iceberg evolution down the fjord. The correlation coefficient reflects the spatial covariance of different iceberg size classes. We performed these calculations for each scene individually, and for all identified icebergs combined. Our results show that the largest iceberg class, with a waterline cross-sectional area between 10,000 and 100,000 m^2, is the least spatially correlated with the other classes (correlation coefficient ranging between $0.344^{+0.131}_{-0.146}$ and $0.490^{+0.111}_{-0.129}$; Table 2). In contrast, the other class sizes are highly spatially correlated with each other (correlation coefficients ranging between $0.814^{+0.047}_{-0.061}$ and $0.980^{+0.005}_{-0.007}$; Table 2). After calculating the spatial correlation of the iceberg classes for each scene independently, we determined that the correlation does not appear to be seasonally variable.

3.3 Iceberg Volume and Effects on the Fjord

The two methods we used to calculate iceberg volume yielded slightly different results (see Table 3). Generally, the volume calculations using Eq. (3) were larger than the volume calculations using Eq. (2). Both methods found that the icebergs with waterline surface areas greater than 1000 m^2 accounted for the majority of the total ice volume present in each scene. Using Eq. (3), the percentage of ice volume that the large icebergs contained ranged from 53% to 88%, and using Eq. (2), the percentage of ice volume that the large icebergs contained ranged from 35% to 74%. The differences in iceberg volume found by the two methods are due to the differences in iceberg geometry assumed by these equations. Importantly,

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the variations in total volume and the proportion of iceberg volume in large icebergs are similar for both approaches, despite the different assumptions in iceberg geometry.

The estimated increase in albedo due to the presence of icebergs for Columbia Fjord ranged from 1.2% to 9.8% (Table 4). The albedo increase was highest in the summer months, corresponding to the increased presence of ice inside the fjord.

To further evaluate the potential for icebergs to affect the fjord waters, we estimated the iceberg residence time inside the fjord. The bulk iceberg residence time for each image is the total volume of icebergs inside the fjord divided by the the average annual calving rate for both arms of Columbia Glacier (Pfeffer, 2013b). The average residence time over all images was 14 ± 6 days using Eq. (2) to calculate iceberg volume, and 15 ± 6 days when using Eq. (3).

4 Discussion

4.1 Overall Iceberg Distributions

Our data reveal spatial patterns in iceberg distribution in Columbia Fjord in 2013. In general, iceberg coverage decreases with distance from the terminus. The observed spike in iceberg ice coverage 2 to 5 km from the terminus (Fig. 5) is somewhat surprising given that icebergs originate at the terminus, and it would be logical to expect the highest concentration of icebergs to be immediately adjacent to the terminus. Potential explanations for this are that the kinetic energy associated with the calving process or the inflow of subglacial meltwater at the grounding line pushes icebergs away from the terminus. Furthermore, only the summer months showed peak iceberg concentration away from the terminus (normalizing total iceberg area to bin area), pointing to a causal role for subglacial meltwater discharge, which is higher in the summer. Alternatively, these patterns of ice concentration in the fjord could be the result of influx of icebergs from the west arm of Columbia Glacier. Figures 4a and 4b show an increase in both the number and area of icebergs in the location where the west arm of Columbia Glacier contacts the fjord. Additionally, circulation patterns within the fjord could be driving these patterns of ice congregation. Near the terminus the fjord is wide, but roughly 4 to 6 km downfjord it narrows to ~2 km before expanding out to a consistent width of ~4.5 km until Heather Moraine. This change in geometry may drive circulation patterns that concentrate icebergs 2-5 km from the terminus.

In addition to these spatial patterns there were seasonal differences in iceberg coverage in Columbia Fjord in 2013, with more icebergs present during the summer months than the spring or fall (Fig. 5). This is consistent with an increase in calving rates caused by warmer air and water temperatures. Warmer fjord waters may increase the rate of submarine melt, which then increases the iceberg calving rates (Luckman et al., 2015; O'Leary and Christoffersen, 2013). In addition, surface meltwater caused by warmer air temperatures can aid the formation of icebergs by infiltrating and enlarging crevasses at the terminus (Van Der Veen, 1998; Weertman, 1973). These processes may all work together to produce increased ice discharge during warm summer months as opposed to the late winter and fall. In calculating the calving rate of Columbia Glacier in 2013, Vijay and Braun (2017) show an increase in the calving rate from March until June/July,

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4.2 Along Fjord Iceberg Distributions

We fit power-law distributions to the data to gain insight – both seasonally and spatially – into the size-distributions of icebergs inside the fjord. Fitting a power-law distribution to the data allows us to more quantitatively understand the spatiotemporal differences in iceberg size distribution because power-law exponents reflect the relative abundance of small icebergs versus large icebergs. Our iceberg distributions were better described by a power-law distribution than by a lognormal distribution, which is consistent with the conclusion from Kirkham et al. (2017) that icebergs near the calving front tend toward a power-law distribution, and icebergs further out in the open ocean fit a lognormal distribution. The decrease in power-law exponents from the Proximal Zone to the Mid-Fjord Zone indicates a decrease in the relative proportion of large icebergs from the Mid-Fjord Zone to the Proximal Zone. This is unsurprising given that we would expect icebergs to melt or fracture rather than grow as they travel from the terminus (Fig. 6). The proportion of large icebergs increases in the Distal Zone (shown by the increase in power-law exponents between the Mid-Fjord and Distal Zones), which is interpreted to be due to the influence of Heather Moraine which grounds large icebergs because it is at most 25 m below the sea surface (Pfeffer, 2013a; Walters et al., 1988). The larger icebergs become grounded until they have melted or broken up sufficiently to pass over, or they are pushed over by strong winds or are able to pass during high tides (Pfeffer, 2015).

Power-law exponents also indicate that there is a greater proportion of smaller icebergs present throughout the fjord in the summer months, including within the Proximal Zone near the terminus. This could indicate that the glacier calves smaller icebergs in the summer. During the summer when air temperatures are higher, meltwater is ubiquitous along the surface of the glacier and can help break calving ice into smaller pieces through hydrofracturing (Van Der Veen, 1998). Alternatively, the icebergs could be more prone to melt and fragmentation during the summer, which would lead to the increase of small icebergs in the Proximal Zone. The power-law exponents found in the summer months were very close to -1.5, which has been shown both experimentally and theoretically to be indicative of dominant brittle fragmentation (Åström, 2006; Spahn et al., 2014). Previous studies examining iceberg size distributions resulting from fragmentation have also calculated power-law exponents close to -1.5 (Bouhier et al., 2018; Crawford et al., 2018; Tournadre et al., 2016). The warmer summer conditions in Columbia Fjord could be responsible for the increased iceberg fragmentation. For all the environmental parameters examined in their study, Bouhier et al. (2018) found that sea surface temperature was the most highly correlated with iceberg fragmentation rates.

We compared the power-law exponents from Columbia Glacier to those calculated for other glaciers to determine the factors that influence iceberg size distribution. Sulak et al. (2017) reported a power-law exponent of -2.00 ±0.06 for Sermilik Fjord, a power-law exponent of -1.87 ±0.05 for Rink Isbrae Fjord, and a power-law exponent of -1.62 ± 0.04 for Kangerlussuup Sermia Fjord. Kirkham et al. (2017) reported a power-law exponent of -2.4 for the icebergs near the calving

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front of Jakobshavn Isbrae, Ilulissat Icefjord. These studies found their power exponents using the icebergs in the entire fjord, therefore we also calculated the power exponent for the entire Columbia Fjord, and averaged our results from each image to produce a value of -1.26 ± 0.05 for the entire study. Our results combined with results from these previous studies show no discernible relationship between power-law exponents and seawater temperatures; however, there is a relationship between power-law exponents and average annual calving flux (Fig. 7) (Howat et al., 2011; Sulak et al., 2017; Vijay and Braun, 2017). A higher calving flux corresponded to a more negative power-law exponent; glaciers with higher discharge rates had higher proportions of small icebergs. This supports the hypothesis of Sulak et al. (2017) that the power-law exponent could be an indicator of glacier productivity, i.e. calving rate.

In calculating the spatial correlation of icebergs inside the fjord, we found that the majority of icebergs followed similar spatial patterns, but that the largest iceberg class was not strongly spatially correlated to any of the other size classes. The largest icebergs contain the majority of the ice inside the fjord, yet they behave differently than the remainder of the iceberg population. Our interpretation of this lack of correlation is that the largest icebergs are running aground on the shallower areas of the fjord, which decouples their spatiotemporal evolution from the smaller icebergs that tend to float more freely and evolve together as they move downfjord. Bathymetric surveys (McNabb et al., 2012a) show that in addition to being shallow along the sides and at Heather Moraine, the fjord contains areas near the glacier terminus with depths around 75 m which are able to ground icebergs with waterline cross-sectional areas larger than roughly 8,500 m^2 [Eq. (4)]. We found that the largest icebergs were located in those shallower areas (Fig. 8). The fact that the largest icebergs behave differently along the fjord than the other icebergs further justifies removing the largest icebergs from the dataset when fitting the power-law equation for size-frequency distribution.

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4.3 Iceberg Effects on the Fjord

Our findings of iceberg distribution throughout the fjord have direct implications for the locations of freshwater input. In contrast to riverine fluxes, freshwater fluxes from icebergs can be spatially distributed throughout the fjord; in contrast to precipitation, these fluxes may be spatially concentrated by factors such as wind stress, ocean currents and bathymetry (Bigg et al., 1997). These factors are reflected in the cumulative distribution of icebergs shown in Fig. 4. The sinuosity of the iceberg density in the Distal Zone is likely related to wind stress or ocean current patterns as there are no related bathymetric features. As melt rate is related to the velocity differential between iceberg velocity and ocean current velocity, either high wind stress or ocean currents produce velocity differentials that increase melt rates (Bigg et al., 1997). Thus, the sinuous iceberg density feature may be associated with elevated freshwater fluxes relative to other regions of the fjord.

In contrast, the presence of large icebergs along the coasts and at Heather Moraine (Fig. 8) is best explained by their grounding on bathymetric features. While a majority of the icebergs examined in this study were located within the first five kilometers of the fjord (Fig. 4b), the largest icebergs also tended to be grounded in the shallow areas of the fjord, namely along the coasts and at Heather Moraine (Fig. 8). Where large icebergs run aground, they release freshwater by melting until they shrink and unground by melting or fracture. Thus, unless fracture processes are dominant, large icebergs may release significant volumes of freshwater over small areas of the fjord. Large icebergs – icebergs with a waterline cross-sectional area greater than 1000 m^2 (Classes 4 and 5) – accounted for less than one percent of the number of icebergs present in the fjord, yet they made up 53-88% of the total iceberg volume in the fjord [Eq. (3)], which is a reflection of the power-law distribution. Freshwater fluxes from these icebergs can have implications for ocean mixing, fjord circulation, and the local ecology (Helly et al., 2011).

To assess the icebergs' impact on fjord water mass characteristics, we compared temperature and salinity profiles – collected July 30-31, 2013; (Arimitsu et al., 2017) – to iceberg keel depth (Fig. 9). These profiles show a vertical structure characterized by a diurnally heated surface layer (ca. 1-13 ºC), a mixed layer (ca. 4 ºC and 26-30 PSU), and a deeper layer (ca. 5 ºC and 30 PSU). The salinity of the surface layer is highly variable (ca. 20-26 PSU). The mixed layer is cooler and fresher than the deeper layer and extends to a depth of ca. 30m in the Mid-Fjord and Distal Zones and ca. 60m in the Proximal Zone. Iceberg keel depths are generally coincident with the depth of the mixed layer; 99% of all iceberg keel depths are found within the mixed layer. While it may be a coincidence that the iceberg keel depth is related to the mixed layer depth, there are a few possible causal relationships to consider. The inverse relationship between salinity and number of iceberg keels present could be the result freshwater from iceberg melting. This freshwater provides a buoyant flux that may significantly enhance vertical mixing from the depth of the iceberg toward the surface (Helly et al., 2011). Additionally, icebergs could mechanically mix the water column by shear produced during iceberg overturning and by current drag against the iceberg surfaces. This could be a significant process at Heather Moraine, where grounded icebergs alter the flow of water in and out of the fjord. Further evidence for iceberg influence on fjord waters at Heather Moraine would be that the salinity profiles taken just outside Heather Moraine are ca. 5 PSU higher than directly inside the fjord.

To further assess the icebergs' effect on fjord characteristics, we consider iceberg melt. However, because our images are taken too far apart to track individual icebergs, we cannot directly measure iceberg deterioration. In addition, we cannot calculate iceberg melt rates for all dates using previously published equations due to lack of information of iceberg velocity and fjord water velocity. We therefore estimate and "effective iceberg melt rate" by dividing contemporaneous calving rate calculated in Vijay and Braun (2017) by the underwater surface area calculated using Eq. (5). The effective iceberg melt rate simply represents the rate of iceberg melting that would be required to balance the calving rate given the estimated underwater surface area of the icebergs. Because we lack information about iceberg surface roughness, we neglect it with the consequence that our surface area calculations are an underestimate, and hence, our calculations of iceberg melt rates are an overestimate. Surprisingly, the effective iceberg melt rates were lowest in the summer months (0.30 ± 0.02 m day^{-1}) and highest in the spring (0.84 ± 0.11 m day^{-1}). To examine what factors might be responsible for this unexpected result, we used the equation for turbulent iceberg basal melting (M_b) presented in Bigg et al. (1997):

$$M_b = 0.58\, \Delta V^{0.8} \frac{\Delta T}{L^{0.2}} \quad \text{Eq. (6)}$$

Where ΔV is the difference between iceberg velocity and fjord water velocity, ΔT is the temperature difference between the surface ice temperature – assumed here to be the melting point of ice – and the temperature of fjord water, and L is the along-fjord length of the iceberg.

We examined both the median and maximum iceberg length for each date to evaluate the influence of L, but the differences in the iceberg melt rates were negligible because L is raised to the power of 0.2. Normalizing ΔV, ΔT, and L by the variables in the July 12a scene (the date closest to the date on which the CTD measurements were taken in the fjord) allows us to examine the relative importance of temperature or velocity differential on iceberg melt rates. If we make the end-member assumption that ΔV remains constant throughout the year and use the observed July 30 seawater temperature of the mixed layer (3 ºC), (Fig. 9), it follows that water temperatures in the spring would have to be higher (8.0 ± 1.1 ºC) than in summer (2.8 ± 0.19 ºC), which is contrary to what is expected. Given this analysis, we attribute the spring increase in iceberg melt rate mainly to increased current shear between icebergs and the surrounding waters (ΔV), which is consistent with previous studies which found higher iceberg melt rates in Greenland fjords in winter due to increased shear (Moon et al., 2018). ΔV was 3.4 ± 0.56 m s^{-1} for the spring scenes, and 0.92 ± 0.08 m s^{-1} for the summer scenes. Possible reasons for this increased winter shear could include stronger winter currents and increased iceberg grounding events due to the greater proportion of large icebergs in the winter months. The difference in temperature between icebergs and the surrounding water may be a secondary factor in enhancing melt rates in the spring, however. The temperature that matters most for iceberg melt is the temperature of the water directly adjacent to the icebergs. Most of the icebergs in this study reside in the Proximal Zone, and in the summer this water is possibly cooler due to increased subglacial discharge and runoff in the summer, as well as increased albedo (Table 4), leading to lower iceberg melt rates.

Finally, icebergs can affect fjord water temperatures by altering its surface reflectivity. The presence of icebergs lowers the amount of solar radiation absorbed by the fjord by increasing the overall albedo of the fjord by 1.2 ± 0.46 to 9.8 ± 3.7 %. Although this increase in albedo is small, it is mostly concentrated near the terminus because the majority of icebergs are found within five kilometers of the terminus. This may be reflected in Fig. 9, which shows that only the surface waters in the Proximal Zone are not subject to warming from insolation, perhaps partly due to the high concentration of reflective icebergs there.

4.4 Comparison to Greenland Fjords

Most recent investigations of icebergs in fjords have focused on the peripheries of the Greenland ice sheet (Enderlin et al., 2016; Enderlin and Hamilton, 2014; Kirkham et al., 2017; Moon et al., 2018; Sulak et al., 2017), which share some similarities and some differences when compared to Columbia Fjord. One difference between our study site and a number of the sites in Greenland is the presence of winter sea ice. Sea ice formation helps create a thick mélange by preventing icebergs and bergy bits from exiting the fjord. This mélange not only increases iceberg residence time in the fjord, but also provides a back stress on the terminus that slows the rate of iceberg calving and terminus velocity (Amundson et al., 2010;

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Icebergs may have the ability to affect the dynamics of the fjord in which they reside by interacting with the deeper fjord waters that have not yet reached the terminus. Because the latent heat of fusion for ice (~335,000 J kg^{-1}) is much greater than the specific heat capacity of water (~4,180 J kg^{-1} K^{-1}), melting a small amount of ice decreases the temperature of a much larger volume of liquid water. Water circulation inside fjords is often represented with a simple 2-D model of buoyancy-driven circulation, in which warm, dense salt water flows into the fjord until it reaches the terminus. There it melts ice and mixes with the resulting fresh water, producing a buoyant layer of colder and less salty water that flows seaward along the fjord surface (Motyka et al., 2003). Salinity profiles taken in the middle of the fjord indicate that the transition from the fresher surface layer to the saltier incoming water is at about 10 m depth (Arimitsu et al., 2017). A small fraction (2.4% by number) of all the icebergs we found in our study are large enough that their keels reach the incoming water layer, based on our calculations of keel depths [Eq. (4)]. If these icebergs persist long enough without breaking up, they have the potential to cool the incoming water before it reaches the terminus, thus affecting the rate of submarine melting at the terminus. In addition, large icebergs (area of ≥ 600 m^2) get hung up on Heather Moraine. The warm water entering Columbia Fjord is forced to spill over Heather Moraine, therefore increasing interactions with the surfaces of grounded icebergs, potentially resulting in a reduction in the temperature and salinity of the inflowing water. ¶
We also expect icebergs to have a cooling effect on the upper, outgoing water layer. The majority of ice volume resides in this layer, and icebergs can extract heat from this layer as they melt. In addition, the presence of icebergs lowers the amount of solar radiation absorbed by the fjord by increasing the albedo (from a 1.2 % increase in November to 9.8% in June). The upper layer experiences the most solar heating and is thus affected the most by the increased albedo from the icebergs. ¶

Walter et al., 2012). In Greenland, winter sea ice formation is widely prevalent (Amundson et al., 2010; Higgins, 1991; Walter et al., 2012), however, sea ice was not present in any of the scenes we examined in detail. Some pancake ice was visible in a satellite image taken on March 26 which was not used in this study, however it was not thick enough to lock in icebergs or provide significant backstress on the glacier terminus. Because maximum sea ice extent in the Arctic is typically reached in March, and oceanographic definition of winter is January-February-March, we consider the March 13 scene to be representative of winter conditions in Columbia Fjord. We found that the mélange coverage was greatest in the summer months when the iceberg coverage was also greatest, however the mélange coverage only amounted to 11 ± 0.99 % (Table 4). Hence, ice mélange in Columbia Fjord appears to be more a function of higher summer calving rates and ice fragmentation rather than resulting from winter-time capture of ice fragments in sea ice. The lack of ice mélange in Columbia Fjord may contribute to the relatively short residence time (a fortnight) of icebergs in this fjord compared to the iceberg residence that may reach over 100 days that were observed in previous iceberg studies in Greenlandic fjords (Sulak et al., 2017; Sutherland et al., 2014).

Icebergs in Greenlandic fjords are often much larger than the ones observed in Columbia Fjord. The largest icebergs in our study have a waterline cross sectional area on the order of magnitude 10^4 m^2, whereas other studies have measured iceberg areas to be around 10^7 m^2 (Kirkham et al., 2017; Sulak et al., 2017). A primary reason for the smaller icebergs in Columbia Fjord is the small height of the calving front. Vijay and Braun (2017) measured the maximum thickness of the terminus to be ca. 300 m between July 2011 and July 2014. One consequence of the small icebergs is the reduced presence of icebergs that penetrate the deeper, incoming water layer. Using Eq. (5), we estimate the iceberg surface area in contact with the incoming waters, averaged over all the dates, to be $2.8 \pm 0.58 \times 10^4$ m^2. This is a small fraction of the surface area of the terminus ($9.7 \pm 3.7 \times 10^5$ m^2) which we calculated using the ice thickness data published in McNabb et al. (2012b). This is a conservative estimate of terminus area because we do not account for the sinuosity or roughness of the terminus, which we also neglected when calculating iceberg surface area. Because we estimate the surface area of the terminus to be approximately two orders of magnitude greater than the surface area of icebergs in contact with the incoming water, we do not believe that the icebergs are contributing as much freshwater to the fjord waters as the terminus itself. However, this should not diminish the importance of icebergs' impact on fjord circulation. We see from the temperature and salinity profiles that icebergs alter the water masses in the fjord system, introducing melt water and forcing mixing of the water column at Heather Moraine. But we do expect iceberg contributions to fjord dynamics to be more significant in fjords where the surface area of icebergs is much greater than the surface area of the glacier terminus.

To highlight the similarities and differences between Columbia Fjord and fjords which have been studied in Greeenland, we compare temperature profiles from Columbia Fjord and Sermilik Fjord. The July temperature profiles from Columbia Fjord look similar to summer temperature profiles collected in Sermilik Fjord (Arimitsu et al., 2017; Moon et al., 2018). Below 200 m depth in both fjords, the water temperature is ca. 4 ºC, but the temperature of the waters above that depth are a few degrees warmer in Columbia Fjord. This is significant because, unlike in Sermilik Fjord where icebergs are large enough to reach 200 m depth, the icebergs in Columbia Fjord are not large enough to reach the lower warmer layer.

Another difference in the temperature profiles between these two fjords is the temperature of the surface waters. The surface temperatures in Columbia Fjord reach as high as 13 ºC, whereas the summer surface temperatures in Sermilik Fjord are close to freezing. This could be due to the lack of mélange reflecting away solar radiation in Columbia Fjord. These warmer temperatures in Columbia Fjord could be causing the icebergs to melt at faster rates. While we do not have velocity measurements for the fjord waters nor the icebergs in Columbia Fjord, our analysis of the effective melt rates we calculated suggest that either the velocity of the water or of the icebergs increases in the winter months compared to the summer months, resulting in greater shear between icebergs and fjord water.

5 Conclusion

In this study we have obtained constraints on the distributions of icebergs inside a large Alaskan temperate fjord with high calving fluxes. The majority of icebergs were found within five kilometers of the terminus, but peak iceberg frequency was reached a few kilometers away from the terminus, particularly in the summer. The iceberg distributions fit a power-law distribution as opposed to a lognormal distribution. The power-law exponents suggest that the icebergs melt or break up as they move away from the terminus, and that large icebergs run aground on Heather Moraine. There is a greater presence of icebergs in the summer months, but those icebergs tend to be smaller. Because the power-law exponents for the summer images are closer to -1.5 than the exponents for the fall and spring images, we attribute the summer increase in small icebergs to intensified iceberg fragmentation by warmer fjord conditions. In addition, we find a correlation between power-law exponents and average annual calving rate, with larger calving rates resulting in increased proportions of small icebergs.

Most of the calved ice was contained within only a small fraction of large icebergs. The largest icebergs (which account for the majority of calved ice) are the least spatially correlated with the other iceberg class sizes, which we attribute to their tendency to ground in the shallow areas of the fjord – namely along the sides and on Heather Moraine. The largest icebergs have the greatest potential to cool the incoming ocean waters before they reach the terminus, however, in Columbia Fjord the surface area of the glacier terminus is thought to surpass the surface area of icebergs in contact with the incoming ocean water, rendering the iceberg cooling effect negligible. The total surface area of the icebergs inside the fjord amounts to 2.9% of the terminus surface area. We expect that only the icebergs at Heather Moraine have the potential to affect the dynamics of the fjord since the shallow water column allows more contact between icebergs and the incoming water. The icebergs do have the potential to cool the outgoing upper layer of ocean waters by increasing the albedo in the summer months, and thereby decrease the solar heating.

Icebergs can affect fjord circulation through spatially distributed introduction of meltwater that is dependent on wind stress, fjord currents, and bathymetry. Ocean and wind forcings control where smaller icebergs release meltwater into the fjord, whereas fjord bathymetry controls where the largest icebergs release meltwater. Salinity and temperature profiles indicate that icebergs may influence the mixed layer depth. To examine further the influence of icebergs on fjord freshwater budget, we calculated an effective melt rate, and found that melt rates were surprisingly higher in the spring months. We

Deleted: Columbia Fjord differs from fjords studied in Greenland that have glaciers with comparable terminus velocities. The Greenland Ice Sheet contains roughly 2.85 x 10^6 km^3 of ice (IPCC, 2001), and much of that ice drains out to the open ocean through fjords. Because of this vast amount of ice, many studies of icebergs in fjords have focused their attention on Greenland (Enderlin et al., 2016; Enderlin and Hamilton, 2014; Kirkham et al., 2017; Moon et al., 2018b; Sulak et al., 2017).¶
A large difference between our study site and the sites in Greenland is the presence of sea ice. Winter sea ice formation helps create a thick mélange by preventing icebergs and bergy bits from exiting the fjord. This mélange not only increases iceberg residence time in the fjord, but also provides a back stress on the terminus that slows the rate of iceberg calving and terminus velocity (Amundson et al., 2010; Walter et al., 2012). In Greenland, winter sea ice formation is widely prevalent (Amundson et al., 2010; Higgins, 1991; Walter et al., 2012), however, sea ice was not present in any of the scenes we examined in detail. Some pancake ice was visible in a satellite image taken on March 26 which was not used in this study, however it was not thick enough to lock in icebergs. This is in spite of the fact that the maximum sea ice extent in the Arctic regions occurs in March. We found that the mélange coverage was greatest in the summer months when the iceberg coverage was also greatest, however the mélange coverage only amounted to 11%. Hence, ice mélange in Columbia Fjord appears to be more a function of higher summer calving rates than winter-time capture of ice fragments in sea ice. This lack of mélange in Columbia Fjord agrees with our finding that icebergs in Greenlandic fjords appear to have longer residence times. We approximated the iceberg residence times in Columbia Fjord to be roughly a fortnight, but in Greenland icebergs can remain inside fjords for over 100 days (Sulak et al., 2017; Sutherland et al., 2014). The residence times in Greenlandic fjords allow longer interactions between icebergs and the incoming seawater before it reaches the terminus.¶
In addition, icebergs in Greenlandic fjords tend to be larger. Not only do the larger icebergs remain in existence longer because their smaller surface area to volume ratio reduces melting, their deeper keels allow for more contact with – and thus more cooling of – the incoming warmer ocean waters. The largest icebergs in our study have a waterline cross sectional area on the order of magnitude 10^4 m^2, whereas other studies have measured icebergs to be around 10^7 m^2 (Kirkham et al., 2017; Sulak et al., 2017). A primary reason for the smaller icebergs in Columbia Fjord is the height of the calving front. Vijay and Braun (2017) measured the maximum thickness of the terminus to be 305 m between July 2011 and July 2014. One consequence of the smaller icebergs is the reduced presence of icebergs that penetrate the lower, incoming water layer. Using the iceberg geometry from Eq. (3) we estimate the iceberg surface area in contact with the incoming waters, averaged over all the dates, to be 2.8 ± 0.58 x 10^4 m^2. This is contrasted with the surface area of the terminus (9.7 ± 3.7 x 10^5 m^2) which we calculated by taking profiles of ice thickness near termini of the main and west arms of ... [1]

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speculate that this higher melt rate in the spring months is due to increased shear between icebergs and fjord water rather than water temperatures. Freshwater input from icebergs is typically omitted from fjord circulation models. By helping determine the relative importance of the variables affecting the location and quantity of iceberg melt, we can better inform models of glacier-ocean interactions.

Data Availability

The imagery used in this study are available via the Polar Geospatial Center.

Author Contributions

SN and ST conceived of the study presented here. SN acquired the data and performed analysis and interpretation of the data with guidance from ST and CB. SN prepared the manuscript with contributions from both ST and CB.

Competing Interests

The authors declare no conflict of interest.

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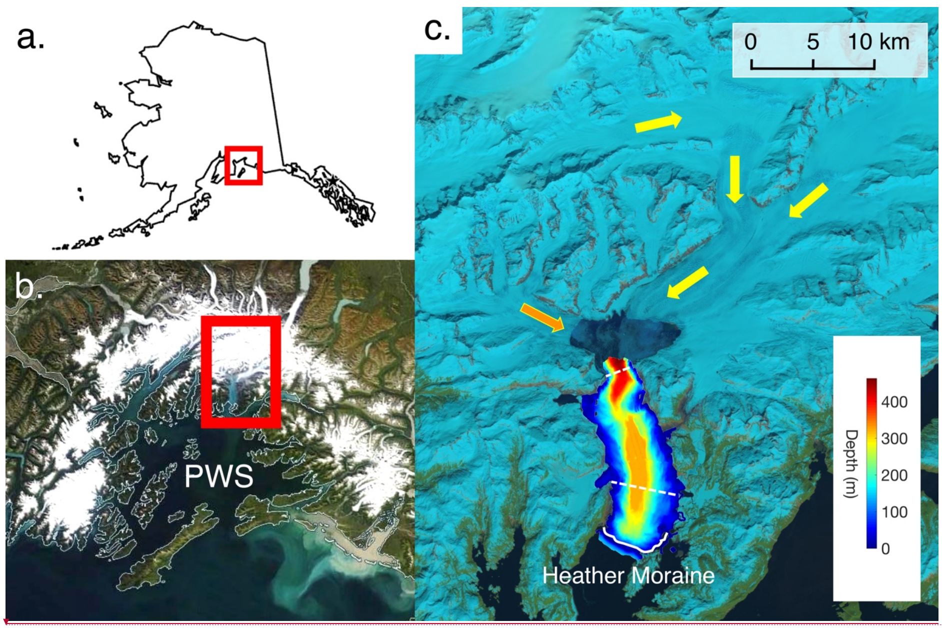

Figure 1: Columbia Glacier. **(a)** Outline of Alaska. **(b)** NASA MODIS image of Prince William Sound (PWS) from World View satellite. **(c)** Landsat image of Columbia Glacier and Fjord in 2013. Yellow arrows indicate flow of the main branch of the glacier. Orange arrow indicates flow of west branch of the glacier. Heather Island is visible along Heather Moraine. White line indicates location of Heather Moraine. Dotted lines delineate the boundaries between the Proximal Zone, the Mid-Fjord Zone, and the Distal Zone. The bathymetry, measured by NOAA Ship RAINIER in 2005, is overlain on the lower portion of Columbia Fjord.

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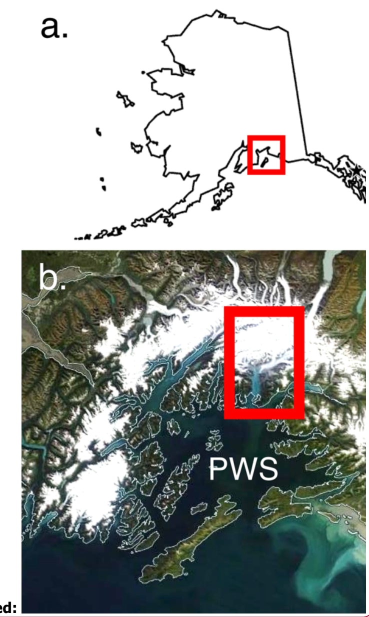

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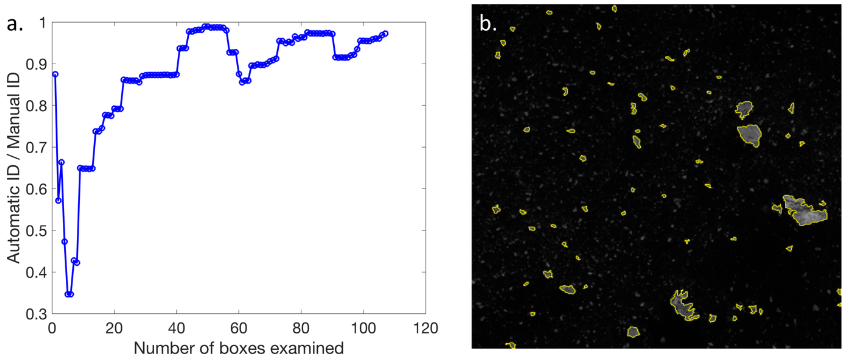


Figure 2: (a) Ratio of automatic iceberg detection to manual iceberg detection as a function of the cumulative number of 250 x 250 pixel squares counted. The total number of boxes counted was 107. (b) Example of iceberg detection by algorithm. White dots not outlined in yellow are too small to be identified as icebergs, and are thus classified as mélange.

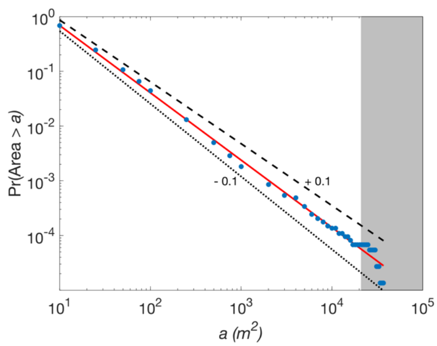
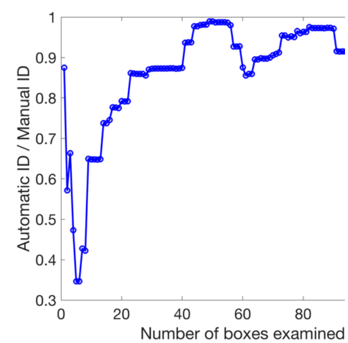


Figure 3: Power-law fit for the iceberg areas in the Proximal Zone on June 10b. The red line represents the best fit, and the black lines represent shifting the power exponent by ± 0.1 – the dotted line indicates a subtraction of 0.1, and the dashed line indicates an addition of 0.1. The icebergs that have been omitted to achieve a significant fit are plotted in the gray box.



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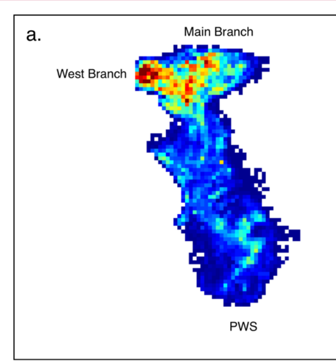

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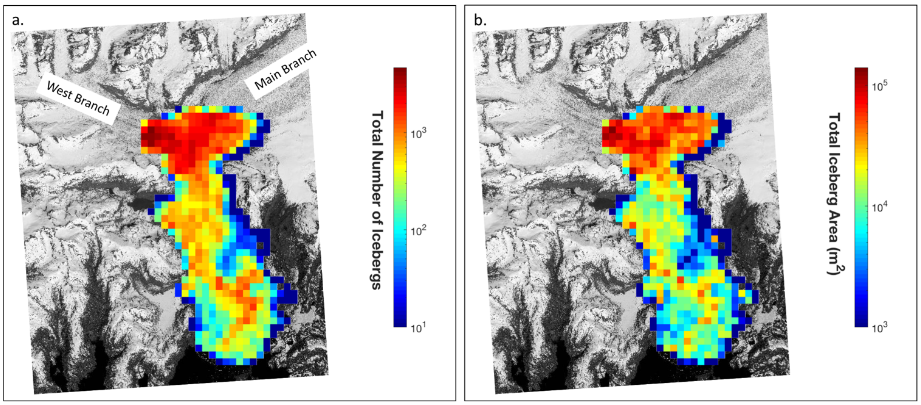

Figure 4: Cumulative iceberg population density and area map. Each grid cell represents a 500m x 500m square. The scenes from March 13, May 06a, June 10a, July 12a, and November 19 were overlain to obtain the total number and area of icebergs inside each grid cell. Data is overlain on a satellite image of the fjord taken by WorldView 1 on June 10, 2013. **(a)** number of icebergs in each grid cell **(b)** area of icebergs inside each grid cell.

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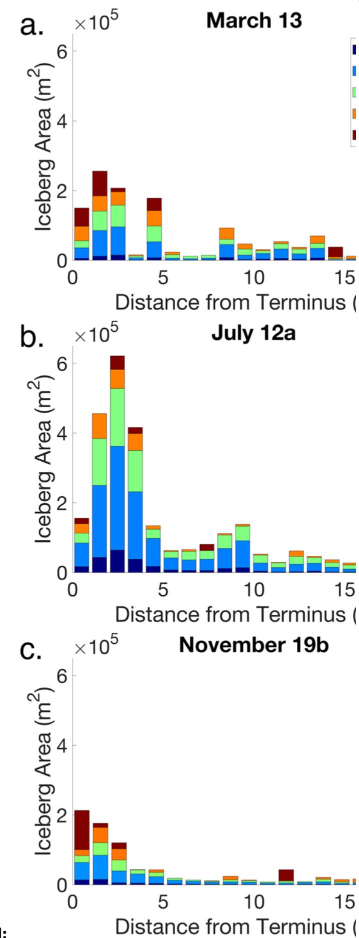

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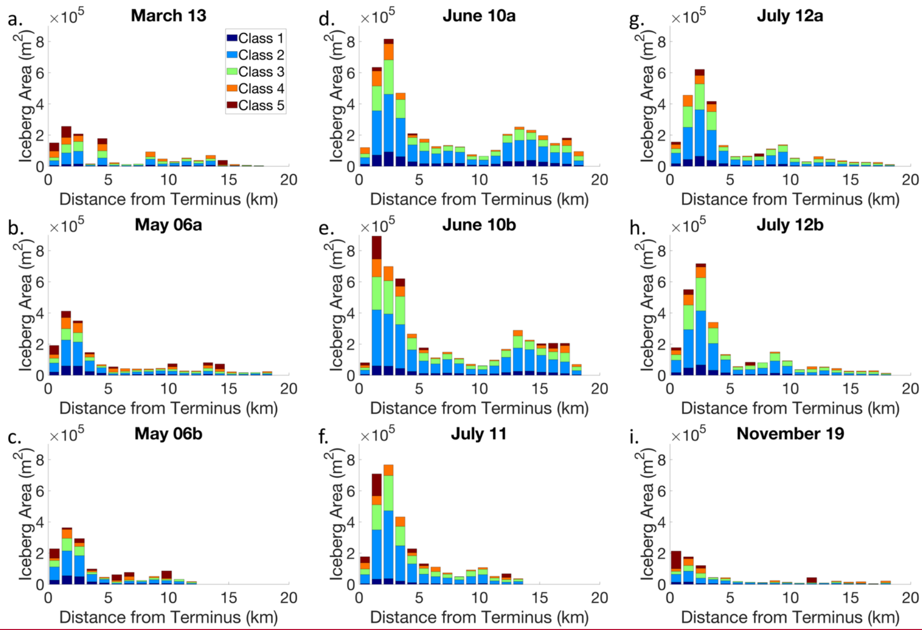

Figure 5: Total area of icebergs per 1 km bin along the fjord. The dates shown here are **(a)** March 13, **(b)** May 06a, **(c)** May 06b, **(d)** June 10a, **(e)** June 10b, **(f)** July 11, **(g)** July 12a, **(h)** July 12b, and **(i)** November 19. The peak of ice coverage inside the fjord is found 2-3 km from the terminus. The icebergs are divided into classes by waterline cross-sectional area, with the smallest icebergs residing in Class 1 and the largest in Class 5. The divisions for the bins were: 0-10 m^2, 10-100 m^2, 100-1,000 m^2, 1,000-10,000 m^2, and 10,000-100,000 m^2.

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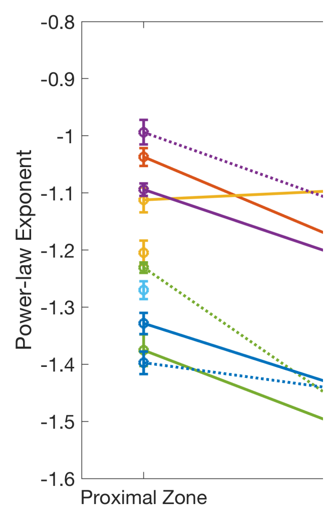

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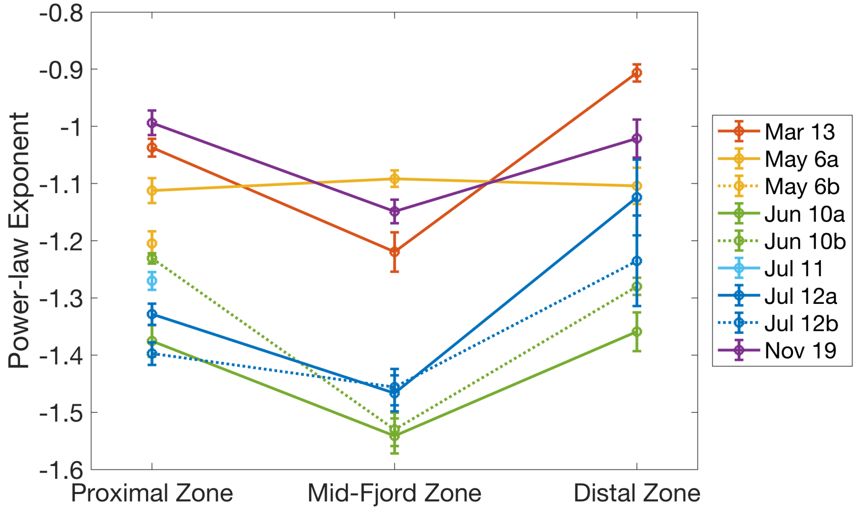

Figure 6: Power-law exponent calculated for each scene. Power-law exponents indicate both a spatial and seasonal discrepancy. The more positive exponent in the Proximal and Distal Zones indicate a higher proportion of large icebergs present near the terminus and Heather Moraine. Additionally, the more positive exponent for the spring and fall scenes indicates a higher proportion of large icebergs present in those respective seasons. The anomalous increase in the power exponent in the mid-fjord zone for May 6a is due to contamination from cloud cover.

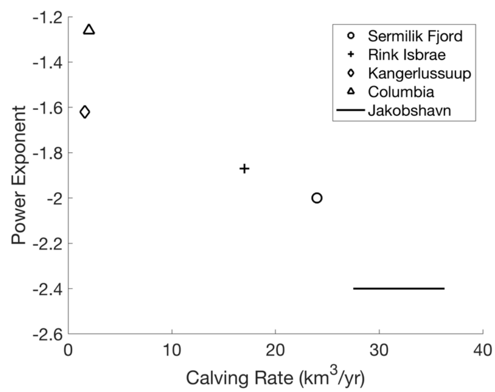

Figure 7: A comparison of published power exponents and glacier calving rates. (The power exponent for Columbia Fjord was calculated in this study.) An increase in the calving rate corresponds with an increase in the proportion of small icebergs present inside the fjord (more negative power exponent).

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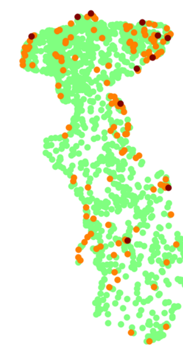

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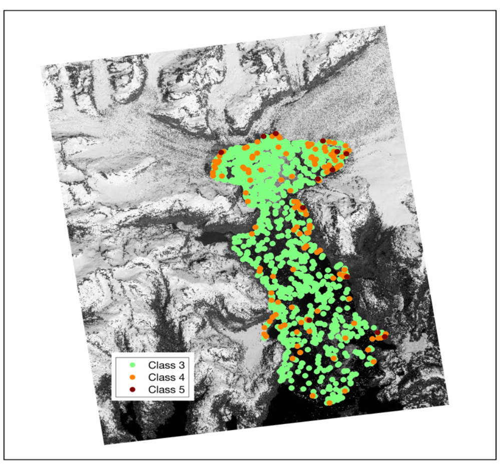

Figure 8: Location of large icebergs by centroid (May 06a). Icebergs in Class 3, Class 4, and Class 5 have waterline cross-sectional areas of 100 – 1,000 m^2, 1,000 – 10,000 m^2, and 10,000 – 100,000 m^2 respectively. The background satellite image was taken by WorldView 1 on June 10, 2013.

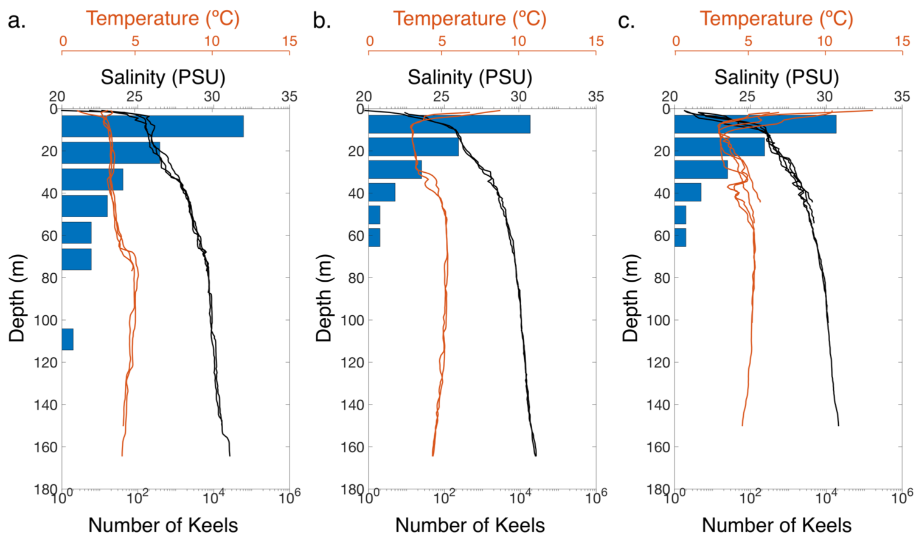

Figure 9: Iceberg keel depths compared to salinity and temperature profiles in Columbia Fjord. Salinity and temperature profiles were collected by the US Geological Survey on July 30 and 31, 2013. Keel depths presented here are from the July 12a icebergs. (a) Proximal Zone (b) Mid-Fjord Zone (c) Distal Zone. Note the log axis for number of keel depths.

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Table 1: Survey of images used in this study. Image processing performed by Polar Geospatial Center prior to our obtaining the images. Satellites used were WorldView 1 and 2 (WV1, WV2). Projection is NAD83. *Time reported in AKDT despite daylight savings ending on November 3.

Reference ID	Date, 2013	Alaska Daylight Time	Sensor	Coverage	Number of Images in Mosaic
March 13	March 13	13:14:44	WV1	Full	2

May 06a	May 06	13:32:05	WV2	Full	3
May 06b	May 06	13:33:02	WV2	Partial	2
June 10a	June 10	13:20:07	WV1	Full	3
June 10b	June 10	13:20:52	WV1	Full	3
July 11	July 11	12:51:12	WV1	Partial	3
July 12a	July 12	14:03:23	WV2	Full	3
July 12b	July 12	14:04:23	WV2	Full	3
November 19	November 19	13:07:18*	WV1	Full	2

Table 2: Correlation between different iceberg class sizes along the fjord for all scenes combined. The red shading corresponds to the size of the error estimates, with the darker shades of red representing larger error. Upper and lower limits on the 95% confidence interval are reported in the lower half of the table.

Size Classes	1	2	3	4	5
1		0.900	0.861	0.814	0.344
2	+ 0.026 - 0.035		0.980	0.845	0.398
3	+ 0.036 - 0.047	+ 0.005 - 0.007		0.867	0.396

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4	+ 0.047 - 0.061	+ 0.040 - 0.052	+ 0.034 - 0.045		0.490
5	+ 0.131 - 0.146	+ 0.124 - 0.141	+ 0.125 - 0.141	+ 0.111 - 0.129	

Table 3: Volume of icebergs in Columbia Fjord for each scene, calculated using Eq. (2) and Eq. (3). * Imagery of fjord is incomplete on these dates.

Date	**Equation (3)**			**Equation (2)**		
	Total Volume of Icebergs	**Volume of Icebergs: Area > 1000m^2**	**Percent Volume of Icebergs with Area >**	**Total Volume of Icebergs**	**Volume of Icebergs: Area > 1000m^2**	**Percent Volume of Icebergs with Area >**

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			1000m²			**1000m²**
Units	km³	km³		km³	km³	
March 13	0.077	0.065	84	0.060	0.042	70
May 06a	0.083	0.067	81	0.070	0.045	65
May 06b*	0.070	0.058	83	0.056	0.036	64
June 10a	0.10	0.055	53	0.12	0.042	35
June 10b	0.16	0.11	67	0.16	0.071	46
July 11*	0.12	0.089	72	0.11	0.054	50
July 12a	0.072	0.042	58	0.077	0.029	38
July 12b	0.074	0.041	56	0.079	0.029	36
November 19	0.057	0.050	88	0.042	0.031	74

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Table 4: Increase in albedo of entire fjord due to presence of ice and percent mélange coverage, calculated for each scene. Both icebergs and mélange are taken into account for the albedo calculations. * Imagery of fjord is incomplete on these dates.

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Date	Relative Albedo Increase (%)	Percent Mélange Coverage (%)

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March 13	2.5 ± 0.95	2.7 ± 0.25
May 06a	4.8 ± 1.8	6.0 ± 0.50
May 06b*	4.0 ± 1.5	2.8 ± 0.24
June 10a	9.8 ± 3.7	11 ± 0.99
June 10b	9.6 ± 3.6	11 ± 0.96
July 11*	6.2 ± 2.3	4.0 ± 0.44
July 12a	7.7 ± 2.9	9.9 ± 0.79
July 12b	7.4 ± 2.8	9.1 ± 0.73
November 19	1.2 ± 0.46	1.1 ± 0.12

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Reviewer #1

Review of: Spatiotemporal Distributions of Icebergs in a Temperate Fjord: Columbia Fjord, Alaska

General comments:

This manuscript presents a study of icebergs in the Columbia Fjord, Alaska during March-November 2013. The authors use high resolution satellite images to look at iceberg distribution and size, applying common scaling factors to estimate volume and keel depth. Based on these iceberg metrics, the authors speculate on the influence of icebergs on fjord water properties and note differences and similarities with studies of Greenland fjord icebergs.

The research has succeeded at a basic characterization of Columbia Fjord icebergs. However, the paper falls short on several important fronts.

- - The research is motivated (page 2, lines 8-21) by noting an interest in icebergs exiting Columbia Fjord, a topic that is not raised again. A second motivation is that the authors point to Alaska fjords as a proxy for Greenland fjords. However, the discussion of this potential relationship is only vague, failing to provide a reader with a sense of where and when this relationship might hold true.
- - The study uses a small sample size, examining only one year. The authors need to provide more information on why only 8 months of data are used. Are images not available from other years? And, if only one year is used, what is the context of this year within the longer periods of observation. Are there reasons to think that this year is dis/similar to other years (e.g., from other published data re: ice discharge, fjord conditions, etc.)? Basing conclusions on such a limited sample provide a weak foundation, so the authors must put in extra work either to increase data or to better contextualize the data that is used.
- - Overall, the explanation and discussion does not provide a detailed account of the implications of the study and the meaning of the results. The paper would benefit from more references to existing work, providing context for the study conclusions and discussion. For example, section 4.1 mentions ocean circulation and ocean temperatures, but doesn't provide any of the detail needed for the reader to understand what is known about Columbia Fjord circulation or temperatures. In another example, the discussion in section 4.4 fails to show an appreciation for the wide range of variables and conditions present across Greenland fjords or the many variables involved in the interactions between icebergs and ocean waters. As a result, the discussion is shallow and the conclusions are too general (e.g., see last paragraph in section 4.4).

Authors' Response: We would like to thank the reviewer for drawing to our attention the fact that our discussion of Columbia Fjord as a potential future Greenlandic fjord is too general. We have addressed this in our revisions. Instead of justifying our study by presenting Columbia Fjord as a potential future Greenland fjord, we have focused our manuscript on the more specific implications of our results. We have amended section 4.4 so that it is now a more *detailed comparison of our findings to measurements which have been previously published in papers covering the topic of icebergs in fjords.*

We were able to obtain satellite imagery of Columbia Fjord for one year (2013). To check if this year was reasonably representative of a longer period of time, we examined publications by the US Geological Survey and Vijay and Braun (2017), both of which presented data on iceberg calving rates for multiple years and indicated that 2013 was a fairly typical year for iceberg production in Columbia Fjord.

Specific comments (by page/line number):

1/19-21. This is a broad and vague statement regarding Columbia Fjord as a proxy for future Greenland fjords. Given the wide range of variables influencing the role of icebergs in fjords and the wide variation in physical environments of Greenland, such a general statement is not particularly useful or well substantiated.

Authors' Response: Thank you for pointing the fact that our comparison of Columbia Fjord to Greenland fjords is not as compelling as it could be. We have removed our statements of Columbia Fjord as a proxy for future Greenlandic fjords. Instead, we just compare the results from our study to those of previous studies of iceberg distribution.

2/8. Given how few times Prince Williams Sound is referred to in the paper, it is preferable to use the full phrase rather than an acronym. In general, acronyms make the reader's job more difficult and should be avoided unless for a phrase used widely throughout the paper.

Authors' Response: We agree that acronyms can be confusing. We have changed all mentions of "PWS" to Prince William Sound to avoid confusion.

2/19. Here, the authors mention that Columbia Fjord represents a potential analog for future Greenland conditions. Given the wide range of fjord types and conditions in Greenland – and that this is mentioned as a main motivation for the paper – the authors need to be more detailed here. What areas of Greenland might be good candidates? Are there any projections (e.g., of near-Greenland ocean temperatures) that suggest when these analog conditions might occur? As a general statement, it's not very useful.

Authors' Response: As stated above, we agree that our comparison to Greenland fjords is too general. We have amended this by instead focusing on comparing our results to other results from previous studies of icebergs in Greenlandic fjords. As part of these amendments we have deleted the sentences in this section where we mention Columbia Fjord being a proxy for future Greenland fjords under warming conditions. (p. 2, l. 15)

2/30. What is "Mean Lower Low Water"? This is not something that most glaciologists will be familiar with. This is also another case when the acronym is unnecessary since it's rarely used.

Authors' Response: Mean Lower Low Water is the elevation datum that the National Oceanographic and Atmospheric Administration (NOAA) uses to reference tidal height *measurements. We keep the mention of Mean Lower Low Water because it is the defined standard elevation of zero above/below sea level, however we have added in a statement clarifying the definition to those who may not be familiar with it. (p. 2, l. 24-25)*

2/35 to 3/1. This sentence does not make sense. Please revise for clarity.

Authors' Response: We have split this convoluted sentence into two simpler sentences for clarity. (p. 2, ll. 30-32)

3/15. Instead of "in all but two cases", go ahead and give the information on which cases. The authors are dealing with a relatively small number of images, so it's best to be specific.

Authors' Response: We have removed "in all but two cases" and instead added in the image names so as to avoid confusion. (p. 3, l. 12)

3/29. Snow does not float on top of water. Ice mélange is usually considered a conglomerate of icebergs, bergy bits, and growlers, sometimes including sea ice. For the most part, the authors use the phrase correctly, but not in this case. Please correct.

Authors' Response: We have removed the mention of snow from this sentence, as recommended. Instead, we have amended our definition of ice mélange and moved it to this place in the manuscript, because it is the first time we mention ice mélange. (p. 3, l. 29)

4/9. Introduce the definition of 'melange' when it is first used. It's also odd to discuss bergy bits and growlers in the preceding sentence and then 'tiny chunks of ice' in this sentence.

Authors' Response: We have moved this definition of ice mélange to the location in the paper where we first mention mélange. (p. 3, l. 29)

4/23-28. At no point do the authors explain the use of 'a' and 'b' images. Is there standard area covered by 'a' v. 'b' images? Are they always made into a mosaic? Are areas double counted? A more important point is also raised in this paragraph – the authors attempt to change the threshold for the Nov. 19a image, but are unsuccessful as alleviating the problem. Nevertheless, the authors then continue to include this data in plots and tables. Knowingly poor data should not be included in analysis. The authors have several options – use manual methods to properly characterize the image, remove the data completely, treat this data separately with additional errors, etc.

Authors' Response: For a few of the dates for which we have repeat images, there are two images labelled 'a' and 'b'. These images are covering the same area from somewhat different angles and were taken by the satellite for the purpose of stereo imagery. They were taken approximately one minute apart. We are able to use both images, and thus label them 'a' and 'b'. We did not explicitly state this in the manuscript previously, so we have now corrected this by adding in a few clarifying sentences. (p. 3, l. 12-19)

Regarding the November 19a imagery, we previously did know about the quality problems with identifying icebergs in this image but decided that there is value in including these flawed data.

However, after reading the reviewer's comment, we decided to discard the November 19a dataset completely because we do agree that the problems with data quality do not justify including this dataset in our analyses.

4/30. In this paragraph, the authors should point to all pertinent figures. For example, point the reader to Fig. 4 for a visual of the 500 m x 500 m squares. Same is true for the first paragraph on page 5.

Authors' Response: Thank you for this suggestion, we have fixed this by adding in references at the appropriate locations. (p. 4, l. 32-33)

5/13. Perhaps 'subdividing at 10, 25...". The current sentence is confusing.

Authors' Response: We have re-written this sentence to make it less confusing. (p. 5, l. 12-14)

5/30. Need to define waterline cross-sectional area at its first use, which is earlier in the paper.

Authors' Response: We have moved our definition of waterline cross-sectional area to the place in the manuscript where we first make use of this term. (p. 5, l. 20-21)

5/30. As best I can tell, the authors do not use waterline cross-sectional area as a proxy for iceberg volume. Instead, they use two methods for determining iceberg volume from waterline cross-sectional area. Later in the paper, they also refer iceberg volume calculated from 'two methods'. Using waterline cross-sectional area would be a third method (and also a worse method than the other two used).

Authors' Response: We do not use waterline cross-sectional area as a proxy for iceberg volume as we actually calculate iceberg volume using two different methods. We have removed the mention of using waterline cross-sectional area as a proxy.

6/7-11. It's not clear why the authors would apply this method for calculating albedo when, I assume, albedo products are available.

Authors' Response: We calculated albedo using this method because the ocean albedo is highly dependent on the angle of incoming solar radiation. In addition, the atmosphere can affect surface albedo measurements made from satellite imagery. We therefore chose this method to avoid these issues and to focus the discussion in our manuscript on the direct contribution of icebergs to the surface albedo. We have added in a sentence stating our reasoning for calculating albedo in this manner. (p. 6, l. 18-20)

6/20-23. The discussion of uncertainty here is an awkward add on to the paragraph. This would be better as a separate section, perhaps combining overall discussion of uncertainty. At minimum, the authors need to discuss the implications of the uncertainties – for example, what percent of the fjord coverage is mélange? Currently, there's no metric for the reader to understand the implications of the numbers given.

Authors' Response: We appreciate the reviewer bringing this to our attention. We have moved the discussion of uncertainty associated with iceberg identification in areas of mélange to the methods section. (p. 4, l. 21-23) In addition, we have presented mélange coverage as a percentage of fjord area for the dates we examined. (Table 4)

6/25. The first half and second half of this sentence say the same thing. Please revise.

Authors' Response: We have revised the sentence to make it less repetitive. (p. 7, l. 2-3)

7/3. Explain the implications of these numbers.

Authors' Response: We are somewhat confused by this comment. Since this is the Results section, we focus on specifying by how much the power exponent of iceberg size distribution varies between the three major sections of the fjord. We discuss the implications of the numbers presented here in the discussion section. To make our discussion of these numbers clearer, we have added clarifying statements to the section of the discussion where we discuss these numbers. (p. 9, l. 4-6)

7/21-25. With such warm water, it seems that iceberg melt would be a substantial component. Is there any published information or other method that the authors can apply to give a sense of the potential magnitude of iceberg melt and its influence?

Authors' Response: We agree that given the temperate conditions of this fjord, iceberg melting would indeed be occurring. The difficulty with estimating iceberg melt in this situation is the lack of information about iceberg velocity and fjord water velocity. Because our images are taken too far apart, we are unable to track individual icebergs and thus calculate their rate of deterioration. However, we have added in calculations of "effective melt rate" to section 4.3 to try and assess the factors responsible for iceberg melt. We have removed the statement about neglecting iceberg melt here because part of what is causing the icebergs to disappear downfjord in our imagery is iceberg melt. Thus, melt does actually factor into our residence time calculations. (p. 8, l. 1-4)

8/1. The sentence says "evidence *for this*", but the sentence before mentions two possibilities. "This" must be specified.

Authors' Response: We have re-worded this statement and clarified what we meant. Thank you for catching this problem. (p. 8, l. 12-14)

9/12. What is the area of interest for "all of Columbia Fjord"? Please show on a figure.

Authors' Response: What is meant by "all of Columbia Fjord" is the entire fjord as defined in the introduction. We have re-worded this sentence in the manuscript text to make this more clear. (p. 9, l. 30)

Section 4.3. This is a shallow discussion of iceberg influence on freshwater. As some points the authors mention temperature changes, at others they mention salinity. Both are likely affected, but this is not well discussed.

Authors' Response: We recognize that this section is too general and does not present significant results. We have re-worked this section to focus more on results, and have created a new figure accompanying this paragraph comparing iceberg keel depths to temperature and salinity profiles in the fjord to visually represent the contribution of freshwater from icebergs at various points along the fjord length. We explore in greater detail the effects icebergs might have on the water masses inside the fjord. In addition, we have made estimations of iceberg melt using an equation from Bigg et al. (1997), which we were able to use by making assumptions about fjord conditions and iceberg velocity. (Section 4.3)

11/2. How can the authors conclude that winter-time capture of ice fragments aren't important when they did not examine winter-time data? The overall discussion in this paragraph also fails to recognize that iceberg residence time is only one factor in how icebergs change ocean water characteristics. For example, ocean water temperature, salinity, and current velocity and direction are also important.

Authors' Response: We have imagery from March 13th, which is before the vernal equinox, i.e., the formal end of the astronomical winter. We do realize that it is standard in meteorological and climatic analyses to consider only December, January, and February to be winter months. However, the winter maximum of Arctic sea ice extent is typically reached in March, often around the time of when our March 13th scene was acquired. We note that the commonly used Levitus World Ocean Atlas uses the definition of winter season as January-February-March. Hence, we do not think that it is unreasonable to consider this scene to be representative of winter time iceberg conditions in Columbia Fjord. (p. 12, l. 28-30) We agree with the reviewer that this section does not address some important ways in which icebergs may affect fjord waters. We have amended this by adding in discussion of fjord water temperature and velocity. (p. 13, l. 19-31)

11/19. Why would the icebergs not be significantly rougher than the calving front?

Authors' Response: Because both icebergs and the terminus are made of the same material and exposed to the same ocean water, we assumed that they would exhibit similar roughness. In our calculation of iceberg and glacier terminus surface area we made the simplifying assumption that they have the same roughness, given that we have no observational constraints on roughness for either surface. We have added in a sentence explaining this, along with the implications of our assumptions. (p. 13, l. 11-12)

12/4. What evidence is there to attribute the iceberg size change to increased crevasse hydro-fracture? Can the authors cite literature on this or point to observations that suggest this (even qualitatively)?

Authors' Response: Thank you for highlighting the problem with our discussions of this issue. Several previous studies have shown that power-law exponents of -1.5 are an indication of brittle fragmentation. The summer power-law exponent values we find in this study are closer to -1.5 in *the summer than in the spring or fall. This seasonal evolution of the power-law exponent supports the proposition that hydro fracture is an important process in summer, when surface melt rates are high and water-filled fractures should be abundant. We have improved our discussion of these issues in the revised manuscript in response to this comment of the reviewer. (p. 14, l. 4-6)*

12/6. How can the authors identify a correlation between anything and average annual calving rate given that they have less than 1 year of data?

Authors' Response: The average annual calving rate that we compared our data to is the average calving rate over 2013, which is the year for which we have data. In addition, Columbia Glacier velocity, flux, and terminus position data presented in reports from the US Geological Survey and Vijay and Braun (2017) indicate that 2013 was a reasonably representative year in terms of iceberg calving rates. We therefore feel it is justified to compare our observations of icebergs in Columbia Fjord in 2013 to an average annual calving rate that was calculated for 2013. We used the average annual calving rate to be consistent with the methods used by the previous studies that we were comparing our data to. We agree that we may not have made this clear in the text, so we have added in a statement in the section in the discussion where we mention this comparison. (p. 9, l. 31)

12/17. Alaska glaciers contributing to sea level rise is poor justification for studying icebergs in and of itself. I feel the authors need to think more deeply about what is unknown and the most important implications of their work.

Authors' Response: We thank the reviewer for this comment. We have removed this statement and instead focused on summarizing our research findings.

Figure 1. It would be useful to label Heather Moraine in the image. 'PWS' label in c. is unnecessary. Is it possible to add the outline of the region in d. to the c. panel?

Authors' Response: We had previously outlined Heather Moraine in panel c, however, we have now added a label to make our outline more clear and noticeable to the reader. We have removed PWS from panel c. Instead of outlining the region covered by panel d in panel c, we have moved that bathymetry shown in panel d so that it overlaps the fjord extent shown in panel c.

Figures 4 and 8. It would be nice to put this data on a map/image background.

Authors' Response: We have added in a satellite image of the fjord taken on June 10, 2013 to the background of figures 4 and 8 to give the reader further spatial context.

Figure 5. Why not show data from all periods? Also, it would be preferable to list the class sizes in the captions.

Authors' Response: We agree that it would be preferable to show the data from all dates. We have included plots from the other images. In addition, we have listed the class sizes in the figure caption.

Figure 6. Bad data should not be included in the plot.

Authors' Response: We assume the reviewer is referring to the November 19a data. We have removed this data from the plot entirely.

Table 2. What is the source of these errors? What does this error represent?

Authors' Response: The errors are the upper and lower limits of the 95% confidence interval. We have clarified this information in the caption.

Tables 3 and 4. Again, bad data should not be included in plots or tables. Either fix it or remove it.

Authors' Response: We assume the reviewer is referring to the data from November 19a. We have removed this data from both tables.

Technical corrections (by page/line number):

2/20. Please remove "in order" for all cases of "in order to". It is unnecessary.

Authors' Response: We have changed all cases of "in order to" to simply "to."

Anonymous Referee #2

Review of tc-2018-230 Spatiotemporal Distributions of Icebergs in a Temperate Fjord: Columbia Fjord, Alaska by S. Neuhaus et al

General comment

The paper analyzes the distribution of icebergs within the Columbia fjord using high resolution (0.5 m) visible satellite images (10 covering a 8 months period in 2013). Classical image processing tools (from Matlab) are then used to detect and estimate the size of the icebergs within the fjord. The results are validated by comparison with manual analysis for selected scenes. The results of the images analysis are then used to compute the time/space distribution of iceberg and the evolution of the distribution of the icebergs' size in time and location within the fjord. The analysis reveals the complex distributions of the iceberg within the fjord as well as the seasonal variability related to the glacier calving rate.

The results are of interest and are worth publishing. However, the motivation of the study should be stated more clearly and if the implication for the future of Greenland icebergs (if kept) should be better justified.

The study is also limited to 8 month and 10 images where certainly much more are available. I know that image processing is quite hard and fastidious but at least the authors should justified why they limited their study to this short data set. Paragraph 4.3 and 4.4 need to be better focused on real results and not on quite shallow general discussions. The distribution of volume and the evolution of the size distribution are important results by themselves. I think that the study could also be improved if simple computation of freshwater flux using ice volume and classical melting law were conducted and presented.

Authors' Response: We would like to thank the reviewer for their comments.

We would like to thank the reviewer for drawing to our attention the fact that our discussion of Columbia Fjord as a potential future Greenlandic fjord is too general. We have made sure to address this in our revisions. Instead of justifying our study by presenting Columbia Fjord as a potential future Greenland fjord, we have focused our manuscript on the more specific implications of our results. We have amended section 4.4 so that it is now a more detailed comparison of our findings to measurements which have been previously published in papers covering the topic of icebergs in fjords.

We have also worked on section 4.3 to make it less general and more focused on our results. We have done this by adding estimated iceberg melt from melt equations published in Bigg et al. (1997), as well as presenting salinity profiles taken inside Columbia Fjord during our study period by the US Geological Survey.

Specific comments
Page 1 line 8 outet=> outlet

Authors' Response: We appreciate the reviewer catching this typo. We have corrected it. (p. 1, l. 8)

- Page 1 line 20: Coloumbia==> Columbia

Authors' Response: We appreciate that the reviewer caught this typo as well. However, we have removed this sentence from the abstract.

- Page 1 line 20 Considering the difference of temperature between Greenland and PWS water and the different conditions of the Greenland fjords this remark is certainly way to general.

Authors' Response: We recognize that our comparison of Prince William Sound in Alaska and fjords in Greenland was far too general. We have amended this by comparing the results from our study to those from previous studies of iceberg distribution.

- Page 3 lines 15-20. For people not familiar with WorldView Satellite explain why there are sometimes two images from the same satellite at the same time. The sentence on the hundredths of second separation is quite useless.

Authors' Response: We agree that there should be an explanation of why the WorldView Satellite would take two images only minutes apart. The images were taken for the purposes of Digital Elevation Model creation using stereo imagery. We have thus added in a few sentences on p. 3, l. 10-19 explaining this. We have also removed the sentence mentioning "hundredths of a second" because it is unhelpful.

- Page 3 line 23 and following; As the study fully relies on the detection and analysis of the WW1 images, it is important to at least present an example of detection (on an image detail) at best to provide the analysis of all images in Supplementary Information.

Authors' Response: To give readers a better idea of what we have done, we have added in an example of iceberg detection to figure 2, as well as adding in a sentence referencing said figure. (p. 4, l. 1-2)

- Page 4 lines 23-26. It is not explain what is the difference between a and b images (see my previous comment). If this is related to different viewing angle it is important to precise it as it might explain the different result (that could be due to a difference in ef- fective resolution). I don't understand the November 19 case (not enough information). There again it could be related to viewing angle and specular reflection on open water (wild guess as we don't have the data and there are not freely accessible).

Authors' Response: Because on a few instances there were two sets of stereo images taken, we had two images taken on the same day. We labelled these images 'a' and 'b' respectively. We *have now added in a few sentences distinguishing 'a' and 'b' images to the text, as well as mentioning that the difference in iceberg identification could be due to viewing angle. Changing the angle at which we view the ocean changes the reflectivity of the ocean, which could therefore affect which pixels were identified as ice versus water. (p. 3, l. 10-19)*

- Page 4 line 32. Why May 06 (a b) is not included? Provide explanation. reference to figure 4 should be included.

Authors' Response: Omitting May 06a from the figure was a mistake on our part. We have fixed this by adding the icebergs from May 06a into figures 4a and 4b. We have also added references in the text to these two figures. (p. 4, l. 32-33)

- Page 5 line 13-14, The sentence is not very clear. The pdf is computed on the following bins.

Authors' Response: We have re-worded this sentence to make it less confusing. (p.5, l. 12-14)

- Page 5 &2.4. This paragraph presents two methods of estimation of the iceberg volume from the satellite iceberg area (which might be different from the waterline cross- sectional area if the water is very clear). A is not a proxy.

Authors' Response: We do not use waterline cross-sectional area as a proxy for iceberg volume as we actually calculate iceberg volume using two different methods. We have removed the mention of using waterline cross-sectional area as a proxy.

- Page 6 line 7-. I think the authors recompute the albedo using fixed ocean and ice value to eliminate solar angle and atmospheric influence but it is not stated.

Authors' Response: Yes, we calculated the albedo using this method in order to avoid issues with atmospheric interference as well as the angle at which solar radiation hits the ocean. We have added in a sentence stating this more clearly. (p. 6, l. 18-20)

- Page 6 lin18-20 Where is the 95% coming from. Figure 4 and 5 don't present proportion but numbers and area. Figure 4 should use a log colorscale to reveal more details of the distribution within the fjord.

Authors' Response: 95% of all the icebergs identified in this study had a waterline cross-sectional area less than or equal to 100 m^2. As this is not readily discernible from the figure, we have removed the reference to it, as well as re-worded the text to make this more clear. (p. 6, l. 28) We have also changed the colorscale of figure 4 to be logscale in order to emphasize iceberg distributions in the fjord.

- Page 6 line 20-24. I don't understand the purpose of this remark. It is part of the detection and analysis method and should be treated there.

Authors' Response: We have moved this to the methods section. (p. 4, l. 21-23)

- Page 6 line 25. Please mention figure 6 from the beginning of the &.

Authors' Response: We have added in a reference to figure 6 in the first sentence of the paragraph. (p. 7, l. 3)

- Figure 6. For May 6 b and Jul 11 there are only estimates for the proximal zone certainly because of the partial coverage. Is it really necessary to keep those two images as they don't really bring any special information/results.

Authors' Response: Despite the fact that there is incomplete coverage for the fjord on May 06b and July 11, we believe there is value in representing the partial data in the figure. The power-law exponents for these two dates show agreement with the power-law exponents in the proximal zone for the other dates in the same seasons.

- Page 7 line 13-15. The comparison of the thickness for a given A using 2 and 3 explains completely the difference observed in Table 3. What is important to note here is that the variations of the total volume, and percentage of volume for large icebergs are very similar using the two formulas although they give very different iceberg thickness (this is certainly due to the strong impact of the power-law distribution of the distribution of the ice volume).

Authors' Response: This is a very good point. We have added in a few sentences mentioning this fact in the text. (p. 7, l. 26-29)

- Page 7 line 19. The summer increase of albedo could implies that the fragmentation is increasing in warmer waters.

Authors' Response: This is an interesting point. We have added in a discussion of iceberg fragmentation into the discussion. (p. 9, l. 18-24)

- Page 7 line 21-25. It is important to explain in detail the computation of the residence time.

Authors' Response: We have clarified our computation of iceberg residence time by stating our methods more explicitly. (p. 8, l. 1-4)

- Page 8 line 23-25 In fact power-law and lognormal are quite similar and power-laws (which do not converge (tend to infinity in 0)) can be used to approximated the tail of lognormal distributions.

Authors' Response: This is an interesting point, however, we are not sure how well it fits into the discussion we are having in this paragraph. We fit both power-law and lognormal distributions to our observed iceberg areas and found that the power-law equation fit much better than the lognormal equation. Kirkham et al. (2017) examined iceberg populations inside fjords and in the open ocean and found that icebergs inside fjords fit power-law distributions more closely, and icebergs in the open ocean fit lognormal distributions more closely. Our findings are consistent with their conclusions.

- Page 9 line 7-17 Two recent studies one from Bouhier et al (https://doi.org/10.5194/tc-12-2267-2018) and one from Crawford et al (https://doi.org/10.1029/2018JC014388) presented size distributions of pieces resulting from icebergs fragmentation with slope close to -1.5 (i.e. the mid_fjord summer slope). The two studies mentioned that this -1.5 slope is in general associated to fragile fragmentation and could in this case indicate that during summer month the main driver of the size distribution within the fjord is the fragmentation.

Authors' Response: We very much appreciate the reviewer bringing these two studies to our attention. We have used their findings, as well as those from other studies of iceberg fragmentation, to expand on brittle fragmentation. We agree that the power-law exponents we find in this study indicate that there is more brittle fragmentation of icebergs during the summer months than the spring or fall. We have added in a number of sentences to the discussion on this topic. (p. 9, l. 18-24)

- Page 9 line 26-27 In fact when computing power-law distribution there is always some problem with the tail of the distribution just because the numbers of samples is too low.

Authors' Response: The reviewer makes a very good point. We have added in a sentence explaining this in the methods section where we first mention removing the tail of the distribution to achieve a better fit. (p. 5, l. 16-17)

Page 9 line 30. This is a direct consequence of the power law distribution.

Authors' Response: We agree with this point and have added in a statement pointing this out in the manuscript text. (p. 5, l. 16-17)

- Page 9-10 &4.3 This paragraph is not very clear and don't present any significant results. It could be of interest if the volume of ice and melting law were used to estimate the fresh water flux from each image.

Authors' Response: We recognize that this section is too general and does not present significant results. We have re-worked this section to focus more on results and have created a new figure accompanying this paragraph comparing iceberg keel depths to temperature and salinity profiles in the fjord to visually represent the contribution of freshwater from icebergs at various points along the fjord length. We have explored in greater detail the effects that icebergs may have on the water masses inside the fjord. In addition, we have made estimations of iceberg melt using an equation from Bigg et al. (1997). (Section 4.3)

- Page 10 &4.4 There is no data in winter in your study.

Authors' Response: We have imagery from March 13th, which is before the vernal equinox, i.e., the formal end of the astronomical winter. We do realize that it is standard in meteorological and climatic analyses to consider only December, January, and February to be winter months. However, the winter maximum of Arctic sea ice extent is typically reached in March, often around the time of when our March 13th scene was acquired. We also note that the commonly used Levitus World Ocean Atlas uses the definition of winter season as January-February-

March. Hence, we do not think that it is unreasonable to consider this scene to be representative of winter time iceberg conditions in Columbia Fjord. We have made this more clear in the text. (p. 12, l. 28-30)

- Page 11 line 1 Where is 11% mélange coming from (not from Table4).

Authors' Response: We calculated the mélange by subtracting the total number of ice pixels by the number of ice pixels that are identified as part of an iceberg. We have included our calculations of mélange into the methods section, as well as adding in percent coverage of mélange into Table 4. (p. 4, l. 21-23)

- Page 11 line 14-15. The computation of the iceberg surface is not obvious. It should be given (in annex).

Authors' Response: We agree that we do not explicitly explain our calculations of iceberg surface area. We have added in the equation we used to calculate iceberg surface area into the methods. (Equation 5)

- Page 12 line 4-6. The -1.5 slope could indicate that there is more fragmentation during summer.

Authors' Response: We agree with the reviewer on this point. We have therefore edited this sentence to include brittle fragmentation. (p. 14, l. 4-6)