Insights on Calving Processes from Fragmentation Theory Applied to Iceberg Size Distributions

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Abstract

Changes in glacier terminus position have been implicated as one of the primary drivers of the rapid changes in glacier dynamics observed across the globe in the last two decades. Iceberg calving exerts a critical control on the terminus position of the vast majority of marine-terminating glaciers, yet calving is relatively poorly understood due to the inherent difficulties in collecting observations of a stochastic process in a dangerous setting. Time-lapse camera and satellite observations suggest that the style of iceberg calving can vary tremendously in both space and time depending on the physical properties of the terminus, ranging from the detachment of giant tabular icebergs every few decades from Antarctic's floating ice shelves to the growlers produced nearly daily from serac topples along Alaska's coast. Here we extract quantitative metrics on the relative importance of calving driven by branching and uncorrelated fractures through application of fragmentation theory to iceberg size distributions extracted from high-resolution digital elevation models for 17 fjords around Greenland. We find that iceberg size distributions typically deviate from the widely-assumed power-law form for icebergs with surface areas >0.05 kmˆ2, with fewer icebergs than predicted by the power-law for larger sizes. Icebergs larger than ˜0.1 kmˆ2 primarily calve as the result of full-thickness penetration of uncorrelated fractures (i.e., as tabular icebergs). Although the dataset is temporally sparse for the majority of the study sites, the data suggest that iceberg formation via branching fractures reaches a seasonal peak in summer, when icebergs up to ˜0.1 kmˆ2 follow power-law distributions. These data provide a novel means to assess the accuracy of iceberg calving models and potentially to constrain the physical characteristics of termini susceptible to the marine ice cliff instability mechanism.

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Iceberg Calving

Iceberg calving and associated terminus position change directly and indirectly control marine glacier and ice sheet mass.

The calving process is relatively poorly understood because it is incredibly difficult to collect observations of calving events.

- calving is a stochastic process & therefore difficult to predict
- the near-terminus region is a dangerous location to install & retrieve instruments

There is a broad spectrum of calving modes:

- low-energy very large tabular iceberg detachment
- high-energy full-thickness iceberg capsize
- moderate-energy submarine or subaerial growler or bergy bit detachment

Fragmentation Theory

Iceberg calving requires either (a) the connection of branching fractures or (b) full-thickness penetration of isolated fractures.

Different fracture patterns produce mathematically-distinct iceberg size distributions:

- branching fractures = power-law distribution with a size cut-off
- isolated fractures = exponential distribution with a size cut-off

$$n(v) = \underbrace{c_1 v^{-\alpha} exp(-v/c_2)}_{\text{branching}} + \underbrace{c_3 exp(-v/c_4)}_{\text{isolated}}$$

Equation 1: Fragmentation curves used to describe iceberg size distributions. *From Åstrom et al. (2021).* v is iceberg size, n(v) is iceberg count divided by iceberg size, and $c_{1\text{-}4}$ are constants tuned to observations.

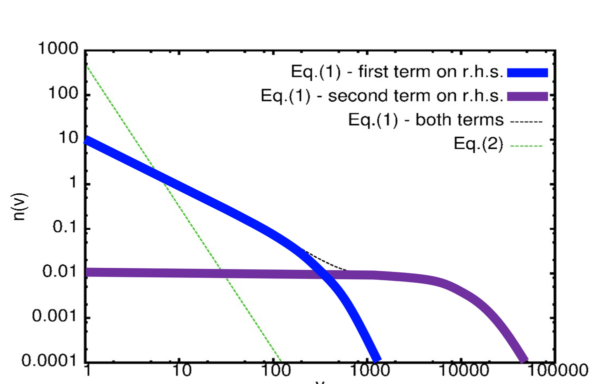


Figure 1: Idealized fragmentation curves. *Modified from Åstrom et al. (2021).*

Application of fragmentation theory to ice mélange size distributions can yield insights into controls on calving.

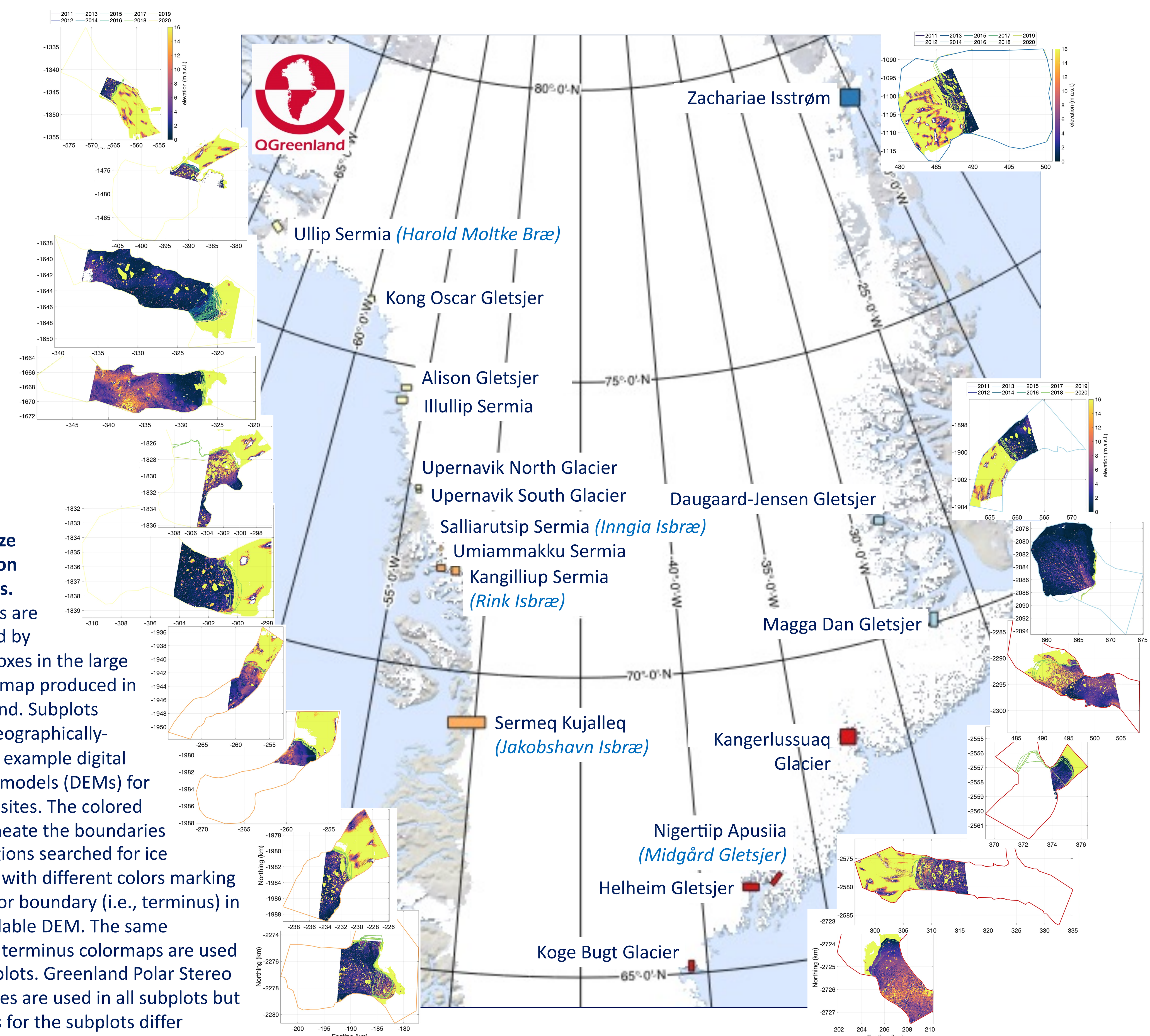
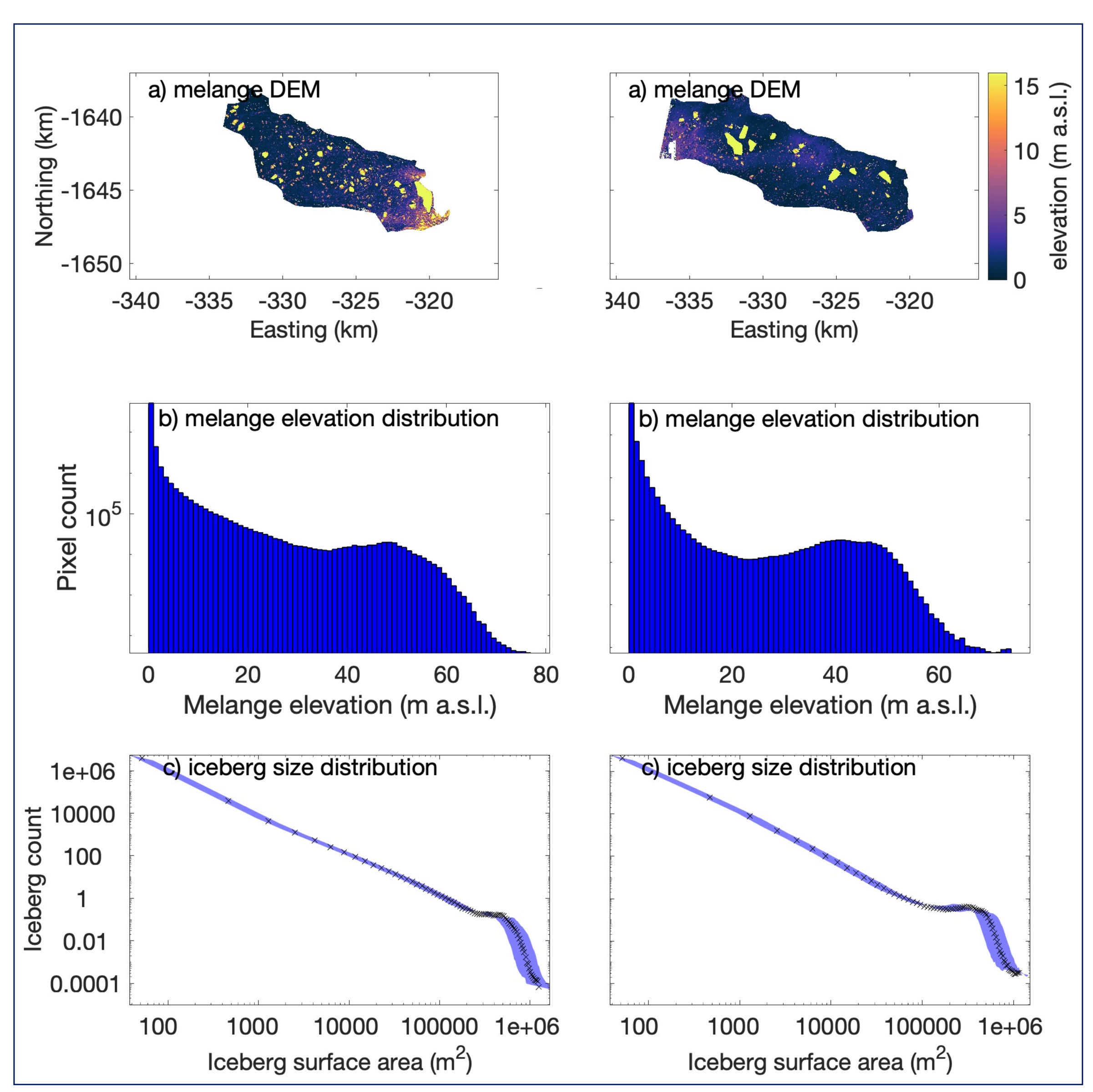


Figure 1: Iceberg size distribution study sites. Study sites are delineated by colored boxes in the large overview map produced in QGreenland. Subplots contain geographically-organized example digital elevation models (DEMs) for the study sites. The colored lines delineate the boundaries of the regions searched for ice mélange, with different colors marking the interior boundary (i.e., terminus) in each available DEM. The same elevation terminus colormaps are used in all subplots. Greenland Polar Stereo coordinates are used in all subplots but the scales for the subplots differ depending on extent of each region.



Figures 3 & 4: Observed iceberg size distributions. (a) Digital elevation models, (b) pixel elevation distributions, and (c) iceberg size distributions for Alison Glacier on May 7 and July 27, 2020, respectively.

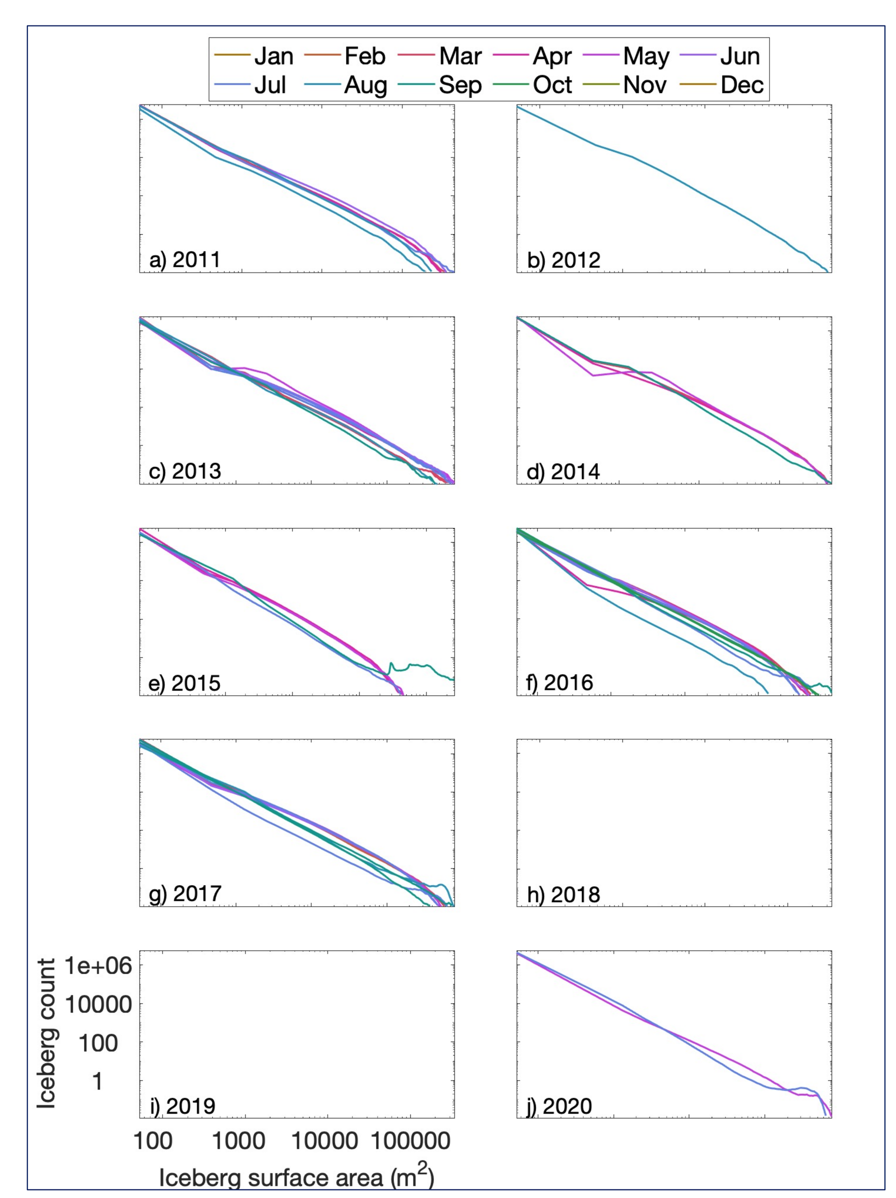


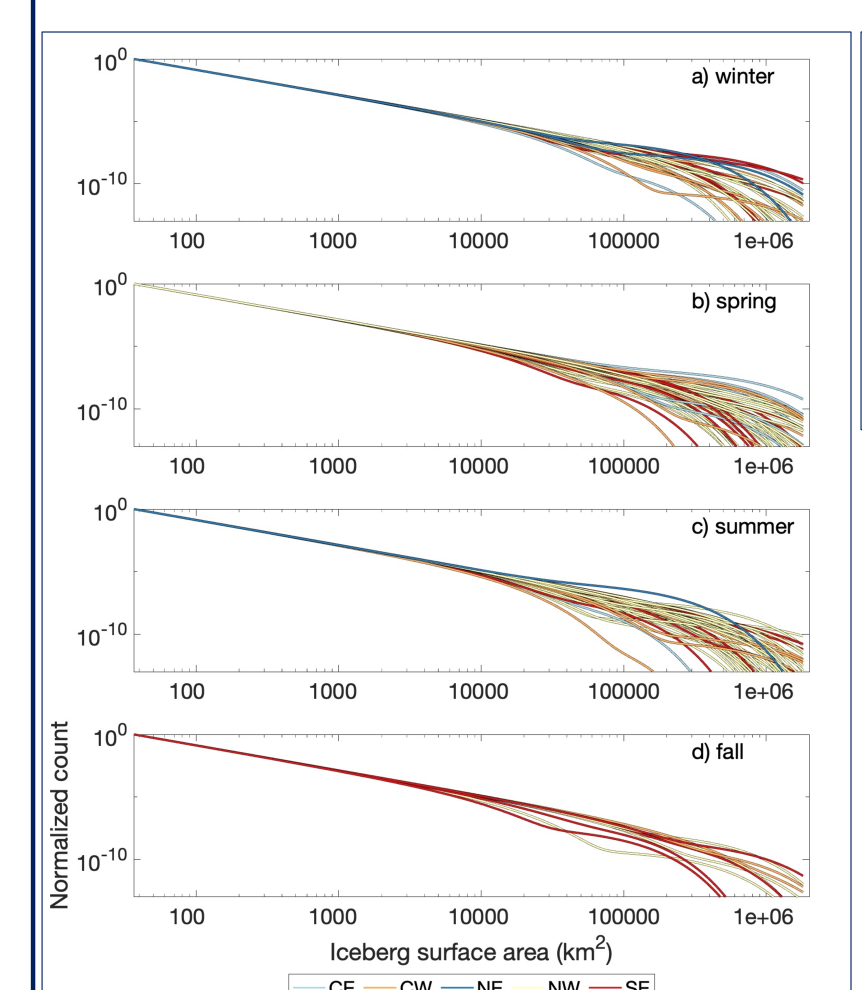
Figure 5: Iceberg size distributions for Alison Glacier for 2011-2020. Colors indicate months. The same axes scales are used for all subplots.

Methods Example: Alison Glacier (Figs. 3-5)

1. Extract iceberg surface elevations from very high-resolution digital elevations of near-terminus ice mélange.
2. Convert ice mélange elevations to iceberg size distributions using width-thickness (i.e., aspect) ratios ranging from 1.7-2.1. See Enderlin et al. (2016) for more details.
3. Fit fragmentation theory curves to normalized iceberg size distributions:
   - automated inversion
   - manual adjustment as necessary

Results

- Uncertainty in iceberg aspect ratios has minimal influence on iceberg size distributions (Figs. 3&4: Blue shading in panel c).
- Power-law can over-predict small iceberg abundance due to rapid submarine melting of growlers & bergy bits.
- No clear seasonal patterns in the shape of the distributions (Fig. 6).



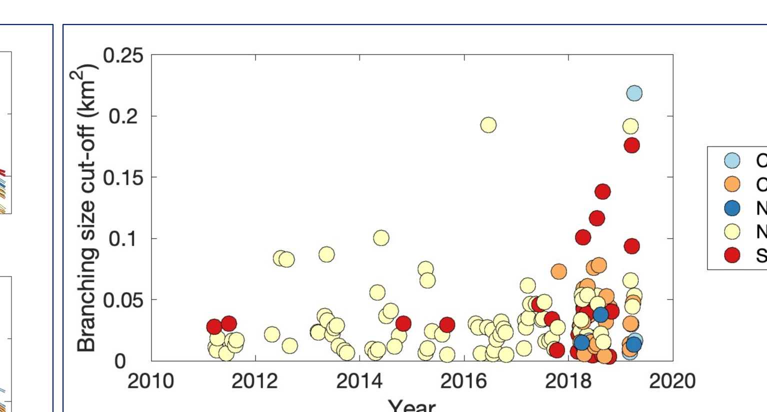


Figure 6 (left): Seasonal fragmentation theory-modeled iceberg size distributions from all cloud-free DEMs available from 2011 through winter 2019. Colors correspond to the different regions. Warmer colors generally correspond with warmer subsurface water temperatures.

Figure 7 (right): The iceberg size that is equally driven by branching and isolated fractures. Larger sizes are representative of tabular icebergs that form as the result of isolated fractures.

- Some seasonality apparent in the iceberg size above which isolated fracture dominates and tabular icebergs form (Fig.7).

Acknowledgements & References

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