Dear Editor,

We have gone through the referee comments on "Greenland Iceberg Melt Variability from High-Resolution Satellite Observations" and have implemented a number of revisions. The manuscript has been noticeably improved and we thank the editor and both referees for their constructive comments.

The responses to the referees' comments are listed below. Referee comments are in black and our responses are in blue.

Thank you for considering the manuscript for publication,
Ellyn Enderlin

Reviewer #1 (Jason Amundson)

Summary:

In this study the authors use digital elevation models derived from satellite imagery to investigate temporal and spatial observations in iceberg melt rates. The paper builds on previous work to provide estimates of iceberg melt rates across several fjords in Greenland, and demonstrates that iceberg melt rates depend on iceberg draft – with the caveat that draft and melt rates are inferred from calculations of subaerial volume and assumed iceberg geometry. Meltwater from icebergs appears to be an important source of freshwater for fjords in Greenland, and therefore this study has important implications for fjord circulation and submarine melting of glacier termini.

Major comments:

Most of my concerns with this paper are related to understanding the numerous sources of uncertainty that are inherent (and unavoidable) in the authors' calculations. It wasn't until I went back to re-read Enderlin and Hamilton (2014) that I realized that these uncertainties had already been addressed in some detail previously. Therefore I think this paper would benefit from a 1-2 paragraph summary of the sources of error and their impact on the melt flux and melt rate calculations. Presumably this summary would be in Section 2. My sense is that the error in the melt flux calculations is small and that those calculations are therefore pretty robust. The depth-averaged melt rate calculations are more tenuous because they rely on an assumed iceberg geometry, which affects both the submerged surface area and the iceberg draft.

We have added a paragraph outlining the various uncertainty sources that can be quantified from the available data, with an additional note to call-out the fact that deviations in iceberg geometries from the assumed (cylindrical) shape cannot be quantified but should be taken into consideration when examining the data.

I would also feel more comfortable with the discussion of how submarine melt rates vary with depth if the paper more explicitly referred to the depth-averaged melt rates and drafts as proxies. For example, I believe that the draft is calculated with something like:

h' = "draft proxy" = V_{sa}/A * \rho_i/(\rho_w-\rho_i),

where h' is the draft proxy, V_{sa} is the subaerial volume, A is the cross-sectional area of the iceberg at the waterline, and \rho_i and \rho_w are the densities of ice and water. Including something along these lines would more precisely indicate what is actually being plotted in the various figures. Something similar could be written out to describe the proxy for the depth-averaged melt rate. Not sure if this correct, but:

m' = 1 / (h' *2*pi*r) * dV_{sm}/dt,

where m' is the proxy for the depth-averaged melt, r is the average radius at the water line, and $V_{sm}= V_{sa}*\rho_i/(\rho_w-\rho_i)$ is the submerged volume. Depending on exactly how this calculation is made, you may be able to cancel out some terms.
We agree with the reviewer that it is beneficial to include equations that clearly demonstrate how we use our surface observations to estimate the iceberg draft, submerged area, and melt rate. We have added the equations used to estimate draft and the area-averaged submarine melt rate. The melt rate equation also contains the equation for the submerged ice area. We did not adopt the specific term "proxy" in the text but made an effort to make it more clear that the draft, submerged area, and melt rate data are estimates that inherently have much larger uncertainties than the volume change estimates because the submerged shapes that we use to compute melt rates will most likely differ from the assumed cylindrical geometries.

My concern is that I'm just not sure how much faith to put in the melt rate vs. draft figures. There seems to be a pretty nice relationship between meltwater flux and submerged area (based on the assumed geometry). Is there a similarly nice relationship between meltwater flux and submerged volume? If not, maybe that can somehow be used to justify the choice of iceberg shape.
The relationships between meltwater flux and submerged area and meltwater flux and iceberg volume are similar. We show the plots of meltwater flux versus submerged area because, as we state in the text, the slope of the best-fit lines can be used as an approximation of the melt rate. As such, we think that the meltwater flux versus submerged area plot is more helpful to show than plots of meltwater flux versus volume.

Also, in the discussion of the observed changes in melt rates at Jakobshavn (page 7), it would be nice to have the calculations of melt rates spelled out in more detail. How did you calculate the change in water velocity that would be needed to increase the melt rate? By how much would you have to change the water temperature to get a similar change in melt rate? Can you exclude our potential sources, such as an incursion of warm water? Did the melange remain intact following the calving event?
We agree with the reviewer that the discussion of melt rate change in Ilulissat Isfjord would benefit from the inclusion of iceberg thermodynamic equations. We have included the equations for turbulence- and buoyancy-driven submarine melt so that it is easier for the reviewer to assess the importance of temperature and velocity change as drivers of changes in melt rates. We point out that, in the absence of changes in relative velocity, the temperature change required to drive the observed increase in deep-drafted icebergs melt rates is physically untenable given the range in water temperature observations from the fjord (see Gladish et al., 2015). These revisions should now make it more clear why we hypothesize that iceberg overturning essentially jump-started fjord circulation, which led to the four-fold increase in melt rates.

Minor comments:
p. 1, line 16: Consider pointing out in the abstract that you don't observe longitudinal variations in melt rates. That seems to be a pretty important finding.
Added.

p. 1, line 30: Sublimation also contributes to ablation.
Added.

p. 2, line 12: Why these seven glaciers?

On p 3. line 27 we have added that these sites were selected based on image availability. Specifically, we selected sites that spanned the majority of the ice sheet and had sufficient WorldView imagery to estimate iceberg melt rates over more than one observation period.

p.2, line 4: Consider citing Alon Stern's JGR paper: The effects of Antarctic iceberg calving-size distribution in a global climate model
Added.

p. 3, line 1: Why the switch in processing schemes?
DEMs through 2014 were produced by Dr. Ian Howat using the SETSM algorithm that was in the final stages of development by his group at The Ohio State University at the time. Dr. Howat agreed to process the DEMs in exchange for information regarding SETSM DEM quality relative to DEMs produced using the NASA Ames Stereo Pipeline (ASP), which was in the process of being installed on the University of Maine's high-performance computing cluster. Following the installation of ASP, we compared several DEMs and found negligible differences in iceberg elevations, motivating us to switch to using ASP so that the DEMs could be produced entirely in-house on demand.

p. 3, line 22: Are any of the icebergs tabular?
For Zachariae Isstrom a large number of icebergs remained upright following their detachment from the glacier's floating ice tongue. Several of the deep-drafted (i.e., >250 m median keel depths) in the other fjords were tabular as well.

p. 5, line 22: Perhaps cite John Mortenson's paper: Heat sources for glacial melt in a sub-arctic fjord (godthabsfjord) in contact with the Greenland ice sheet
Added.

Reviewer #2 (Anonymous)
This paper investigates iceberg submarine melt variability in fjords for icebergs calved from seven large tidewater glaciers around the Greenland coast between 2011-16. The paper uses a method developed and presented previously in a detailed paper (Enderlin and Hamilton 2014) and utilises Worldview Imagery to generate iceberg DEMs. The paper shows clearly how the estimated iceberg submarine melt-rates show distinct melt patterns that one would expect based both on hydrographic observations and variations in latitude and iceberg draft. In the main, the paper is very clearly written and the findings are well supported by the analyses and data while the conclusion provides a very succinct and clear summary of the paper highlighting the key findings and the considerable potential of the method utilised.

There are a few areas where the paper is a little unclear and these are outlined below; in particular, some changes to the Figures would improve the clarity of the paper. On occasions, just a little more text is needed to aid the reader and any such additions will not detract from the paper as it is not overly long.

P1, l17 – I was a somewhat unclear what you meant in the abstract when stating that you do not resolve "coherent" temporal variations in melt rates. After reading the paper, this became clearer but I think it makes sense to state more clearly here in the abstract that you do resolve coherent 'seasonal or interannual patterns in your iceberg melt-rates'.
Changed.

P1, l27 – worth adding that the size distribution of the calved icebergs as well as the volume calved is crucial to the spatial distribution of iceberg freshwater fluxes.
Added.

P2, l17-18 – important to add the caveat here that this is true as long as the iceberg in question is floating.
Revised for clarity.

P2, l21-23 – I think that you should also add other satellite platforms to your list of additional potential methods that could be used to derive elevation time-series.
Added.

P2, l31-32 – You state that "A comparison of the DEMs produced using the SETSM and ASP algorithms indicates that the accuracy of iceberg elevations is unaffected by the choice of the algorithm used to construct DEMs". You have presumably carried out some kind of analysis to demonstrate that this is the case; in which case, it would be beneficial to report briefly (even in one line) what "unaffected" means by referring to one example of the results derived from analysis on one of your iceberg data-sets.
We have changed the sentence so that it is more clear that a comparison of the datasets indicates that switching between the two algorithms does not introduce systematic biases into our results: "A comparison of the DEMs produced using the SETSM and ASP algorithms indicates that the accuracy of iceberg elevations derived from the algorithms are comparable, allowing us to switch from the use of SETSM DEMs for 2011-2014 images to ASP DEMs for 2015-2016 images without biasing our results." We do not show iceberg elevation maps or provide specific numbers for SETSM- and ASP-derived DEMs because a detailed cross-comparison is outside the scope of the manuscript. Noh and Howat (2015) discuss the quality of their algorithm and we refer the reviewer to their manuscript and Shean et al. (2016) for details on the quality of ice DEMs produced using the ASP algorithm.

Fig. 1. Each location map (insets b – h) needs a scale (unless the scale is the same in all of them in which case a scale is still needed somewhere). Furthermore, it would help to show clearly where the calving fronts of the glaciers are; this may be obvious in some figures either from visual clarity (g) or site familiarity (e) but for many, especially d, f and g, it's not really clear where the icebergs have come from. (I might add that it does become clear when I enhance the scale on the pdf to 400%, as the images are very high quality, they are just very small at the resolution of the current figure). And this information is needed to help make sense of the text on P3, l26-29.
All small panels have the same scale so a scalebar has been added to only panel b and a note about the scaling has been added to the legend. The terminus location in each panel has also been added.

Furthermore, in Figure 1 and in all subsequent figures, I think you should re-order the glacier legend box and symbols from b) to h) i.e. Kong Oscar, Alison, Upernavik etc ending with Koge Bugt rather than alphabetically as currently which is much more confusing for the reader.
Changed.

Fig. 2 and p4, l6. It would be very helpful to include the estimated submarine melt rates, derived from each linear polynomial, within the individual figure boxes (a – g).
Added.

P4, L16. Ref. should be to Jackson and Straneo, not et al.
Corrected.

P4, l18 – there are seven plotted symbols in Figure 1h) associated with Koge Bugt, not the six suggested in the text. Why the discrepancy?
Thank you for pointing this out. There are seven icebergs and the text has been corrected.

P4, l21. The confidence for the Koge Bugt datasets, as currently explained, seems a little misplaced given the sample size. In particular, from Fig 1, it looks as though one of the icebergs sampled is a considerable distance from the others and perhaps in more open waters 'atypical' of the other fjord samples. As such, are you sure you are observing "typical melt conditions" and not getting spurious results due to anomalous sampling (particularly given the small sample size and thus significance of one anomalous data point to your overall results for KB).
Although the one iceberg in the sample set is several kilometers down-fjord from the other icebergs, this is not one of the icebergs with the exceptionally high melt rates. Also, it is important to note that all the small panels in Figure 1 have the same scaling, so the iceberg located farthest from the terminus is actually not exceptionally far away from the glacier relative to observations from other fjords. Furthermore, we are confident that our interpretation is not skewed by one anomalous data point that is not representative of melt conditions near the terminus because there is actually a deep-drafted iceberg with a melt rate of ~0.75 m/d during each observation period.

P4, l31 – will detailed in-situ data become more widely available as part of the OMG programme?
Yes, the number of in situ hydrographic observations available around Greenland will drastically increase as a result of NASA's OMG program. Future research will explore whether there are any coincident in situ hydrographic observations and remotely-sensed iceberg melt rates.

P5, l8 – The results for individual glaciers (b-h) would be of much more use if the y scale was reduced from 0 – 0.4 m/d as opposed to 1m (with the exception of Koge Bugt) so that the (valuable) details in the variable melt-rates could be seen more clearly.
We agree that the variability with depth is hard to discern in panels b-h, which is why we have also included the normalized data in panel a. We have modified the y-scaling so that it now goes from 0-0.9 m/d but choose to keep the same scaling for panels b-h so that the melt magnitudes can be directly compared between panels.

P5, L12-13. The broad description relating to melt rate with iceberg draft is not really correct when integrating the Upernavik and Jakobshavn Isbrae results. The melt rate actually continues to decrease in draft bin 200-250m at JI, not "increase" again as suggested in L13. Hence the dip is broader than the 150-200m dip that you suggest. I think you just need to be a bit broader in your depth categorisation for the "approximate depth of the interface" for the cold-warm boundary (and I presume that it does vary between fjord systems). Furthermore, the melt rate appears to dip again at JI in the 350-400 m bin (actually dropping back to shallow 'cold' water values). Given the integrative nature of your area averaged melt rate estimates (L20), this low value for the 350-400m bin would pretty much suggest zero melt rates at the 350-400 depth given the much higher median melt rate from the previous 300-350m bin. Can you comment on either the reliability of this 350-400m estimate (there are zero error bars so presumably it is just one estimate) or whether this sudden drop may be meaningful in terms of a dramatic decrease in melt rate at a certain depth in Ilulissat Isfjord?
We have modified this section slightly to reflect the observation that the dip in melt rates extends to a deeper water depth in Ilulissat Isfjord than in the Upernavik region. We also point out that the melt rate estimate for

350-400 m-depth is based on one observation from March 2011. As discussed in section 3.3, the March 2011 melt rates in Ilulissat are exceptionally low and this low melt rate estimate should not be considered as an indication that melting actually ceases below 350 m-depth.

P5 re depth dependency and Fig. 3. In addition to the above, I think that suggesting that depth the dependency "is particularly pronounced for icebergs calved from the Upernavik glaciers (Fig. 3d) and Jakobshavn Isbræ (Fig. 3e)" is rather misleading. With the normalised data, it is perhaps most pronounced at Helheim and Zachariae. Based on Fig. 3a, one might argue that JI is the most atypical in the 200-400m depth bins.
We agree that the normalized data show marked increases in melt rates for Helheim and Zachariae below ~200 m-depth but the actual magnitude of the increase with depth is much smaller for Zachariae (0.01 to 0.1 m/d) than for Upernavik (0.03 to 0.26 m/d) and Jakobshavn (0.11 to 0.41m/d). Although the magnitude of the melt rate change with depth is comparable to Helheim (0.16 to 0.32 m/d), the depth dependency of the melt rate is less pronounced for individual observation periods (see Fig 4) than observed for Upernavik and Jakobshavn. Hence our focus on Upernavik and Jakobshavn in the paper.

P5, l22-24 – presumably extent of sea ice and melange are also relevant to the stratification and circulation over different timescales?
Sea ice and ice mélange extent likely influence the wind stress exerted on the surface water layer, as well as the temperature and salinity of surface and possibly near-surface waters. As such, we have added that they likely influence fjord circulation, with references to papers describing mélange meltwater fluxes in Helheim and Jakobshavn's fjords (Enderlin et al., 2016) and the influence of sea ice extent on melting of Petermann Glacier in northern Greenland (Shroyer et al., 2017), as supporting examples.

Fig. 4. I found this Figure extremely hard to interpret, in particular because it was very hard to see the gray-scale 'colour' of the year fill, especially when stars are used as symbols at JI and Koge Bugt. I would suggest changing the symbols so that they are all squares or circles (like Upernavik or Alison – check to see which looks better) and put the name of each glacier in the top left corner of each box (i.e. a) Kong Oscar through g) Koge Bugt).
In reality, there is so much complexity in the plots, I am not sure whether a seasonal or interannual pattern would be visible even if one were present. As such, I feel that the line that "the lack of a coherent temporal signal across all study sites does not preclude the existence of temporal variations" is pretty much spot on. It would be good to see on a single graph, for your most frequently sampled glacier, a time series of melt-rate v time (on x-axis) for each 50m draft bin. I am sure that you have tried this but I just think it would be good to show, in a more visibly obvious way, that there is no clear seasonal or temporal pattern, something which I feel Fig. 4 fails currently to do.
We agree that the fill color of the star symbols was difficult to see and we have enlarged the symbols so that the color difference is more obvious. We have kept the different symbols, however, because they are intended to help colorblind readers distinguish the different fjord locations in the normalized melt rate plot (Fig 3a). We have also plotted time series of the binned melt rates, as shown below, to support our interpretation that there are no consistent temporal variations in melt rates across all study sites. In the figure, the panels are arranged in the same order as Figures 1-4 (panel locations in the approximate locations of the study sites). The marker edge and line colors distinguish the observation depths, with the colors gradually transitioning from black for the near-surface observations to orange at 350-400 m-depth. In this figure, it is clear that the differences in the periods of observation obscure any temporal patterns across all sites. We have chosen not to add this figure to the paper because we feel it is unnecessary to include two plots addressing the same data, particularly because it

demonstrates a null result. However, if the editor feels strongly that this plot should be included, we can finish formatting this figure and include it in the text.

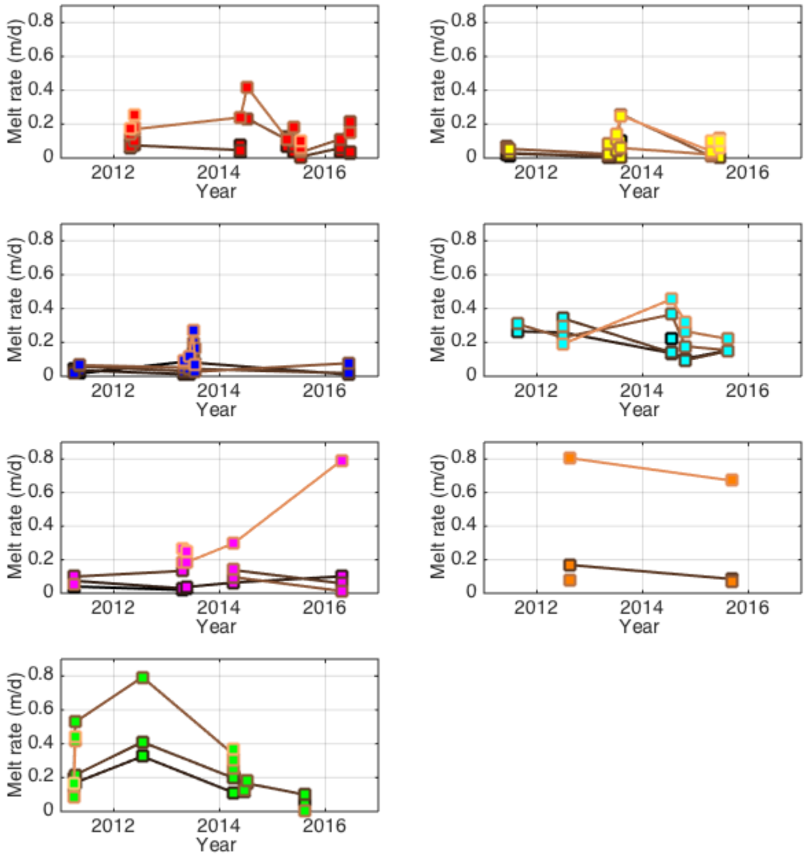

Fig. 5. Again, I think the choice of stars as the symbol makes the gray scale fill very hard to see.
We have enlarged the symbols so they are easier to see. Since the focus of this plot is point out the rapid change in melt rates from March to April in 2011, which we call-out in boxes, we think that enlarging the symbols is a sufficient modification to address the reviewer's comment.

P7, l5-6. If you are not going to go in to the details of your velocity change calculation, you at least need to refer to the paper/equation/parameterisation that you use to make the claim that "the water velocity would need to increase from an average of approximately
0.05m/s to 0.3 m/s to produce the _0.12m/d to _0.46m/d increase in the area-averaged melt rate". It would also help to know what change in water temperature would also give the increased melt rate if you kept the velocity at 0.05 m/s?

We have added iceberg melt equations here and elaborated on why we hypothesize that changes in velocity primarily drove the observed increase in the melt rate. Namely, temperature variations within the range of observed temperatures in Ilulissat Isfjord are not sufficient to drive such a large increase in melting. This should hopefully be more clear with the text revisions and inclusion of the melt equations.

P7, l7. Full stop after "hypothesis".
Changed.

P7, l8. Better to say "..from Sermilik Fjord in south-east Greenland suggests that. . ."
Changed.

Greenland Iceberg Melt Variability from High-Resolution Satellite Observations

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Abstract. Iceberg discharge from the Greenland Ice Sheet accounts for up to half of the freshwater flux to surrounding fjords and ocean basins, yet the spatial distribution of iceberg meltwater fluxes is poorly understood. One of the primary limitations for mapping iceberg meltwater fluxes, and changes over time, is the dearth of iceberg submarine melt rate estimates. Here we use a remote sensing approach to estimate submarine melt rates during 2011-2016 for 637 icebergs discharged from seven marine-terminating glaciers fringing the Greenland Ice Sheet. We find that spatial variations in iceberg melt rates generally follow expected patterns based on hydrographic observations, including a decrease in melt rate with latitude and an increase in melt rate with iceberg draft. However, we find no longitudinal variations in melt rates within individual fjords. We do not resolve coherent seasonal to interannual patterns in melt rates across all study sites, though we attribute a four-fold melt rate increase from March to April 2011 near Jakobshavn Isbræ to fjord circulation changes induced by the seasonal onset of iceberg calving. Overall, our results suggest that remotely-sensed iceberg melt rates can be used to characterize spatial and temporal variations in oceanic forcing near often inaccessible marine-terminating glaciers.

1 Introduction

The Greenland Ice Sheet discharges ~550 Gt of icebergs per year (Enderlin et al., 2014). This accounts for approximately a third to a half of the total freshwater flux from Greenland to the surrounding fjords and ocean basins (Bamber et al., 2012; Enderlin et al., 2014; van den Broeke et al., 2016). Unlike surface meltwater runoff fluxes from the ice sheet and tundra, which primarily enter the ocean system from point sources (subglacial discharge channels and terrestrial rivers, respectively), icebergs act as distributed freshwater sources. The spatial distribution of iceberg freshwater fluxes is dependent on a number of factors, including the volume and size distribution of ice calved from each glacier, which varies substantially over a range of spatial scales (Enderlin et al., 2014), and the solid-to-liquid conversion rate of an iceberg's freshwater reserves. Although surface sublimation and melting, wave erosion, and submarine melting all contribute to iceberg ablation, the solid-to-liquid conversion rate should primarily be dictated by submarine melting because of the strong dependence of total ablation on the surface area over which each process acts (e.g., Enderlin et al. (2016), Moon et al. (2017)).

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Depending on the rate of submarine melting, the submerged surface area over which submarine melting occurs, and the residence time of icebergs in Greenland fjords, up to half of iceberg discharge can be converted to liquid freshwater before entering the open ocean (Mugford and Dowdeswell, 2010; Enderlin et al., 2016). The location where iceberg meltwater enters the ocean system is proving important for local to global ocean circulation (Luo et al., 2016; Stern et al., 2016), yet the spatial distribution of iceberg meltwater fluxes has been largely overlooked because it cannot be estimated from existing hydrographic observations (Jackson et al., 2016). Where iceberg residence times can be estimated from, for example, iceberg tracking (Sulak et al., 2017), these data can be paired with remotely-sensed iceberg size and area distributions (Enderlin et al., 2016; Sulak et al., 2017) and empirical iceberg melt rates to estimate iceberg freshwater fluxes. However, there are only a handful of locations around Greenland where there are sufficient water temperature and velocity records to constrain empirical iceberg melt rate estimates in iceberg-congested fjords (e.g., Bendtsen et al. (2015), Gladish et al. (2015), Jackson et al. (2016)). To address the dearth of iceberg melt rate estimates in Greenland's fjords, here we use a satellite remote sensing method to construct time series of submarine melt rates and meltwater fluxes for icebergs calved from seven large outlet glaciers spanning the periphery of the Greenland Ice Sheet (Fig. 1). Although the iceberg melt estimates constructed using this remote sensing method are limited to irregular observation periods during 2011-2016, the data provide the most comprehensive observationally-constrained estimates of Greenland iceberg melting to date.

2 Methods

As a freely-floating iceberg ablates, the elevation of its surface lowers in proportion to the iceberg's volume loss so that the iceberg remains in hydrostatic balance with the water in which it is submerged. This principle enables the estimation of iceberg meltwater fluxes (i.e., volume lost due to submarine melting per unit time) from repeat remotely-sensed surface elevation observations. Here we follow the approach of Enderlin and Hamilton (2014) to estimate changes in surface elevation using very high-resolution stereo satellite images acquired by the WorldView constellation of satellites. We note that this method could also be applied to elevation time series from terrestrial laser scanners, stereo imagery acquired by unmanned aerial vehicles or other satellite platforms, or GPS-derived elevations, but we focus on WorldView data because, unlike data acquired from the other platforms, WorldView data can be used to construct multi-year records of iceberg elevation change around the entire ice sheet periphery. Using this approach, we produce iceberg melt estimates from multiple observation periods during 2011-2016 (Fig. 1, Table 1) for seven large marine-terminating glaciers across southeast, northeast, and western Greenland that have sufficient WorldView image archives to estimate iceberg melt rates for more than one observation period.

For each study site, we used a combination of the Surface Extraction with TIN-based Search-space Minimization (SETSM) (Noh and Howat, 2015) and NASA Ames Stereo Pipeline (ASP) (Shean et al., 2016) to construct very high-resolution (2 m

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horizontal resolution, ~3 m vertical uncertainty (Enderlin and Hamilton, 2014)) digital elevation models (DEMs) of iceberg-congested waters. A comparison of the DEMs produced using the SETSM and ASP algorithms indicates that the accuracy of iceberg elevations derived from the algorithms are comparable, allowing us to switch from the use of SETSM DEMs for 2011-2014 images to ASP DEMs for 2015-2016 images without biasing our results. DEMs were constructed over the entire stereo image domain so that bedrock and water surface elevations could be used to co-register DEMs (Enderlin and Hamilton, 2014).

To estimate the change in iceberg volume between image acquisition dates, we applied the same DEM-differencing approach as Enderlin and Hamilton (2014) and Enderlin et al. (2016): changes in iceberg surface elevation were manually extracted from repeat co-registered DEMs, then converted to estimates of iceberg volume change under the assumption of hydrostatic equilibrium. The contribution of iceberg surface melting to the observed volume change was estimated from the daily runoff time series for the nearest glaciated pixel in the Regional Atmospheric Climate Model (RACMO) for Greenland (van Meijgaard et al., 2008; van Angelen et al., 2014), then subtracted from the ice volume change estimates to yield ice volume loss due to submarine melting. Although there are slight differences in runoff estimates generated by RACMO v2.3 (used for 2011-2014) and v2.4 (used for 2015-2016), the version of RACMO used in our analysis had no appreciable influence on ice volume loss partitioning because volume loss due to surface melting constituted <5% of total volume change. We converted our estimates of ice volume lost via submarine melting to estimates of liquid freshwater flux (cubic meters of meltwater produced per day) and average submarine melt rates (meters per day) over the submerged iceberg areas. To estimate the average draft (i.e., keel depth) and submerged area of each iceberg, we assumed that the submerged iceberg shapes can be approximated by cylinders with dimensions defined by the iceberg surface elevation and surface area estimates (Enderlin and Hamilton, 2014). Under this assumption, the draft (d) is estimated as

$$d = \frac{\rho_i}{\rho_{sw} - \rho_i} z, \qquad (1)$$

and the area-averaged melt rate ($\dot{m}$) is estimated as

$$\dot{m} = \frac{\Delta V / \Delta t}{2\pi r d + \pi r^2}, \qquad (2)$$

where z is the median ice surface elevation, ρ_i and ρ_{sw} are the ice and sea water densities, respectively, ΔV is the change in volume between image acquisition dates, Δt is the time between image acquisition dates, and r is the average radius of the iceberg surface in each image pair. Submerged iceberg shapes are likely to be more complex than the cylindrical shapes used herein but are impossible to discern from surface observations alone. However, good agreement among iceberg melt rates derived via DEM-differencing and empirical melt rates estimates in Helheim’s fjord (Enderlin and Hamilton, 2014; FitzMaurice et al., 2016), and winter submarine melt rates for Helheim’s terminus (Sciascia et al., 2013), suggests that submerged iceberg shapes can be reasonably approximated by cylinders.

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Uncertainty in the submarine meltwater flux, submerged area, draft, and melt rate estimates are described in detail in Enderlin and Hamilton (2014) and are, therefore, only summarized briefly here. All errors are propagated through our calculations, then summed in quadrature. Potential errors arise from (1) surface elevation errors, (2) uncertainty in the operator-defined iceberg tracking, (4) uncertainties/changes in the ice and ocean water densities used to convert elevation change to volume change, (5) surface melt over- or under-estimation, and (6) changes in the iceberg surface area between image acquisitions. Systematic and random errors in iceberg elevations are minimized through vertical coregistration of iceberg DEMs using neighboring open water elevations and through spatial averaging, respectively. Uncertainties introduced by manual translation and rotation of iceberg masks in repeat DEMs are quantified through repeated delineation of each iceberg. Ice and water densities are assumed to vary by up to 10 kg m^{-3} and 2 kg m^{-3}, respectively, between observations. A conservative surface meltwater uncertainty of 30% is applied to account for RACMO uncertainties and potential deviations in the melt rate of icebergs from the nearest glacierized RACMO grid cell. The surface area uncertainty is defined as the temporal range about the mean. The typical (i.e., median) uncertainties in the submarine meltwater flux, draft, submerged area, and melt rate are 25.6%, 2.7%, 3.2%, and 27.6%, respectively. It is important to note, however, that deviations in iceberg shapes from the assumed cylindrical geometries represent an unquantifiable source of uncertainty that is not taken into account in our draft, submerged area, and melt rate uncertainty estimates.

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3 Results and Discussion

We extracted a total of 637 iceberg meltwater flux and melt rate estimates near the termini of seven large marine-terminating outlet glaciers fringing the Greenland Ice Sheet periphery and spanning March-October of 2011-2016 (Table 1; Enderlin, 2017). The number of estimates varies widely, with 3 to 27 melt estimates per observation period (mean=15). In general, the number of estimates is inversely proportional to the distance between the icebergs and their parent glaciers and the time period between image acquisitions, restricting our analysis to icebergs located within ~10 km of the glacier termini and to time spans of 3-67 days.

3.1 Regional Patterns

In line with previous analyses of meltwater fluxes for icebergs calved from Helheim Glacier in the southeast (Enderlin and Hamilton, 2014) and Jakobshavn Isbræ in the west (Enderlin et al., 2016), we find that the meltwater flux generally increases with the submerged iceberg area (Fig. 2). Linear polynomials fit to all meltwater flux and submerged area estimates at each study site provide a means to quantify regional variations in the efficiency of iceberg melting around Greenland. Variations in the slope of the linear polynomial fit reflect regional differences in the rate of submarine melting (Fig. 2). The site-specific meltwater flux area-based parameterizations, correlation coefficients, and root mean square error estimates are listed in Table 1. We generally find the highest melt rates near Koge Bugt and Helheim glaciers in the southeast (>0.35 m/d), with slightly lower melt rates in the Disko Bay (Jakobshavn) and Upernavik regions in the central west (~0.25-0.35 m/d). Icebergs calved from Alison and Kong Oscar glaciers in the Baffin Bay region in the northwest melt at slightly slower rates than those in the central west (~0.14-0.24 m/d). The lowest melt rates are found for icebergs calved from Zachariæ Isstrøm in the northeast (~0.12 m/d).

The observed large-scale spatial patterns in melt rate generally follow expected variations based on regional differences in subsurface ocean temperatures (e.g., Straneo et al. (2012)) and surface meltwater runoff (e.g., van den Broeke et al. (2016)), which drives summertime fjord circulation (Jackson and Straneo, 2016). There are, however, some notable exceptions. The average melt rate estimate for Koge Bugt is nearly double the average melt rate for icebergs calved from Helheim Glacier despite similar water temperatures near the fjord mouths (Sutherland et al., 2013). Although our Koge Bugt dataset includes only seven icebergs across two observation periods, we observe melt rates of >0.6 m/d during both observation periods, increasing our confidence that the difference in average melt rates reflects variations in typical melt conditions at the two study sites and is not due to observational uncertainties or anomalous melt conditions. We also find a discrepancy in the predicted latitudinal decrease in the iceberg melt rates in northwest Greenland, where we observe lower melt rates for icebergs calved from Alison Glacier than the more northerly Kong Oscar Glacier. We hypothesize that the strengthened latitudinal gradient in the southeast and reversed gradient in the northwest are due to spatial variations in turbulent melting below the waterline associated with differences in near-surface water temperatures and/or relative velocity (i.e., difference in water and iceberg velocities) for icebergs located in kilometers-long iceberg-congested fjords (Helheim and Alison) versus freely-floating icebergs in close proximity to the open ocean (Koge Bugt and Kong Oscar). Additional in situ water temperature and velocity observations are required to test this hypothesis, but if proven true, it suggests that near-terminus hydrography is strongly influenced by fjord geometry.

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3.2 Local Patterns

Although detailed *in situ* hydrographic analyses of Greenland's glacial fjords are limited in space and time, existing observations indicate that there are much steeper gradients in water temperature and velocity in the vertical plane (i.e., with depth) than in the horizontal plane (i.e., along fjord) (Sutherland et al., 2014; Bendtsen et al., 2015; Gladish et al., 2015; Jackson et al., 2016). As such, we expect to find pronounced variations in melt rates for icebergs that do and do not penetrate into the relatively warm and salty water masses found below ~100-200 m-depth around the ice sheet periphery (Straneo et al., 2012; Moon et al., 2017) but no discernible variations in melt rates with distance from the parent glacier.

To examine the depth-dependency of iceberg melt rates, we first sorted the icebergs according to their median draft. After parsing the icebergs into 50 m-increment draft bins, we calculated the medians of all the area-averaged melt rate estimates (hereafter the median melt rate) and draft estimates in each bin. Figure 3 shows the binned median melt rates and drafts for each study site. For all study sites, the median melt rates are generally smaller for icebergs in the upper ~200 m of the water column than those that penetrate to greater depths (Fig. 3a, Figs. 3b-h). The depth-dependency of iceberg melt rates is particularly pronounced for icebergs calved from the Upernavik glaciers (Fig. 3d) and Jakobshavn Isbræ (Fig. 3e) in the central west. For Upernavik, the median melt rate increases from the surface down to ~150 m-depth, decreases slightly over the 150-200 m depth range, then increases again below 200 m-depth. For Jakobshavn, the median melt rate increases from the surface down to ~150 m-depth, decreases down to ~250 m-depth, then increases again down to 350 m-depth. Although there is an apparent decrease in the melt rate below 350 m-depth, this melt estimate is from one observation in March 2011 when melt rates were particularly low, as discussed more below. The dip in melt rates at ~200 m-depth coincides with the approximate depth of the interface between the colder near-surface waters and warmer sub-surface waters observed in Jakobshavn's fjord (Ilulissat Isfjord) (Gladish et al., 2015) and the Upernavik fjord system (Fenty et al., 2016), where water velocities should be relatively slow and turbulent melting should reach a local minimum (Moon et al., 2017). These observations suggest that our remote sensing method may be capable of resolving the depth of the near- and sub-surface water interface where hydrographic observations are difficult or impossible to acquire, such as near the termini of calving glaciers. However, we caution that the area-averaged melt rates obtained using this approach likely under-estimate the trend of increasing melt rates with depth because of the integrative nature of our area-averaged melt rate estimates.

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3.3 Temporal Patterns

The stratification and circulation of water masses near Greenland's glacier termini likely vary over weekly to inter-annual time scales with changes in wind direction (Jackson et al., 2014), glacial meltwater discharged from the base of the glacier termini (Mortenson et al., 2011; Cowton et al., 2015), sea ice/ice mélange extent (e.g., Enderlin et al. (2016) and Shroyer et al. (2017)), and the properties of water masses advected along the continental shelf (Holland et al., 2008; Mortenson et al., 2011). To investigate potential temporal variations in iceberg melt rates, we parsed our observations according to their observation periods and computed the median melt rate and median draft for each draft bin over the individual observation periods (Fig. 4). Our data suggest that across all study sites there were neither substantial seasonal nor inter-annual changes in melt rate during 2011-2016, though limited observations from Jakobshavn's fjord (discussed below) demonstrate that the lack of a coherent temporal signal across all study sites does not preclude the existence of temporal variations.

Our finding that, overall, there is no seasonal or inter-annual variation is in contrast to empirical melt estimates, which suggest there should be pronounced seasonal differences in iceberg melt rates (Mugford and Dowdeswell, 2010) primarily due to the strong dependency of iceberg melting on water velocities (Bigg et al., 1997; FitzMaurice et al., 2016; FitzMaurice et al., 2017). The lack of substantial coherent temporal variability in our iceberg melt rate estimates may be influenced by a number of factors. First, the number of repeat DEMs and timing of DEM acquisitions varies substantially from year-to-year and between study sites, making it difficult to infer seasonal and inter-annual patterns from our dataset. Second, our remotely-sensed melt rates integrate variations in melt rate with depth and over the time interval between DEM acquisition dates. The depth integration likely has little influence on shallow-drafted icebergs that are bathed in relatively homogeneous water but may substantially reduce the melt rates for deep-drafted icebergs, as previously mentioned. The time-integrative nature of our remotely-sensed melt rates means that high-frequency variations in iceberg melting are smoothed-out. Temporal smoothing is likely to be particularly important during the seasonal transition from winter conditions (i.e., expansive sea ice, little subglacial meltwater discharge, synoptic-scale changes in fjord circulation) to summer conditions (i.e., open water with fjord circulation driven by subglacial discharge) (Jackson et al., 2014), which may lead to rapid changes in submarine melt rates. Finally, uncertainties in the melt rate estimates introduced by observational uncertainties, particularly uncertainty in the submerged iceberg shape, may also partially obscure temporal variations in iceberg melting over seasonal to inter-annual time scales. While our results here validate our use of time-averaged melt rates in the spatial analyses presented above, further research on temporal variations in iceberg melt is necessary to determine whether changes in iceberg meltwater fluxes over time have an appreciable impact on local-to-regional ocean circulation, motivating the need for more detailed time series of iceberg melt rates around Greenland.

Despite the limited ability of our remotely-sensed iceberg melt estimation method to detect seasonal to inter-annual iceberg melt rate variations over the relatively long, irregular observation periods typically available from WorldView DEMs, our results indicate that the method is capable of detecting abrupt changes in iceberg melting when the DEM repeat interval is short and coincides with large changes in iceberg melt conditions. Melt rates compiled for icebergs calved from Jakobshavn Isbræ indicate that there was a nearly four-fold increase in deep-drafted iceberg melt rates in Ilulissat Isfjord between late March and early April 2011 (Fig. 5). This rapid increase in iceberg melting coincided with the appearance of distinct lateral shear margins in the April 6th WorldView image of the fjord's extensive ice mélange, which were not present in a March 19th WorldView image. Surface air temperatures observed at the closest on-ice automatic weather station (673 m a.s.l.; 67.097°N, -49.933°E) lapsed to sea level indicate that regional air temperatures were well below freezing (daily mean temperatures <-10°C) for 20 of 24 days between the image acquisitions; thus, the appearance of the shear margins cannot be easily explained by surface melting. We suggest that shear margins instead appeared as a result of abrupt mélange motion away from the terminus during a large calving event. Seismic data recorded in Ilulissat, at the fjord mouth, confirm that the earliest large-scale calving event of 2011 occurred on April 3rd, 3 days prior to the beginning of our second observation period.

Based on the large change in deep-drafted melt rates and coincident onset of seasonal calving, we hypothesize that iceberg over-turning during the calving event altered the stratification and circulation of the fjord water masses, which rapidly increased iceberg melt rates at depth. Although the size of the calving event and the degree of mixing within the water column are unknown, laboratory experiments of iceberg over-turning indicate that the amount of energy released during a large calving event is far more than enough to entirely mix the water column within 1 km of Jakobshavn's terminus (Burton et al., 2012). To assess whether mixing-induced changes in water temperature or velocity was the more likely driver of the observed change in melt rate, we turn to the thermodynamic equations of submarine melting. Turbulent melting due to horizontal water shear past an iceberg is estimated as

$$\dot{m}_{turbulent} = 0.58v^{0.8}\frac{T_{sw}-T_i}{L^{0.2}}, \quad (3)$$

and buoyancy-driven melting is

$$\dot{m}_{buoyant} = (7.62\times10^{-3})T_{sw} + (1.29\times10^{-3})T_{sw}^2, \quad (4)$$

where v is the relative water velocity (i.e. water velocity with respect to the iceberg velocity), T_{sw} and T_i are the temperature of the sea water and ice, respectively, and L is the iceberg length. In the absence of changes in relative velocity, variations in water temperature within the range observed in Ilulissat Isfjord (Gladish et al., 2015) are insufficient to drive the four-fold increase in deep-drafted melt rates. However, for an ice temperature of -5°C (Vieli and Nick, 2011) and a water temperature of 2°C (Gladish et al., 2015), the relative velocity would need to increase from an average of approximately 0.06 m/s to 0.31 m/s to increase the turbulence-driven melt rate of large (~500 m-long) icebergs from ~0.12m/d to ~0.46m/d. The persistent ice mélange near the Jakobshavn terminus prevents acquisition of the water temperature and velocity time series required to test this hypothesis. However, water velocity data from Sermilik Fjord in southeast Greenland suggest that velocities of ≥0.3 m/s (Jackson et al., 2014) are possible in Greenland's deep glacial fjords. Moreover, given the mostly below-freezing air temperatures observed over this period of rapid change, it is unlikely that the inferred changes in fjord circulation were triggered by the seasonal onset of glacier meltwater-enhanced subglacial discharge at depth in the fjord. Therefore, we interpret the four-fold increase in melt rates as an indication that full-thickness calving events from large glacier termini may significantly alter the hydrographic properties of Greenland's glacial fjords, with a measurable influence on iceberg melt.

4 Conclusions

Here we apply a remote sensing method to construct submarine melt rate and meltwater flux time series for icebergs calved from seven large marine-terminating outlet glaciers spanning the Greenland Ice Sheet edge. We find that for each study site, the meltwater flux from icebergs can be reasonably approximated as a linear function of the submerged iceberg area. Differences in the rate of iceberg melting between study sites generally follow expected geographic patterns based on variations in ocean temperature and surface meltwater runoff from the ice sheet, with the highest melt rates in the southeast, decreasing melt rates with increasing latitude along the west coast, and the lowest melt rates in the northeast. We hypothesize that deviations from the expected latitudinal patterns are due to variations in the prevalence of icebergs and/or near-terminus water circulation associated with different fjord geometries, emphasizing the potential importance of Greenland fjord geometry on iceberg (and glacier) melt rates.

At finer spatial scales, our observations support the expected depth-dependency of iceberg melt rates in the highly-stratified water fringing Greenland: at each study site, melt rates are low and fairly uniform down to ~200 m-depth then gradually increase down to ~350 m below the sea surface. Although our melt rate time series across all study sites do not reveal

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coherent temporal variations in melting, observations compiled for Jakobshavn Isbræ's fjord suggest that abrupt changes in melt conditions do occur. Furthermore, these changes at depth can potentially be monitored using the remote sensing approach applied here. The data compiled for Jakobshavn Isbræ also suggest that full-thickness calving events may be important for fjord circulation and iceberg melt, though additional melt rate estimates with ~weekly temporal resolution, possibly from terrestrial laser scanner or unmanned aerial vehicle observations, are required to test the effect of calving on sub-surface melt conditions.

Overall, we conclude that the DEM-differencing approach provides an excellent means to quantify spatial variations in iceberg melting and potentially resolve rapid temporal changes in iceberg melting when elevation observations with short repeat intervals are available. Quantification of iceberg melt rates around Greenland, and beyond, will enable the construction of more accurate ice sheet freshwater flux boundary conditions in ocean models and an improved understanding of the impacts of terrestrial ice mass loss on ocean circulation. Furthermore, if spatial and temporal patterns in iceberg melting can be linked to variations in water temperature and/or velocity, then remotely-sensed iceberg melt rates may be useful for inferring changes in iceberg and glacier melt conditions in glacial fjords in the absence of in situ hydrographic observations.

Data Availability

The location, median surface elevation, surface elevation uncertainty, and vertical co-registration for each observation date and estimates of the ice volume change rate, uncertainty in the ice volume change rate, average draft, range in draft, average surface area, range in surface area, average submerged area, and range in submerged area between observation dates for all icebergs in our analysis can be accessed at https://arcticdata.io/catalog/#view/doi:10.18739/A20N7C.

Author Contributions

E.M.E. developed the methods used to extract iceberg melt data from WorldView digital elevation models, extracted data for two study sites, supervised data extraction performed by coauthors, compiled and analyzed the data, and wrote the manuscript. C.J.C., W.H.K., and A.C. compiled satellite images, constructed digital elevation models, and extracted iceberg melt data for five study sites. T.M. assisted with manuscript preparation and revisions. G.S.H. assisted with method development.

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References

Bamber, J., van den Broeke, M., Ettema, J., Lenaerts, J., and Rignot E.: Recent large increases in freshwater fluxes from Greenland in the North Atlantic, Geophys. Res. Lett., 39, L19501, doi:10.1029/2012GL052552, 2012.

Bendtsen, J., Mortensen, J., Lennert, K., and Rysgaard, S.: Heat sources for glacial ice melt in a west Greenland tidewater outlet glacier fjord: The role of subglacial freshwater discharge, Geophys. Res. Lett., 42, doi:10.1002/2015GL063846, 2015.

Bigg, G. R., Wadley, M. R., Stevens, D. P., and Johnson, J. A.: Modelling the dynamics and thermodynamics of icebergs, Cold Regions Sci. Tech., 26, 113-135, 1997.

Burton, J. C., Amundson, J. M., Abbot, D. S., Boghosian, A., Cathles, L. M., Correa-Legisos, S., Darnell, K. N., Guttenberg, N., Holland, D. M., and MacAyeal, D. R.: Laboratory investigations of iceberg capsize dynamics, energy dissipation and tsunamigenesis, J. Geophys. Res., 117, F01007, doi:10.1029/2011JF002055, 2012.

Cowton, T., Slater, D., Sole, A., Goldberg, D., and Nienow, P.: Modeling the impact of glacial runoff on fjord circulation and submarine melt rate using a new subgrid-scale parameterization for glacial plumes, J. Geophys. Res.: Oceans, 120, 796-812, doi:10.1002/2014JC010324, 2015.

Enderlin, E.: Greenland Icebergs: WorldView Digital Elevation Model derived Melt Data, 2011-2016, Arctic Data Center, doi:10.18739/A20N7C, 2017.

Enderlin, E. M., and Hamilton, G. S.: Estimates of iceberg submarine melting from high-resolution digital elevation models: applications to Sermilik Fjord, East Greenland, J. Glaciol., 60, 224, 1084-1092, doi:10.3189/2014GoJ14J085, 2014.

Enderlin, E. M., Howat, I. M., Jeong, S., Noh, M.-J., van Angelen, J., and van den Broeke, M. R.: An improved mass budget for the Greenland Ice Sheet, Geophys. Res. Lett., 41, 866-872, doi:10.1002/2013GL059010, 2014.

Enderlin, E. M., Hamilton, G. S., Straneo, F., and Sutherland, D. A.: Iceberg meltwater fluxes dominate the freshwater budget in Greenland's iceberg-congested glacial fjords, Geophys. Res. Lett., 43, 11287-11284, doi:10.1002/2016GL070718, 2016.

Fenty, I., Willis, J. K., Khazendar, A., Dinardo, S., Forsberg, R., Fukumorim I., Holland, D., Jakobsson, M., Moller, D., Morison, J., Münchow, A., Rignot, E., Schodlok, M., Thompson, A. F., Tinto, K., Rutherford, M., and Trenholm, N.: Oceans Melting Greenland: Early results from NASA's ocean-ice mission in Greenland, Oceanog., 29, 4, 72-83, doi:10.5670/oceanog.2016.100, 2016.

FitzMaurice, A., Straneo, F., Cenedese, C., and Andres, M.: Effect of a sheared flow on iceberg motion and melting, Geophys. Res. Lett., 43, 12520-12527, doi:10.1002/2016GL071602, 2016.

FitzMaurice, A., Cenedese, C., and Straneo, F.: Nonlinear response of iceberg side melting to ocean currents, Geophys. Res. Lett., 44, 5637-5644, doi:10.1002/2017GL073585, 2017.

Gladish, C. V., Holland, D. M., Rosing-Asvid, A., Behrens, J. W., and Boje, J.: Oceanic boundary conditions for Jakobshavn Glacier. Part I: Variability and renewal of Ilulissat Icefjord Waters, 2001-14, J. Phys. Ocean., 45, 3-32, doi:10.1175/JPO-D-14-0044.1, 2015.

Holland, D. M., Thomas, R. H., de Young, B., Ribergaard, M. H., and Lyberth, B.: Acceleration of Jakobshavn Isbræ triggered by warm subsurface ocean waters, Nature Geosci., 1, 659-664, doi:10.1038/NGEO316, 2008.

Jackson, R. H., and Straneo, F.: Heat, salt, and freshwater budgets for a glacial fjord in Greenland, *J. Phys. Ocean.*, doi:10.1175/JPO-D-15-0134, 2016.

Jackson, R. H., Straneo, F., and Sutherland, D. A.: Externally forced fluctuations in ocean temperature at Greenland glaciers in non-summer months, Nature Geosci., 7, 503-508, doi:10.1038/NGEO2186, 2014.

Luo, H., Castelao, R. M., Rennermalm, A. K., Tedesco, M., Bracco, A., Yager, P. L., and Mote, T. L.: Oceanic transport of surface meltwater from the southern Greenland Ice Sheet, Nature Geosci., 9, 528-532, doi:10.1038/NGEO2708, 2016.

Moon, T., Sutherland, D. A., Carroll, D. Felikson, D., Kehrl, L., and Straneo, F.: Subsurface iceberg melt key to Greenland fjord freshwater budget, Nature Geosci., in press, 2017.

Mortsenson, J., Lennert, K., Bendtsen, J., and Rysgaard, S.: Heat sources for glacial melt in a sub-Arctic fjord (Godthåbsfjord) in contact with the Greenland Ice Sheet, J. Geophys. Res., 116, C01013, doi:10.1029/2010JC006528.

Mugford, R. I., and Dowdeswell, J. A.: Modeling iceberg-rafted sedimentation in high-latitude fjord environments, J. Geophys. Res., 115, F03024, doi:10.1029/2009JF001564, 2010.

Noh, M. J., and Howat, I. M.: Automated stereo-photogrammetric DEM generation at high latitudes: Surface Extraction with TIN-based Search-space Minimizations (SETSM) validation and demonstration over glaciated regions, GISci. Remote Sens., doi:10.1080/15481603.2015.1008621, 2015.

Sciascia, R., Straneo, F., Cenedese, C., and Heimbach, P.: Seasonal variability of submarine melt rate and circulation in an East Greenland fjord, J. Geophys. Res. Oceans, 118, 2492-2506, doi:10.1002/jgrc.20142, 2013.

Shean, D. E., Alexandrov, O., Moratto, Z. M., Smith, B. E., Joughin, I. R., Porter, C., and Morin, P.: An automated, open-source pipeline for mass production of digital elevation models (DEMs) from very-high-resolution commercial stereo satellite imagery. *ISPRS J. Photogram. Remote Sensing* 116, 101-117. doi: 10.1016/j.isprsjprs.2016.03.012, 2016.

Shroyer, E. L., Padman, L., Samelson, R. M., Münchow, A., and Stearns, L. A.: Seasonal control of Petermann Gletscher ice-shelf melt by the ocean's response to sea-ice cover in Nares Strait, J. Glaciol., 63, 324-330, doi:10.1017/jog.2016.140, 2017.

Stern, A. A., Adcroft, A., and Sergienko, O.: The effects of Antarctic iceberg calving-size distribution in a global climate model, J. Geophys. Res. Oceans, 121, 5773-5788, doi:10.1002/2016JC011835, 2016.

Straneo, F., Sutherland, D. A., Holland, D., Gladish, C., Hamilton, G. S., Johnson, H. L., Rignot, E., Xu, Y., and Koppes, M.: Characteristics of ocean waters reaching Greenland's glaciers, Ann. Glaciol, 53, 60, doi:10.3189/2012AoG60A059, 2012.

Sulak, D. J., Sutherland, D. A., Enderlin, E. M., Stearns, L. A., and Hamilton, G. S.: Iceberg properties and distributions in three Greenlandic fjords using satellite imagery, Ann. Glaciol., 1-15, doi:10.1017/aog.2017.5, 2017.

Sutherland, D. A., Straneo, F., Stenson, G. B., Davidson, F. J. M., Hammill, M. O., and Rosing-Asvid, A.: Atlantic water variability on the SE Greenland continental shelf and its relationship to SST and bathymetry, J. Geophys. Res.: Oceans, 118, 847-855, doi:10.1029/2012JC008354, 2013.

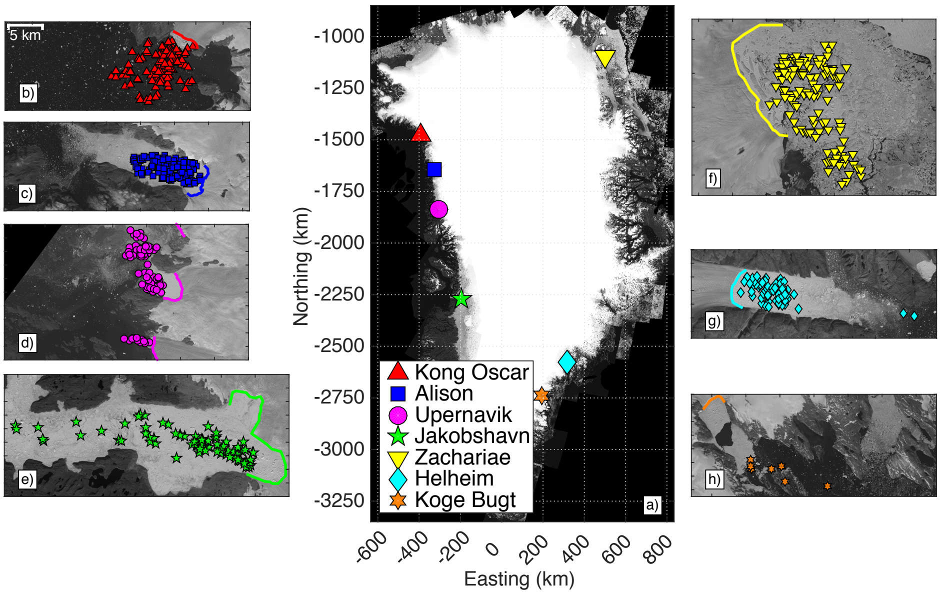
Sutherland, D. A., Straneo, F., and Pickart, R. S.: Characteristics and dynamics of two major Greenland glacial fjords, J. Geophys. Res. Oceans, 119, 3767–3791, doi:10.1002/ 2013JC009786, 2014.

van Angelen, J. H., van den Broeke, M. R., Wouters, B., and Lenaerts, J. T. M.: Contemporary (1960-2012) Evolution of the Climate and Surface Mass Balance of the Greenland Ice Sheet, Surv. Geophys., 35, 1155-1174, doi:10.1007/s10712-103-9261-z, 2014.

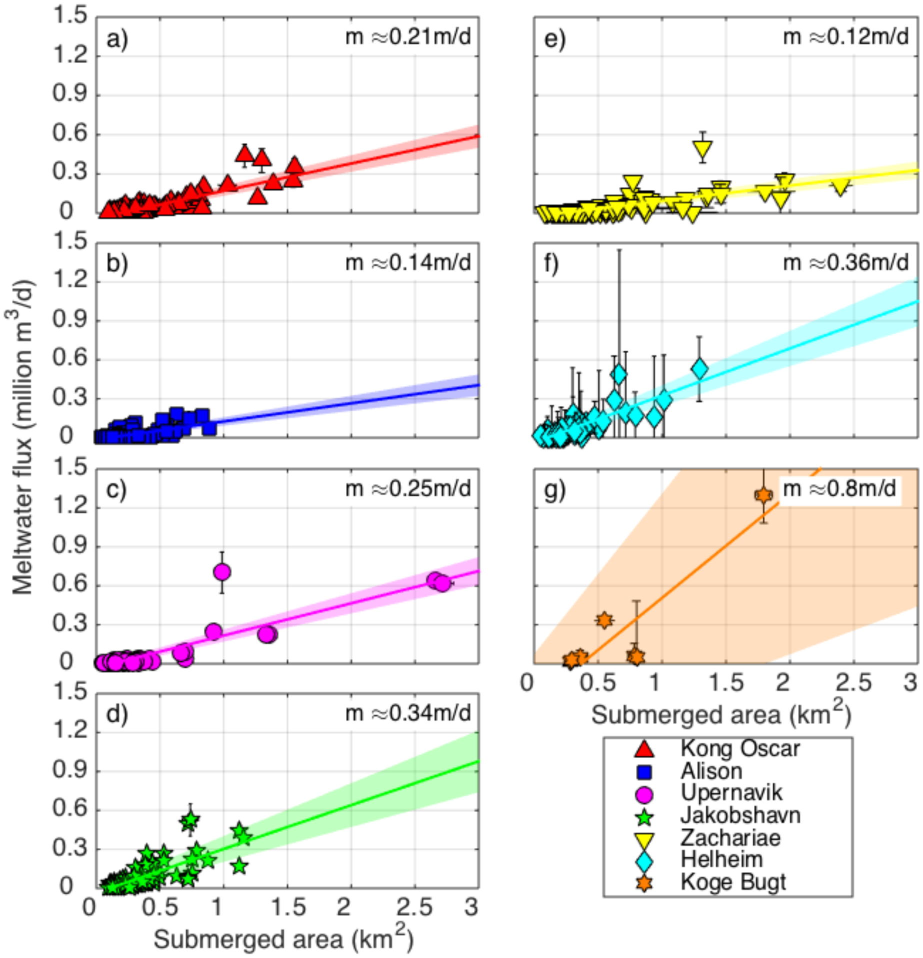
van den Broeke, M. R., Enderlin, E. M., Howat, I. M., Munneke, P. K., Noël, B. P. Y., van de Berg, W. J., van Meijgaard, E., and Wouters, B.: On the recent contribution of the Greenland Ice Sheet to sea level change, The Cryosphere, 10, 1933-1946, doi:10.5194/tc-10-1933-2016, 2016.

van Meijgaard, E., van Ulft, L. H., van de Berg, W. J., Bosveld, F. C., van den Hurk, B., Lenderink, G., and Siebesma, A. P.: The KNMI regional atmospheric climate model RACMO version 2.1, De Bilt, 2008.

Vieli, A., and Nick, F.: Understanding and modelling rapid dynamic changes of tidewater outlet glaciers: Issues and implications, Surv. Geophys., 32, 437-458, doi:10.1007/s10712-011-9132-4, 2011.



5 **Figure 1: Location of Greenland icebergs included in this study. (a) The locations of the glaciers from which the icebergs calved overlain on the GIMP image mosaic. The different iceberg sources are distinguished by symbol color and shape (see legend). (b-h) Locations of all study icebergs overlain on summer 2016 Landsat 8 panchromatic images of (b) Kong Oscar Glacier, (c) Alison Glacier, (d) Upernavik Glacier, (e) Jakobshavn Isbræ, (f) Zachariæ Isstrøm, (g) Helheim Glacier, and (h) Koge Bugt Glacier. The same scale, shown in panel b, is used in panels b-h. Termini of the icebergs' glacier sources are delineated with colored lines in panels b-h.**



5 **Figure 2: Liquid freshwater fluxes (millions of cubic meters per day) plotted against the estimated submerged area (square kilometers) for all icebergs sampled near the terminus of (a) Kong Oscar Glacier, (b) Alison Glacier, (c) Upernavik Glacier, (d) Jakobshavn Isbræ, (e) Zachariæ Isstrøm, (f) Helheim Glacier, and (g) Koge Bugt Glacier. Vertical error bars indicate the meltwater flux uncertainties due to random DEM errors, ice density uncertainties, surface meltwater flux uncertainties, and manual iceberg delineation errors. Horizontal error bars indicate the range of submerged iceberg areas predicted for cylindrical submerged geometries using surface elevation and map-view surface area estimates extracted from repeat DEMs. Linear polynomials fit to the datasets compiled for each study site are plotted as thick colored lines and the surrounding shaded envelopes encompass their 95% confidence intervals.**

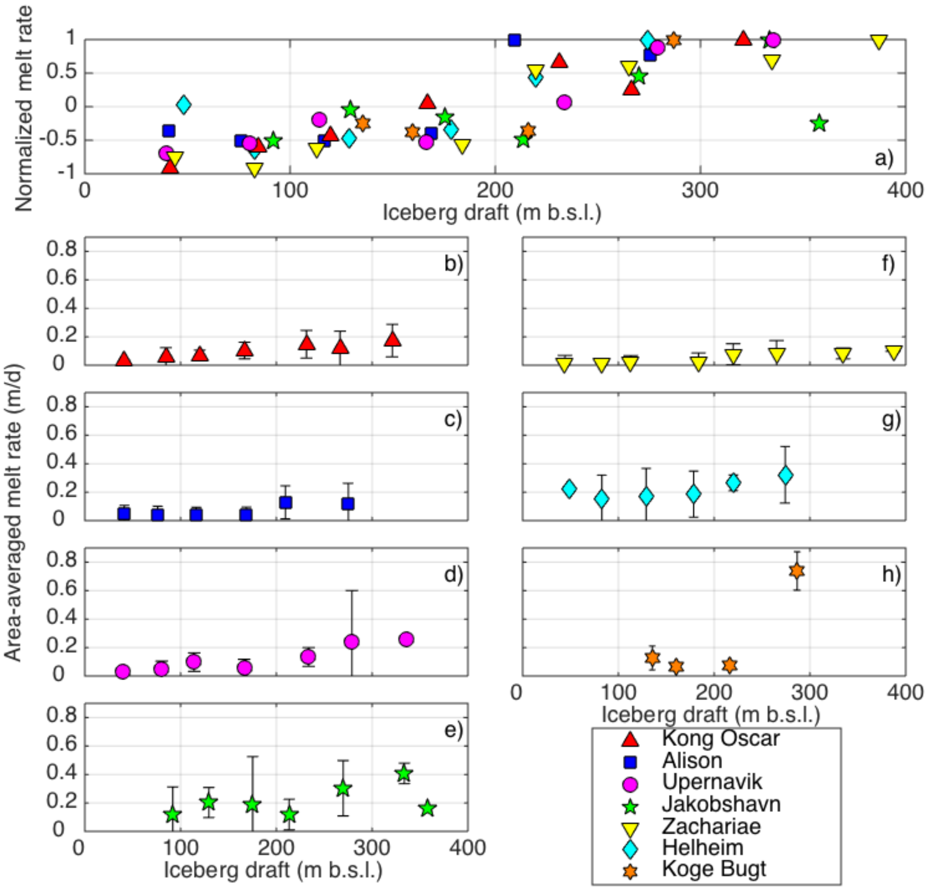


Figure 3: Plots of melt rate variability with draft. (a) Normalized melt rate plotted against median draft (meters below sea level). Normalized melt rates less than zero are below the observed average and values greater than zero indicate above-average melt rates. (b-h) Area-averaged melt rate (meters per day) plotted against median draft (meters below sea level) for icebergs near the terminus of (b) Kong Oscar Glacier, (c) Alison Glacier, (d) Upernavik Glacier, (e) Jakobshavn Isbræ, (f) Zachariæ Isstrøm, (g) Helheim Glacier, and (h) Koge Bugt Glacier. In all panels, icebergs are sorted into 50 m-increment draft bins and the symbols mark the median values for each draft bin. In (b-h), vertical error bars bound the range of melt rates.

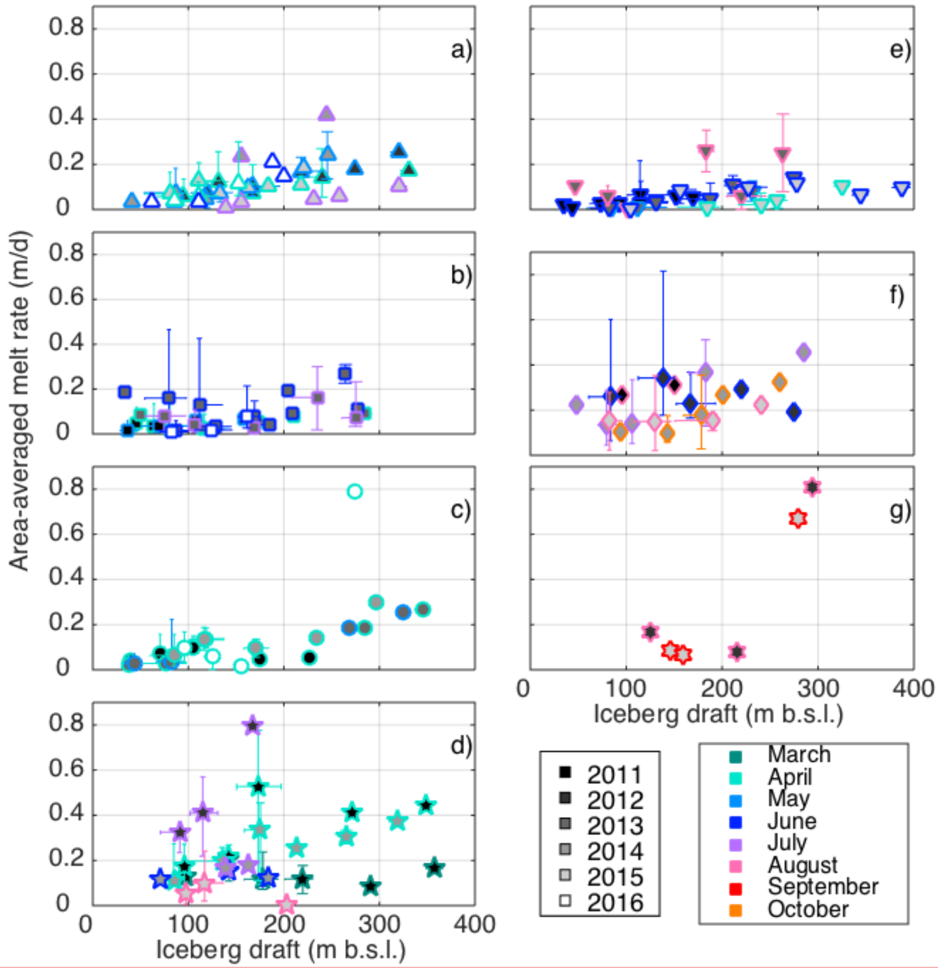


Figure 4: Area-averaged iceberg melt rate (meters per day) plotted against median draft (meters below sea level) for icebergs sampled near the terminus of (a) Kong Oscar Glacier, (b) Alison Glacier, (c) Upernavik Glacier, (d) Jakobshavn Isbræ, (e) Zachariæ Isstrøm, (f) Helheim Glacier, and (g) Koge Bugt Glacier. For each observation period, icebergs were organized into 50 m-deep draft bins and the median melt rate and draft were computed. The symbols mark the median values and the error bars mark the range of estimates for each draft bin. The face colors and edge colors of the symbols indicate the year and month of the observations, respectively (see legends).

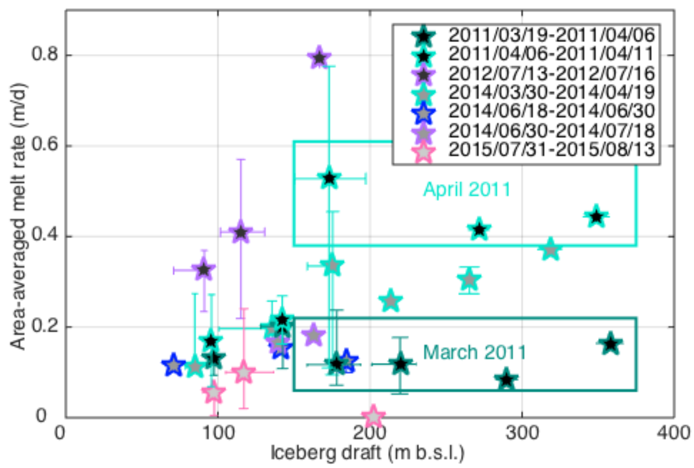


Figure 5: Area-averaged submarine melt rates plotted against median draft for icebergs calved from Jakobshavn Isbræ, west Greenland, into Ilulissat Isfjord. As in Figure 4, the symbols mark the median values and the error bars mark the range of estimates for each draft bin. The face colors and edge colors of the symbols indicate the year and month of the observations, respectively, as described in the legend. Deep melt rate estimates for the time period of rapid, significant change are circled for emphasis.

Glacier	Year	Period	Observations	ΔV/Δt = f(Asub)
Alison	2011	03/25-04/11	19	0.140A-13878 (R = 0.69 & RMSE = 24120)
		04/11-06/10	24	
	2013	04/10-05/12	16	
		05/12-06/22	18	
		06/22-07/07	25	
		07/07-07/22	22	
	2016	05/08-07/14	16	
Helheim	2011	08/21-08/24	3	0.363A-37746 (R = 0.84 & RMSE = 53704)
	2012	06/24-06/29	18	
	2014	07/02-07/31	20	
		10/16-10/30	14	
	2015	08/10-08/16	16	
Jakobshavn	2011	03/19-04/06	22	0.338A-34434 (R = 0.74 & RMSE = 74454)
		04/06-04/11	14	
	2012	07/13-07/16	13	
	2014	03/30-04/19	19	
		06/18-06/30	6	
		06/30-07/18	3	
	2015	07/31-08/13	8	
Koge Bugt	2012	08/09-08/13	4	0.803A-295723 (R = 0.91 & RMSE = 219609)
	2015	08/30-09/16	3	
Kong Oscar	2012	04/14-04/26	22	0.209A-38413 (R = 0.85 & RMSE = 40447)
		04/26-06/11	20	
	2014	05/04-06/13	18	
		06/13-08/04	3	
	2015	04/06-04/19	13	
		05/12-06/11	13	
		06/11-08/12	7	
	2016	03/18-05/19	16	
		05/19-07/20	4	
Upernavik	2011	03/26-04/12	21	0.248A-31052 (R = 0.88 & RMSE = 61611)
	2013	04/12-04/30	17	
		04/30-06/03	16	
	2014	03/28-04/17	20	
	2016	04/16-04/27	9	
Zachariae	2011	05/31-06/08	21	0.118A-23772 (R = 0.75 & RMSE = 43816)
		06/08-07/10	24	
	2013	04/01-06/05	23	
		06/05-07/25	27	
		07/25-08/10	15	
	2015	04/01-05/01	17	
		06/02-07/02	9	

Table 1: (column 1) Glacier names, (columns 2-3) observation periods, (column 4) number of observations, and (column 5) meltwater flux parameterizations. In column 5, the correlation coefficients and root mean square error estimates for the linear area-based meltwater flux parameterizations are also provided.