Sensitivity of geodetic glacier mass balance estimation to DEM void interpolation

Robert McNabb[1], Christopher Nuth[1], Andreas Kääb[1], and Luc Girod[1]

[1]Department of Geosciences, University of Oslo, Postboks 1047 Blindern, 0316 Oslo, Norway

Correspondence: Robert McNabb (robert.mcnabb@geo.uio.no)

Abstract. Glacier mass balance is a direct expression of climate change, with implications for sea level, ocean chemistry, oceanic and terrestrial ecosystems, and water resources. Traditionally, glacier mass balance has been estimated using in-situ measurements of changes in surface height and density at select locations on the glacier surface, or by comparing changes in surface height using repeat, full-coverage digital elevation models (DEMs), also called the geodetic method. DEMs often have gaps in coverage ("voids") based on the nature of the sensor used and the surface being measured. The way that these voids are accounted for has a direct impact on the estimate of geodetic glacier mass balance, though a systematic comparison of different proposed methods has been heretofore lacking. In this study, we determine the impact and sensitivity of void-filling methods on estimates of volume change. Using two spatially complete, high-resolution DEMs over Southeast Alaska, USA, we compare 11 different void-filling methods on a glacier-by-glacier and regional basis. We find that a few methods introduce biases of up to 20% in the regional results, while other methods give results very close (<1% difference) to the true, non-voided volume change estimates. Finally, we independently show using ASTER DEMs that some of best-performing methods are more robust than others, depending on the properties of the original DEMs, and therefore recommend that studies compare a few of these methods to estimate the uncertainty introduced by filling DEM voids.

1 Introduction

Glacier mass balance responds directly to climatic influences, and therefore long-term records of glacier mass balance reflect changes in climate. Traditional estimates of glacier mass balance have involved *in-situ* seasonal or annual measurement of the changes in surface height and density at select locations, and extrapolation of these sparse measurements to the entire glacier (the glaciological method; see, e.g., Cogley, 2009). This provides a temporally dense time series for an individual glacier, but for very large glaciers or at regional scales, it is neither practical nor even possible. As of June 2018, the World Glacier Monitoring Service has mass balance measurements for only 450 of the more then 200,000 glaciers worldwide. More recently, glacier mass balance is calculated over longer time spans and with larger spatial coverage by differencing remotely sensed surface elevation measurements of glaciers. Integrating these differences over the glacier basin produces an estimate of volume change. With careful consideration of the multi-annual surface change of snow, firn, and ice composition (e.g., Huss, 2013), this so-called geodetic approach provides the total mass change of a glacier. Unlike the glaciological method, the geodetic method does not require extrapolation of sparse measurements to the entire glacier surface, and thereby can be used to calibrate and/or

validate time series of mass balance measurements that have been obtained through the glaciological method (Elsberg et al., 2001; Zemp et al., 2010, 2013; Andreassen et al., 2016). With the current increase in the number of available, accurate Digital Elevation Models (DEMs) derived from airborne and in particular space-borne sensors, measurements of glacier mass balance using the geodetic method are and will be more prevalent, providing proper spatial accounting of the glacier water resources
5 on the planet.

In this study, we focus on the estimation of geodetic mass balance from Digital Elevation Models. In general, wide coverage DEMs are created from sensors on aerial or satellite platforms falling into two categories, optical and radar. DEMs derived from optical sensors have the advantage of measuring the snow and ice surface directly, but data availability is subject to weather and light conditions, which can often be cloudy or dark in most glaciated regions around the globe. In addition, low-contrast
10 areas on glacier surfaces, such as in the accumulation area, can often result in missing data or data voids. DEMs derived from radar sensors are weather- and illumination-independent, as the active sensor acquires data even through cloud cover and polar night. However, glaciers tend to occur in areas with steep and/or rough topography, and layover and shadow can confound efforts to unwrap elevations on glaciers (e.g., Rignot et al., 2001; Shugar et al., 2010). In addition, radar signals penetrate snow and ice differently, depending on the properties of the surface, as well as the frequency of the signal; this penetration
15 results in a spatio-temporal systematic bias in surface measurement that is still poorly understood and constrained (e.g., Rignot et al., 2001; Dall et al., 2001; Gardelle et al., 2012; Dehecq et al., 2016). DEMs derived from airborne laser scanning (e.g., Geist et al., 2005; Abermann et al., 2010; Andreassen et al., 2016) are highly accurate, spatially complete, and mostly avoid the penetration issues associated with radar-derived DEMs. Such DEMs are expensive to produce, however, and have similar requirements as optical sensors and aerial photography, i.e., clear sky or high clouds, conditions that can be difficult to find
20 over glaciers.

In the most ideal scenarios to calculate geodetic mass balances from repeat DEM differencing, the entire glacier would be sampled systematically and with similar accuracy. In the most commonly used DEMs for glacier mass balance described above, zones of missing data (hereafter called "voids") are rather common, and may severely bias estimates depending upon how these regions are accounted for (e.g., Kääb, 2008; Berthier et al., 2018). Several different methods have been applied in the
25 literature, and we briefly summarize them here. They include bilinear interpolation of elevation or elevation differences (e.g., Kääb, 2008); filling with an average value from a surrounding neighborhood (e.g., Melkonian et al., 2013, 2014); multiplying a mean value by glacier-covered area (e.g., Surazakov and Aizen, 2006; Paul and Haeberli, 2008; Fischer et al., 2015); and estimating elevation change as a function of elevation, and either integrating this curve with the glacier hypsometry directly or using it to fill unsurveyed values (e.g., Arendt et al., 2002, 2006; Kohler et al., 2007; Berthier et al., 2010; Kronenberg et al.,
30 2016). In addition, we can classify these methods into "global" and "local" types, where "global" methods use data from an entire region or group of glaciers, while "local" methods fill voids using only information from an individual glacier basin, or from data closely surrounding the voids.

While various methods are used in individual studies, the sensitivity of geodetic mass balance estimates to various interpolation methods is not clear. An overarching comparison of the numerous methods is lacking, and their subsequent effects
35 on volume change estimates at both local and regional scales. In this paper, we use two high-quality, radar-derived DEMs.

Biases in the volume change estimates exist due to differences in seasonal timing and radar penetration; as such, the estimates presented here should not be interpreted as mass balance estimates for these glaciers. We apply 11 different methods to fill artificially-produced voids in this spatially complete DEM difference pair, and compare the resulting estimates of volume change glacier-by-glacier and regionally to determine the potential impact and sensitivity on volume change estimates. This study aims to quantify the effects of different void-handling approaches, and to suggest the void-handling methods best suited for accurate volume change estimation.

2 Data

2.1 Study Area

To test the impact of void-filling methods on estimates of volume change, we chose the area surrounding Glacier Bay and Lynn Canal, Alaska, USA (Fig. 1). This area contains over 700 individual glacier basins (Randolph Glacier Inventory (RGI) v6.0; Pfeffer et al., 2014; RGI Consortium, 2017), with glaciers ranging from sea level to over 4000 m a.s.l. Additionally, the region is home to a wide range of glacier types, including surge-type glaciers, retreating (and advancing) tidewater glaciers, and both large and small valley glaciers. As such, it is an ideal region to estimate the effects of using spatially incomplete DEMs to estimate glacier volume changes, as it provides a diverse sample of glacier types, sizes, and altitude ranges.

2.2 DEMs

2.2.1 SRTM

We use the Shuttle Radar Topography Mission (SRTM) C-band global 1-arcsecond dataset as the reference DEM in this study. The SRTM was acquired in February 2000 aboard the Space Shuttle Endeavour, flying both C-band and X-band instruments (Van Zyl, 2001). This nearly global DEM is temporally consistent and therefore ideal and commonly used for geodetic mass balance estimation. We have selected this dataset, and not the US National Elevation Dataset (NED) as have other studies of the region (e.g., Arendt et al., 2002, 2006; Larsen et al., 2007; Berthier et al., 2010), as it was produced by digitizing 1948 USGS contour maps (Larsen et al., 2007) which contained large biases at higher elevations on glaciers (see, e.g., Arendt et al., 2002, *supplemental material*).

Owing to the nature of the instrument, the acquisition, and the topography in the region, there are holes/voids in the SRTM data on steep slopes due to shadowing and layover effects (e.g., Rignot et al., 2001). Filled SRTM products, such as the one distributed by CGIAR Consortium for Spatial Information (Jarvis et al., 2008), typically use the NED dataset to fill these gaps, which can introduce significant anomalies and discontinuities into the on-glacier elevations. As these holes are typically small and confined to the glacier margins in steep-sloped areas, we used the un-filled SRTM dataset and update glacier areas in our calculations (when necessary) to ignore these no-data regions, assuming they do not belong to the glacier. These original SRTM voids will thus not affect our sensitivity analysis on estimates of volume change.

2.2.2 IfSAR

As part of the Statewide Digital Mapping Initiative, the State of Alaska is producing an interferometric synthetic aperture radar (IfSAR) DEM of the entire state. The data are acquired from airborne radar operating in X-band and P-band, and are provided in a native resolution of 5 m mosaics. In our study area, flights were flown in summer 2012 and 2013. These data are available from the U.S. Geological Survey, see https://lta.cr.usgs.gov/IFSAR_Alaska. As of September 2017, 92% of the state has been covered through this initiative, with 57% of the statewide data available for download (https://nationalmap.gov/alaska/).

2.2.3 Glacier Outlines

We use the Randolph Glacier Inventory v6.0 data as a base to mask glacier basins (RGI Consortium, 2017). As the IfSAR DEMs are only available over Alaska, and not adjacent areas in British Columbia and Yukon, we have selected only glaciers that fall 90% or more by area within Alaska. Additionally, we have removed any glaciers that fall 10% by area or more in both collection years, in order to ensure that we are using temporally consistent data to estimate volume change. Finally, we remove any glacier basins that are smaller than $1 \, \text{km}^2$. This results in a total of 443 individual glacier basins used for the analysis.

3 Methods

We first calculate the "true" volume change by directly differencing the IfSAR and SRTM DEMs after co-registration following Nuth and Kääb (2011), and subsequently summing the elevation differences multiplied by pixel area within each glacier outline. Ordinarily, using DEMs derived from radar of different bands, especially those acquired in different seasons such as the SRTM (February) and IfSAR (typically August/September), would require a consideration of the effects of differential radar penetration in snow and ice, as well as a temporal correction accounting for the difference in season, before converting elevation changes to a mass balance value (Haug et al., 2009; Kronenberg et al., 2016). In this region, the SRTM is known to have particularly high levels of penetration that cause significant biases when used in geodetic mass balance calculations (Berthier et al., 2018). As our interest in this study is in isolating the effect of void interpolation methods on estimates of volume change, we ignore the differential penetration and temporal mismatch between our DEMs. We therefore highlight that biases will exist in the numbers provided in this study and do not recommend interpreting these relative estimates of glacier volume change.

3.1 Artificial Void Generation

In order to investigate the effects of filling voids, we first simulate voids in the IfSAR DEM to reflect the distribution and size of voids that might be expected in DEMs derived from optical stereo sensors. Correlation masks from 99 MicMac ASTER (MMASTER)-processed stereo scenes (Girod et al., 2017) provides the basis for void simulation as low correlation areas represent failure of the stereographic reconstruction and elevation determination. We thus use areas of low correlation in the

ASTER scenes to mimic voids, providing a way to ensure that our artificial voids are similar to what would normally be seen in DEMs derived from optical stereo sensors.

We average and mosaic the 99 ASTER correlation masks together, and select a mean correlation threshold of 0.5 to serve as the lower bound for acceptable correlations. This choice of threshold is based on a visual inspection of the mask produced,

5   and the desire to mimic the ASTER data as much as possible. To further investigate the effects of interpolation method on the estimates of volume change, we also increase the threshold to 0.7, comparing the differences for a select few interpolation schemes. For each threshold value, we apply the resulting mask to the IfSAR DEMs, producing voids as shown in Fig. 2.

3.2   Void Filling

The following is a brief summary of the different methods used to fill the artificially-generated voids in the DEM and dDEM

10   products. We have split the methods into three general categories, "constant" interpolation, "spatial" interpolation, and "hypsometric" interpolation.

3.2.1   Constant Methods

For the so-called "constant" interpolation methods, we calculate the mean (median) elevation differences of the non-void pixels for each glacier basin, then multiply this value by the area of the glacier basin, thereby obtaining an average volume change

15   for the glacier basin. Examples of this method in the literature include Surazakov and Aizen (2006); Paul and Haeberli (2008); Fischer et al. (2015).

3.2.2   Spatial Methods

1. *Interpolation of elevation*. This method, applied to the DEM containing voids (here, the IfSAR DEMs), interpolates raw elevation values of the surrounding pixels to fill voids. The resulting interpolated DEM is differenced from the

20   second DEM, followed by calculation of the volume changes. Examples of this approach can be found in Kääb (2008); Pieczonka et al. (2013); Pieczonka and Bolch (2015). Though Pieczonka and Bolch (2015) uses ordinary kriging to fill gaps, we choose to use linear interpolation because the voids over the glaciers are relatively small, and for further comparison with the results of Kääb (2008).

2. *Interpolation of elevation differences*. Two original, unfilled DEMs are differenced to create a DEM difference (dDEM).

25   Then, the voids in the dDEM are filled using bilinear interpolation. An example of this approach can be found in Kääb (2008); Zheng et al. (2018).

3. *Mean elevation difference in 1 km radius*. For each void pixel, we calculate the average elevation difference based on on-glacier pixels within a 1 km radius of the void pixel. Examples of this approach can be found in Melkonian et al. (2013, 2014).

3.2.3   Hypsometric Methods

The so-called "hypsometric" methods are based on the assumption that there is a relationship between elevation change and elevation. They can be further sub-divided into "global" and "local" approaches, depending on whether the mean is calculated using data from the entire region (i.e., "global") or for an individual glacier basin only (i.e., "local"). The global approach is often used by altimetry studies to extrapolate measurements from only a few glaciers to a regional scale (e.g., Arendt et al., 2002; Johnson et al., 2013; Nilsson et al., 2015).

1. *Mean (median) elevation difference by elevation bin.* Here, the original, unfilled DEMs are differenced, and the entire dDEM is binned according to the original elevation for each pixel within the glacier outlines. The mean (median) elevation difference for each bin is then calculated and multiplied by the area of each elevation bin to get a volume change. The sum of the volume change of each individual bin then gives the volume change for the glacier. This method is used by, e.g., Kääb (2008); Berthier et al. (2010); Gardelle et al. (2013); Papasodoro et al. (2015); Kronenberg et al. (2016); Brun et al. (2017); Dussaillant et al. (2018). If a glacier has an elevation range of 500 m or more, we use 50 m wide bins; otherwise we choose elevation bins that are 10% of the glacier elevation range.

2. *Polynomial fit to elevation difference by elevation bin.* The original, unfilled DEMs are differenced, and a polynomial is fit to the elevation differences as a function of the original elevation. This elevation curve is then integrated over the glacier hypsometery in order to calculate a volume change. Based on examples from the literature, such as Kääb (2008), we have chosen a third-order polynomial.

3.3   Uncertainties

To estimate the uncertainties in the true volume changes, we first co-register each DEM (SRTM, 2012 and 2013 IfSAR campaigns) to ICESat, using the method described by Nuth and Kääb (2011). We can then use the triangulation procedure described in Paul et al. (2017) to estimate the residual bias $\varepsilon_{\mathrm{bias}}$ after co-registering the DEMs to each other; i.e. the uncertainty in correcting the mean bias between the DEMs. We also estimate the combined random error in elevation, $\varepsilon_{\mathrm{rand}}$ by calculating the RMS difference of the population of dDEM pixels on stable ground. For each glacier, the error in volume change $\varepsilon_{\Delta V}$ can be estimated as:

$$\varepsilon_{\Delta V}^2 = (\varepsilon_{\Delta h} A)^2 + (\varepsilon_A \overline{\Delta h})^2, \tag{1}$$

with A the glacier area, ε_A the error in glacier area (here assumed to be 10%), and $\overline{\Delta h}$ the mean elevation change on the glacier. To account for spatial autocorrelation, as well as the two sources of uncertainty in the elevation differences ($\varepsilon_{\mathrm{bias}}$ and $\varepsilon_{\mathrm{rand}}$), $\varepsilon_{\Delta h}$ can be written:

$$\varepsilon_{\Delta h} = \frac{\sqrt{\varepsilon_{\mathrm{rand}}^2 + \varepsilon_{\mathrm{bias}}^2}}{\sqrt{n/(L/r)^2}}, \tag{2}$$

where n is the number of pixels (i.e., measurements) that fall within the glacier outline, L is the autocorrelation distance (here assumed to be 500 m), and r is the pixel size (30 m). Finally, we can combine equations (1) and (2) to obtain:

$$\varepsilon_{\Delta V} = \sqrt{\left(A \frac{\sqrt{\varepsilon_{\text{rand}}^2 + \varepsilon_{\text{bias}}^2}}{\sqrt{n/(L/r)^2}} \right)^2 + \left(\varepsilon_A \overline{\Delta h} \right)^2}. \tag{3}$$

4   Results and Discussion

4.1   Void Distribution

Fig. 3 shows the void and area frequency distributions per normalized glacier elevation bin and the mean and median elevation difference per normalized elevation bin. Most glaciers (73.6%, 329 glaciers) have a total void percentage below 20%, with only a small number (8%, 36 glaciers) having more than 40% voids. Voids are distributed similarly to glacier area with respect to normalized glacier elevation, and most of the voids, as well as most of the glacier area, are found in the middle third of the glacier elevation range. These void and area distributions, along with the range of elevation changes, suggests that the middle third of the glacier elevation range is the most important to ensure correct estimation; that is, uncertainties introduced by interpolating over voids in the upper and lower thirds of the elevation range will be muted, owing to the typically smaller areas and percentage of voids in these ranges.

4.2   Individual Glaciers

The initial, non-voided maps of elevation differences for the 2012 and 2013 IfSAR acquisition areas are shown in Fig. 4. In general, the pattern of elevation change is negative, especially at lower elevations, as noted in other studies (e.g., Larsen et al., 2007; Johnson et al., 2013; Melkonian et al., 2013, 2014; Berthier et al., 2018). Some exceptions include Margerie, Johns Hopkins, and Rendu Glaciers in the 2012 acquisition area, and Taku Glacier in the 2013 acquisition area (cf. Fig. 1). Margerie, Johns Hopkins, and Taku Glaciers are some of the few currently advancing tidewater glaciers in Alaska (e.g., McNabb and Hock, 2014; Motyka and Echelmeyer, 2003; Truffer et al., 2009), while Rendu Glacier has been previously identified as a surge-type glacier (Field, 1969). The pattern of elevation change shown on Rendu Glacier in the elevation difference maps, with thinning at higher elevations and pronounced thickening at lower elevations, is suggestive of a surge sometime between February 2000 and August 2012 (e.g., Raymond, 1987; Björnsson et al., 2003).

These contrasting patterns of elevation gain and elevation loss inform some of the patterns shown in Fig. 5. Generally speaking, the global hypsometric methods are the farthest from the true values, which is perhaps not surprising in a region with a variety of elevation change patterns such as this one. Glaciers that are far from the average volume change of -0.11 km^3 will tend to be far from the true volume change when the volume change is estimated with the regional values, as the data used do not reflect conditions at that particular glacier. As a result, volume changes for glaciers losing much more volume than the average tends to be overestimated, while volume changes at glaciers that are losing less than the average, or even increasing in volume, tends to be underestimated. Methods which use data from a particular glacier outline, or in a small area close to the

particular glacier outline, tend to do a much better job of reproducing volume changes over each of these glaciers than do these global methods.

We also see little overall difference between the two linear interpolation methods. Kääb (2008) estimated the difference between these two methods for glaciers on Edgeøya, Svalbard, to be 1 ± 12 m RMS. If we convert the volume change estimates
5   to a mean elevation change for the glaciated areas, we obtain a mean difference of 0.00 ± 0.01 m for these two methods. This difference is due to the fact that Kääb interpolated between contour lines over an entire ice cap, whereas we interpolate over much smaller areas that are confined by mountains, with much smaller differences on either side of a void. Thus, the effects of the different interpolation methods are muted. Additionally, Kääb used contour lines derived from aerial images with low contrast at higher elevations, which are likely biased as a result. We would most likely see similar results if we had used the
10   NED DEM as reference, rather than the SRTM, as the NED was produced from similarly low-contrast aerial images.

The statistical summary for the difference in volume change estimates over all glaciers individually (Table 1) shows that on average, mean and median differences to the true values are generally low ($<0.001\,\mathrm{km}^3$), as are root mean square (RMS) values (typically $<0.2\,\mathrm{km}^3$, with the exception of the global hypsometric methods). This pattern does not hold, however, for the larger glaciers, which tend to have a much larger spread in estimates of volume change, and therefore appear to be more
15   sensitive to the various methods. The percentage of estimates that fall within the uncertainty range of the true volume change estimates for most of the methods is quite high, around 95%. One notable exception is the median multiplied by glacier area method described in section 3.2.1, which aside from the global hypsometric methods, shows the fewest number of glaciers for which the interpolated value falls within the uncertainty (77.85%), shows the largest individual overestimation at $2.32\,\mathrm{km}^3$, the largest mean and standard deviation ($0.02\pm0.15\,\mathrm{km}^3$), and the largest RMS difference ($0.15\,\mathrm{km}^3$), and the worst agreement
20   with the regional volume change estimate ($8.3\,\mathrm{km}^3$ overestimation).

Fig. 6 shows the elevation change over Taku Glacier, with holes filled in for the nine non-constant methods. As mentioned previously, the spatial methods (Fig. 6b-d) and the local hypsometric methods (Fig. 6h-j) show the most similarity to the original elevation changes (Fig. 6a), with some subtle differences. The hypsometric methods have the effect of smoothing out the patterns of elevation change, whereas the spatial interpolation methods tend to preserve the original spatial patterns within
25   elevation bands. Near the dividing lines between glacier basins, discontinuities can be seen in the local hypsometric maps, compared to the gradual changes across dividing lines seen in the original elevation changes and the spatially-interpolated maps. This suggests that the choice of glacier basin outlines can have an impact on the resulting volume change estimates. Finally, the global hypsometric methods (Fig. 6e-g), taking data from the region, do not faithfully reproduce the anomalous elevation change patterns for Taku Glacier.

30   For the largest 20 glaciers in the dataset (all $>100\,\mathrm{km}^2$), which represent 61% of the total glacier area for the glaciers studied, as well as 68.8% of the volume change in the region (a total of -49.9 km^3), we see a number of patterns related to each of the methods. Fig. 7 shows that for these largest glaciers, most of the methods fall within $\sim\pm0.5\,\mathrm{km}^3$ of the true value, with significant outliers for some methods on some glaciers. For example, each of methods for glacier RGI60-01.27102 (Hole-in-the-Wall Glacier) are clustered quite close to the true value, with the exception of the global methods. Hole-in-the-Wall
35   Glacier is directly adjacent to Taku Glacier, and is also slightly gaining mass, thus leading to the discrepancy with the regional

averages. In general, the global methods under- or over- estimate volume change, with only a few cases where the results within the uncertainty of the true value. For another glacier, RGI60-01.21001 (Riggs Glacier), the non-global methods give a value within $\sim 0.15 \, \text{km}^3$ of the true value, while the global methods are still within $\sim 0.35 \, \text{km}^3$; the number of voids induced on this glacier are relatively small overall (19% of the glacier area), and the elevation change pattern for this glacier is also in line with

5   the regional trends (strong elevation loss at lower elevations, small gain at higher elevations).

Fig. 8 shows a box plot of the distribution for each method for the glaciers shown in Fig. 7. Again, we see that the best-performing methods, based on the size of the interquartile range and then mean difference of each interpolated volume change estimate, are the spatial interpolation methods, the local hypsometric methods, and the mean dH constant method.

Table 2 shows the differences to the true volume change for two glaciers with some of the largest deviations from the true

10   values. The median elevation change estimate for Field Glacier has the largest overall change from the true value for the non-global methods, at $+2.32 \, \text{km}^3$, while the global fits for Taku Glacier have the largest negative changes, all over $-3.50 \, \text{km}^3$. These differences are most likely for the reasons discussed above: the data being used to estimate volume change for Taku Glacier are far more negative than reality. For Field Glacier, only the median elevation change method and the global methods perform particularly poorly; the rest are all within $\pm 0.36 \, \text{km}^3$ of the true estimate of $-3.02 \, \text{km}^3$ (12%). As shown in Fig. 9, this

15   is most likely because of the heavy slant towards very negative elevation changes in the elevation change distribution for Field Glacier. Those positive values of elevation change found on the glacier are relatively small as compared to the negative values, and so the median is pulled heavily towards zero, greatly underestimating the volume change.

Based on the results for individual glaciers, the best methods (i.e., that introduce the least uncertainty/bias and the estimates closest to the original, non-voided estimates) appear to be linear interpolation of elevation change, the mean hypsometric

20   approach, and the 1km neighborhood approach.

4.3 Regional Totals

While the differences when averaged over all glaciers tends to be close to zero, the differences in the regional estimates can vary substantially, as shown in Table 1. The methods that came closest to the "true" volume change for the region were local mean hypsometric method, linear interpolation of elevation differences, and the global mean hypsometric method, which all yielded

25   estimates within $0.4 \, \text{km}^3$ (0.8%) of the regional total. A form of the global mean hypsometric method is one that is often used in altimetry-based studies to extrapolate measurements to unsurveyed glaciers, either using absolute or relative elevation (e.g., Arendt et al., 2002; Kääb et al., 2012; Johnson et al., 2013; Larsen et al., 2015), and this result would indicate that relatively little bias is introduced to the regional estimate through this form of extrapolation.

The next best estimates after the three closest were the local median and polynomial hypsometric methods, linear interpo-

30   lation of elevation, and the 1 km average method, all coming within $2 \, \text{km}^3$ (4%) of the regional total. One explanation for the value for the elevation interpolation method is as discussed in Kääb (2008): elevations on the glacier surface are not necessarily self-similar in a given area, and elevations can vary greatly even on relatively small length scales. As for the 1 km neighbour-hood method, it may be that 1 km is too large of an area to try to average over for some glaciers in this region, or it may be that

the neighbourhood window used is including values from neighbouring glaciers that have very different patterns of elevation change, thus behaving more like a "global" method in some areas.

The methods that came the farthest from the regional total were the median elevation change method, as discussed above, and the global polynomial hypsometric method, both over/underestimating the regional total volume change by over $8\,\mathrm{km}^3$,

5   well above the uncertainty of $5.21\,\mathrm{km}^3$. In contrast to this, estimating volume changes using the global median hypsometric method overestimated the regional total volume change by $4.47\,\mathrm{km}^3$. While for an entire glacier basin, the median elevation change skews very heavily towards zero due to the asymmetry in positive and negative values of elevation change, this is not necessarily the case for an elevation bin. As noted by Kääb (2008), and borne out by the elevation change interpolation method, elevation changes tend to be rather self-similar on small spatial scales, and the median change for an elevation bin tends to be

10   a more accurate reflection of the actual elevation change.

4.4 Increasing void area

By increasing the threshold used to induce voids from 0.5 to 0.7, we were able to estimate how sensitive the different methods are to the size of voids in the DEMs. As might be expected, the overall number of glaciers for which the interpolated volume changes fall within the uncertainty drops across all methods, though not completely evenly. The global methods are rather

15   insensitive to the increase in voids, likely because the increase is muted on the regional scale as compare to the individual glacier scale

For the largest 20 glaciers shown in Fig. 7, Fig. 10 shows the difference in volume change estimate for each of the methods. Overall, most glaciers do not have large differences for most of the methods ($<0.15\,\mathrm{km}^3$). The global methods tend to show the least change, while the constant methods and spatial methods tend to show larger, though still relatively small, differences.

20 ### 4.5 ASTER differences

One caveat remains when using methods such as linear interpolation of elevation differences. To illustrate this, we used ASTER DEMs acquired on 13 August 2015 over a portion of the 2012 IFSAR acquisition area, and differenced these DEMs to the SRTM. Compared to the IfSAR DEM, the ASTER DEMs are quite noisy in the accumulation areas of glaciers, owing to the low contrast, and hence low correlation, between the original images in the ASTER scenes. As such, even after correlation

25   masking, there is significant noise in the DEM difference map (Fig. 11a). When these values are linearly interpolated, the resulting dDEM shows clear interpolation artefacts and elevation changes that differ greatly from the original IfSAR/SRTM differences, biasing the estimated volume changes (Fig. 11b). For the 91 glaciers covered by these ASTER DEMs, the other "best" estimates named above (local mean hypsometric and global mean hypsometric) provide a volume change estimate of $\sim0\,\mathrm{km}^3$, whereas linear interpolation of elevation differences yields a volume change of $3.4\,\mathrm{km}^3$. Looking further at this, this

30   discrepancy is almost entirely due to one glacier, Johns Hopkins - linear interpolation of elevation changes yields a volume change estimate of $3.6\,\mathrm{km}^3$ for this glacier, while the other estimates give only $\sim2\,\mathrm{km}^3$. Thus, we caution against using a direct linear interpolation of elevation differences to fill voids without first filtering or otherwise removing potential outliers, or when the distances between known values are quite large in relation to the glacier width; that said, the local mean hypsometric

approach used by many studies performs just as well as linear interpolation of elevation differences, appears to be more robust against this kind of noise, and is easily implemented in place of linear interpolation.

5 Conclusions

We have compared 11 different methods for filling voids in DEM difference maps over glaciers, and compared the effects of
5 these different methods on estimates of glacier volume change. Three methods, linearly interpolating elevation changes, the so-called local mean hypsometric method, and the so-called global mean hypsometric method, performed remarkably similarly in estimating the regional total volume change, differing from the true estimate by less than one percent; the first two methods also performed well on an individual glacier basis. For the input data we have used, linearly interpolating elevation differences tends to produce elevation change maps that look the most similar to the original maps. This may not hold, however, for voids
10 that take up a larger portion of the glacier area, where the assumption that elevation changes are similar over small distances may be violated, and interpolation artefacts would introduce larger uncertainties. Additionally, this may not hold for DEMs that are noisier, especially in low-contrast areas such as the accumulation zones of glaciers; as such, we caution against adopting this method without first considering the characteristics of the DEMs beings used. In terms of individual glacier estimates, using the mean elevation change per elevation bin multiplied by the glacier hypsometry performs quite well, which perhaps
15 explains its widespread use in studies of glacier volume change and geodetic mass balance.

Taken on average, most of the methods perform well for the glaciers in the region, with low mean, median, and RMS differences for all methods, though large outliers skew the differences in the regional totals. Using the median elevation change for a glacier, multiplied by the glacier area, tends to work quite poorly, owing to the asymmetrical distribution of positive and negative elevation change values; i.e., the glaciers in the region tend to have significantly more negative values of elevation
20 change than positive values. Unless there is good reason to think the distribution of elevation changes for a particular glacier or region is more symmetrical, this method should be avoided; the same can be said for using a median hypsometric approach, which does not do as well as the mean hypsometric approaches, although this may not always be the case when there is significant noise in the original DEMs. As might be expected, using regional data to estimate the volume change of an individual glacier quite often does poorly, though the regional total volume change can be well-approximated in this way.

25 In summary, the effect of DEM voids on estimates of geodetic mass balance depends on the size of the voids, the magnitude and spatial pattern of changes on the glaciers, as well as the nature of the DEMs used. The choice of void-filling method is important, and if not considered properly, biases many times the uncertainty of the volume change measurement can be induced, while on the regional level, biases of up to 20% can be induced. The choice of "best method" will depend on the goal of the study, as well as the nature of the voids in the DEMs and the changes of the glaciers. Interpolation methods using
30 elevation differences from an individual glacier, or differences within a close proximity to an individual glacier, tend to be the most accurate and robust. If the DEMs used have significant noise, or have large holes, however, linear interpolation may not be suitable. If attempting to estimate geodetic mass balance for unsurveyed glaciers, as is needed in many altimetry-based studies, only a global method will suffice, though the mass balance estimate for a given unsurveyed glacier should not be taken at

face value. As each of these different methods are relatively easily implented, however, a comparison of the different methods should be attempted in order to provide a measure of the uncertainty introduced by filling holes in the data.

Competing interests. The authors declare that no competing interests are present.

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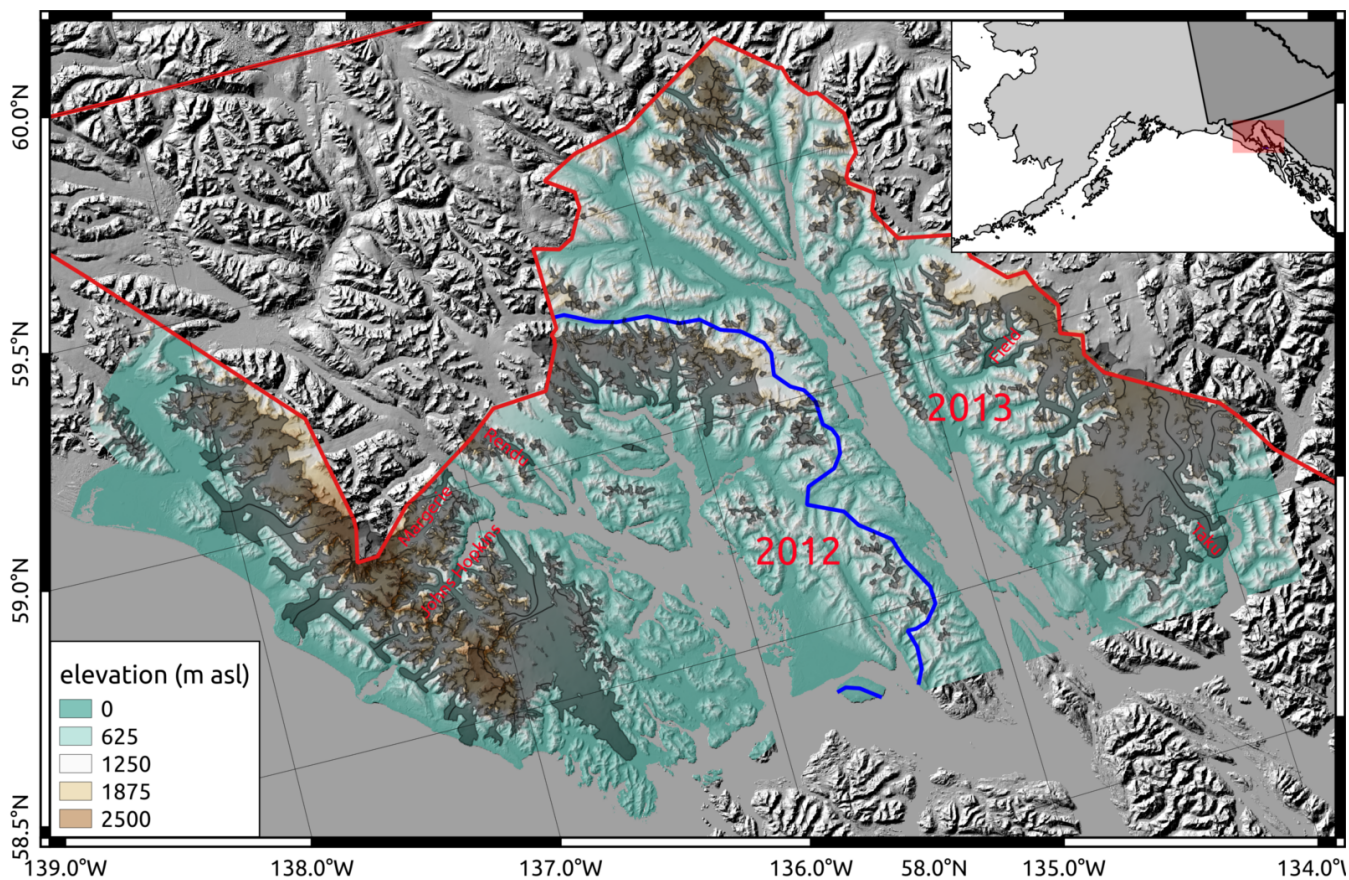
Figure 1. Study area in Southeast Alaska, USA. IfSAR DEMs are displayed overtop US NED and Canadian Digital Elevation Model (CDEM) hillshade. Blue line indicates boundary between 2012 and 2013 acquisitions. Named glaciers are discussed further in the following sections.
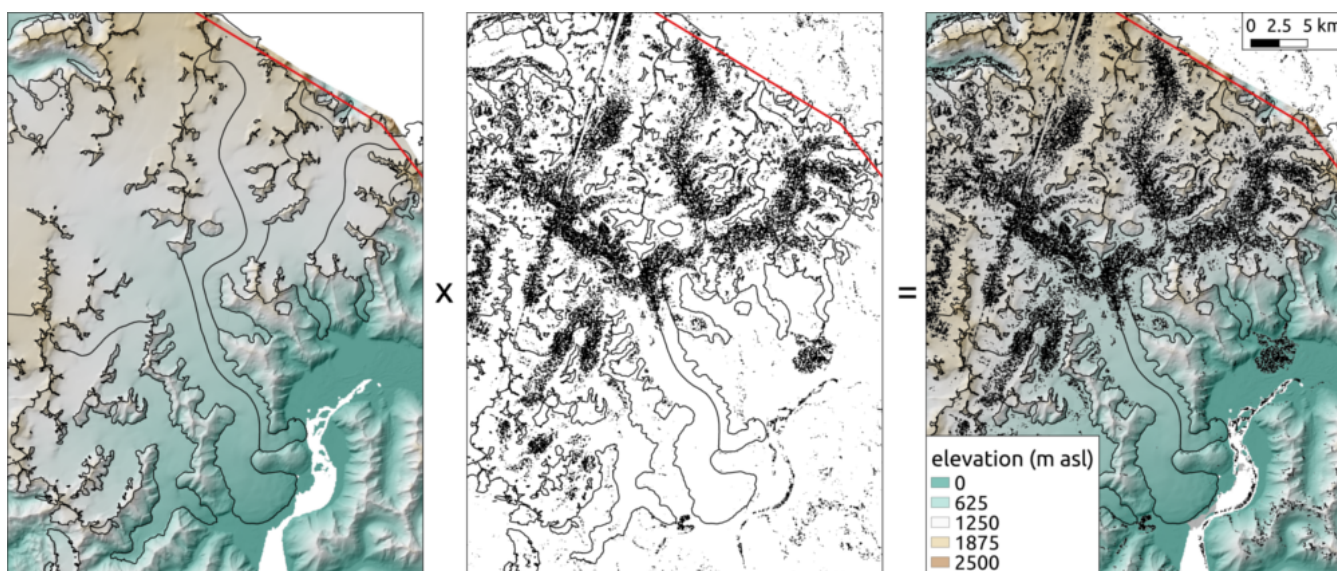
Figure 2. Example of masking procedure over Taku Glacier, with RGI outlines shown in black. The IfSAR DEM (left) is masked using the composite correlation mask from the ASTER products (middle), to produce a DEM (right) with holes (in gray) similar to expected voids in an optical DEM. In the middle panel, black represents areas where the ASTER correlation is below the chosen threshold.
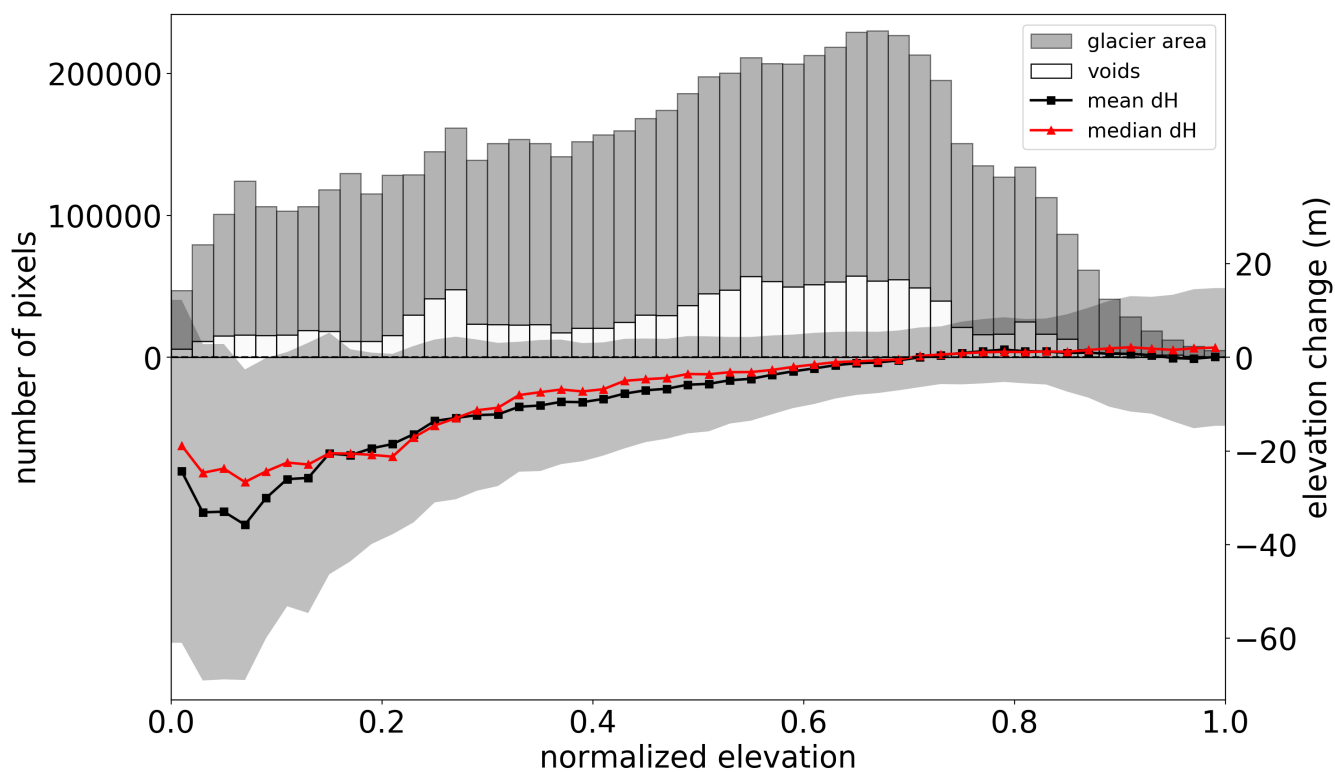
Figure 3. Distribution of glacier area and voids by normalized elevation, and mean and median elevation changes.
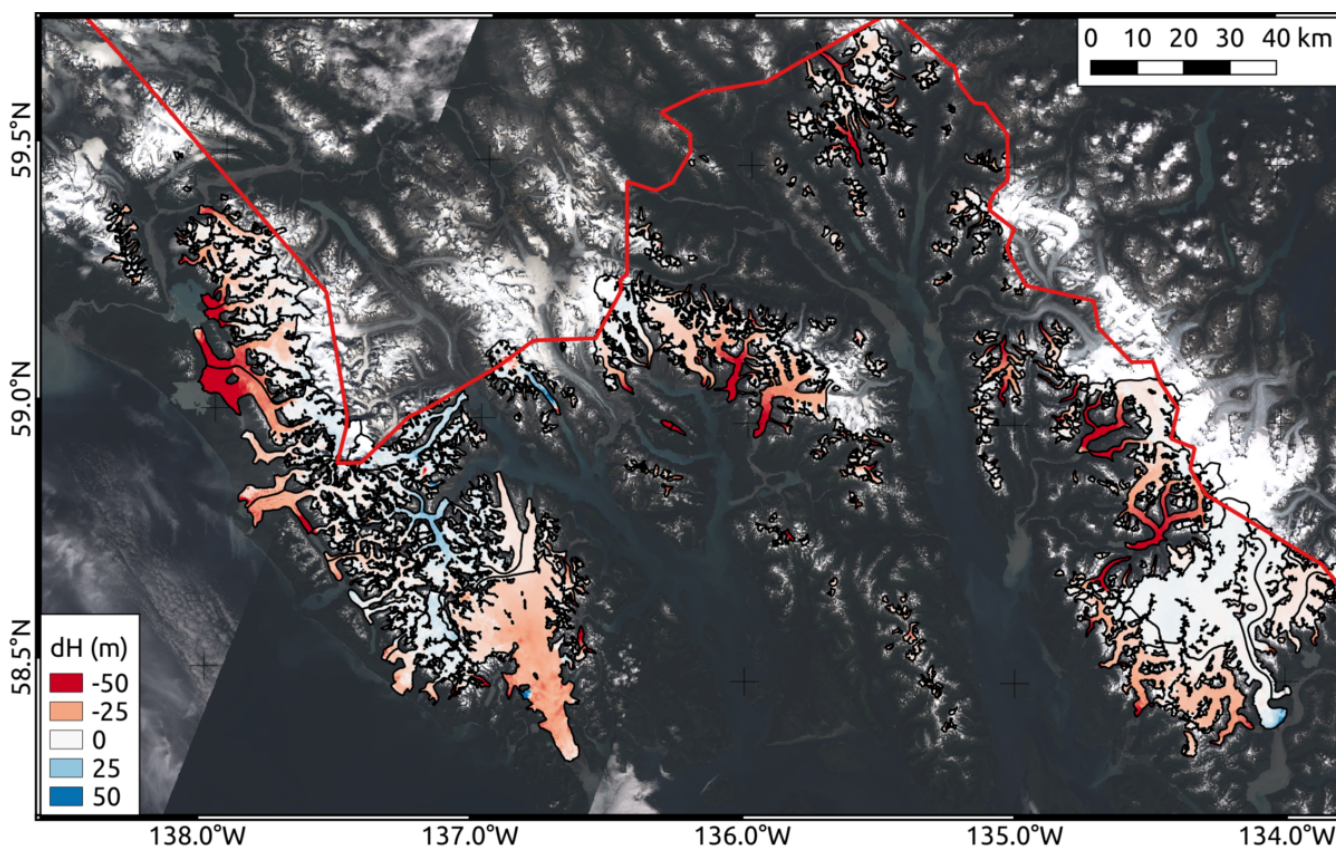
Figure 4. Non-voided, true elevation changes over the study area. Note contrasting patterns of thinning and thickening at lower elevations over glaciers labelled in Fig. 1., compared to the region in general. Background image is a mosaic of Landsat 8 scenes from 2013.
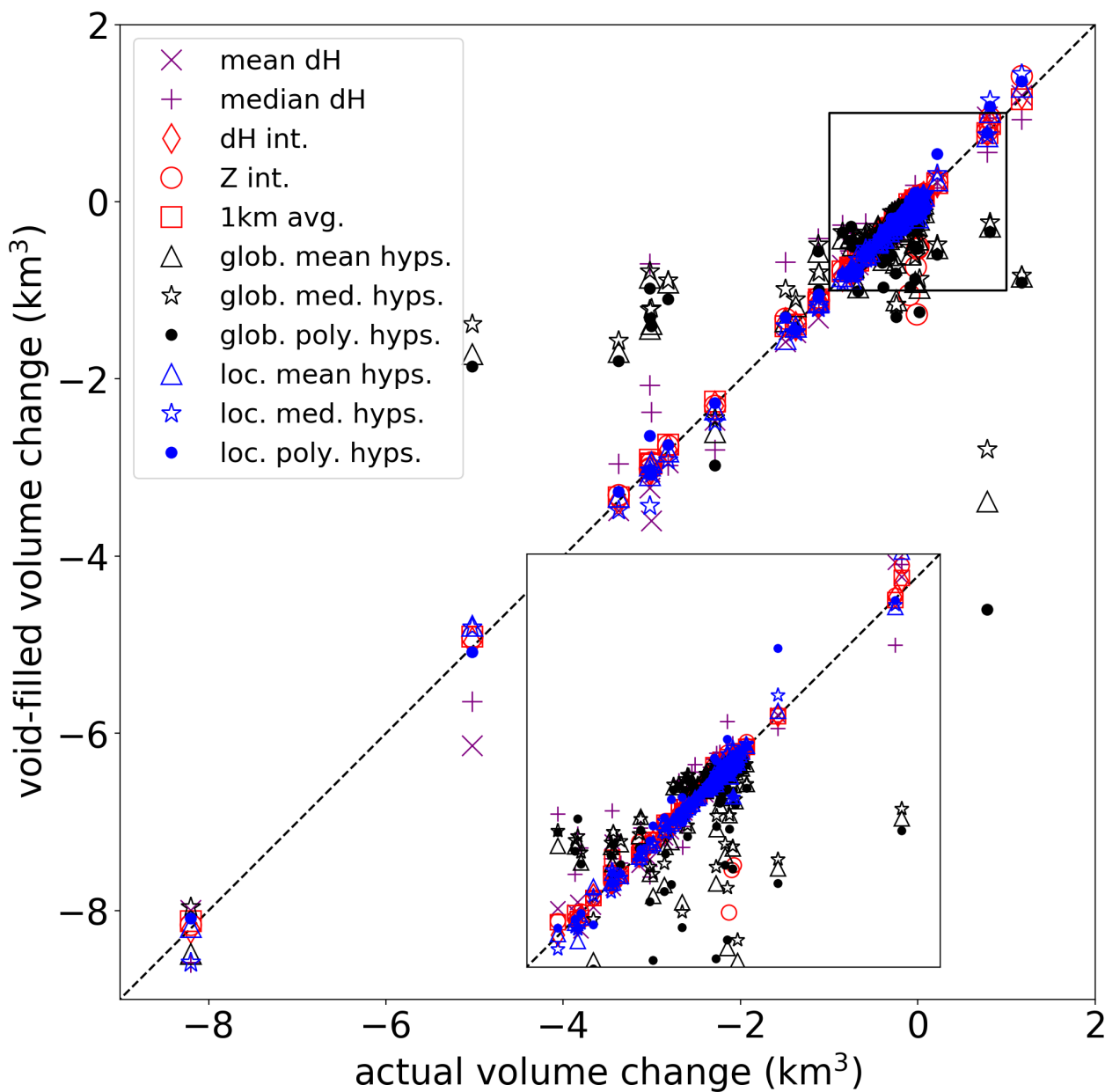
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Figure 5. Void-filled volume change estimate for individual glacierss vs. true volume change. Inset shows detail around $x = [-1, 1]$, $y = [-1, 1]$.
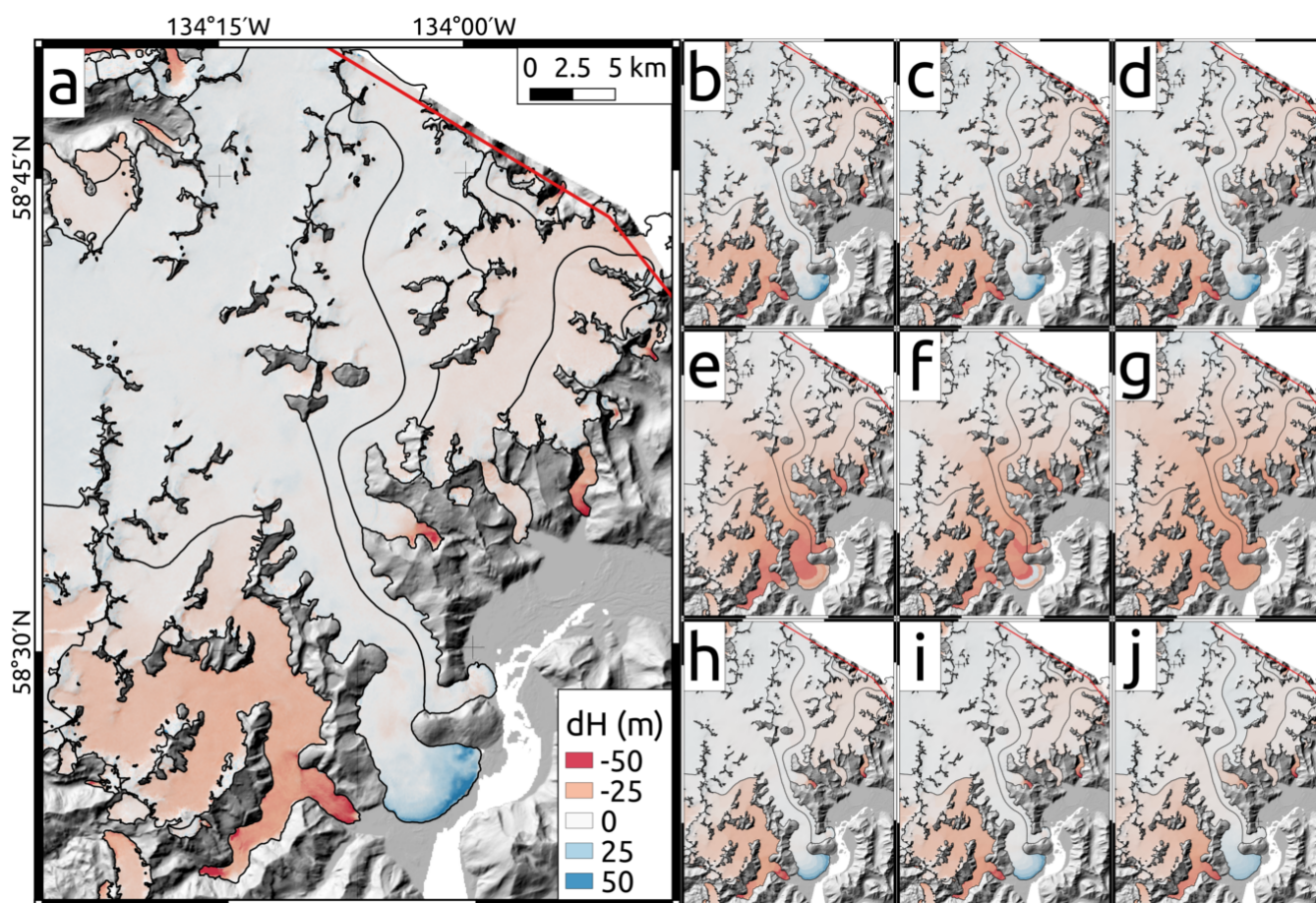
Figure 6. Final dH maps for Juneau Icefield and Taku Glacier. (a) Initial, non-voided dH; (b) dh Interpolation; (c) elevation interpolation; (d) 1 km neighbourhood; (e) global mean dH bins; (f) global median dH bins; (g) global polynomial fit; (h) local mean dH bins; (i) local median dH bins; (j) local polynomial fit. Note that the global interpolation schemes in panels e-g show primarily surface lowering, in contrast to the actual signal of no change or surface increase, as well as increased notability of individual glacier outlines in panels h-j.
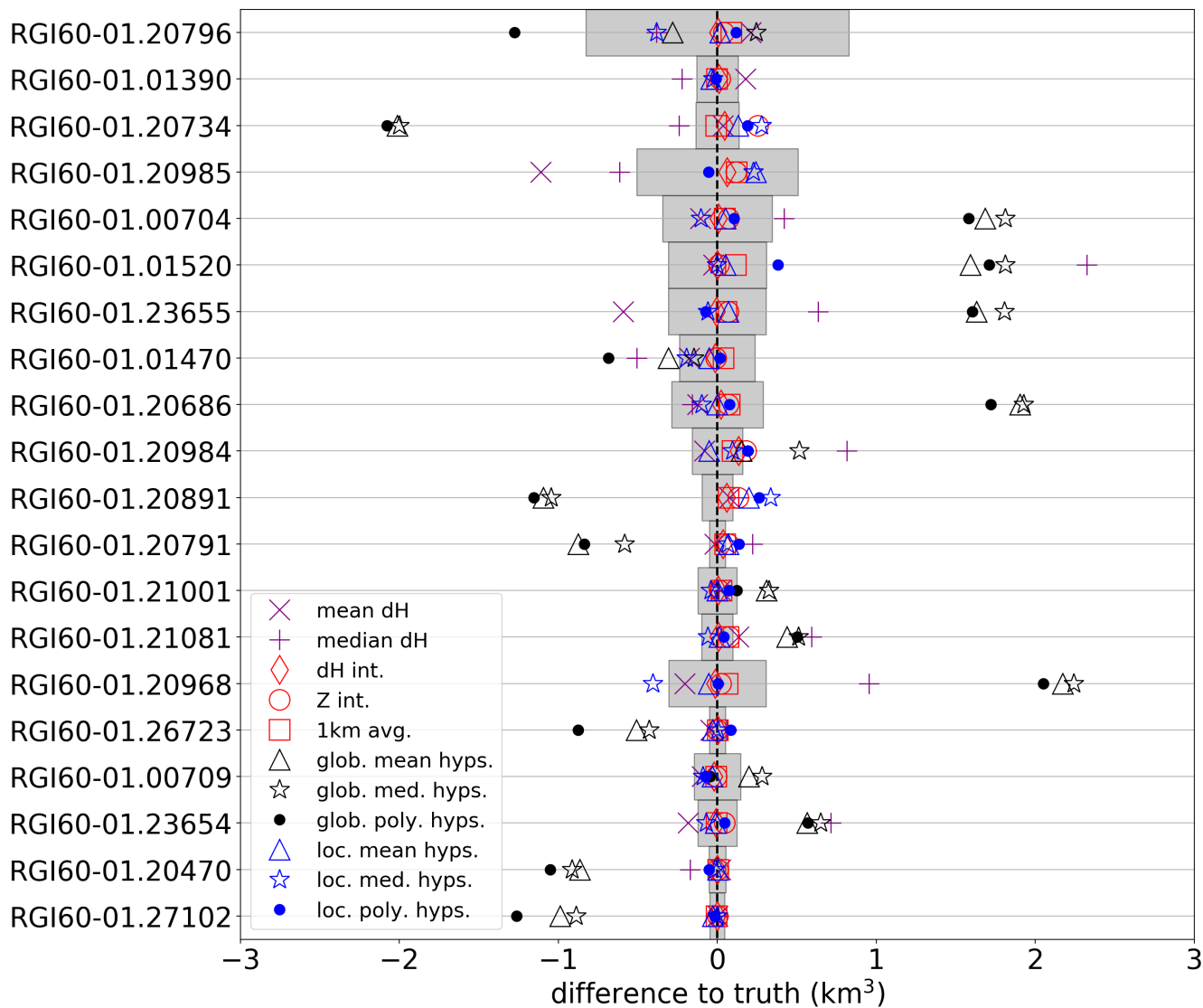
Figure 7. Comparison to true volume change for glaciers larger than $100\,\mathrm{km}^2$. Gray bars indicate uncertainty estimate for each glacier.
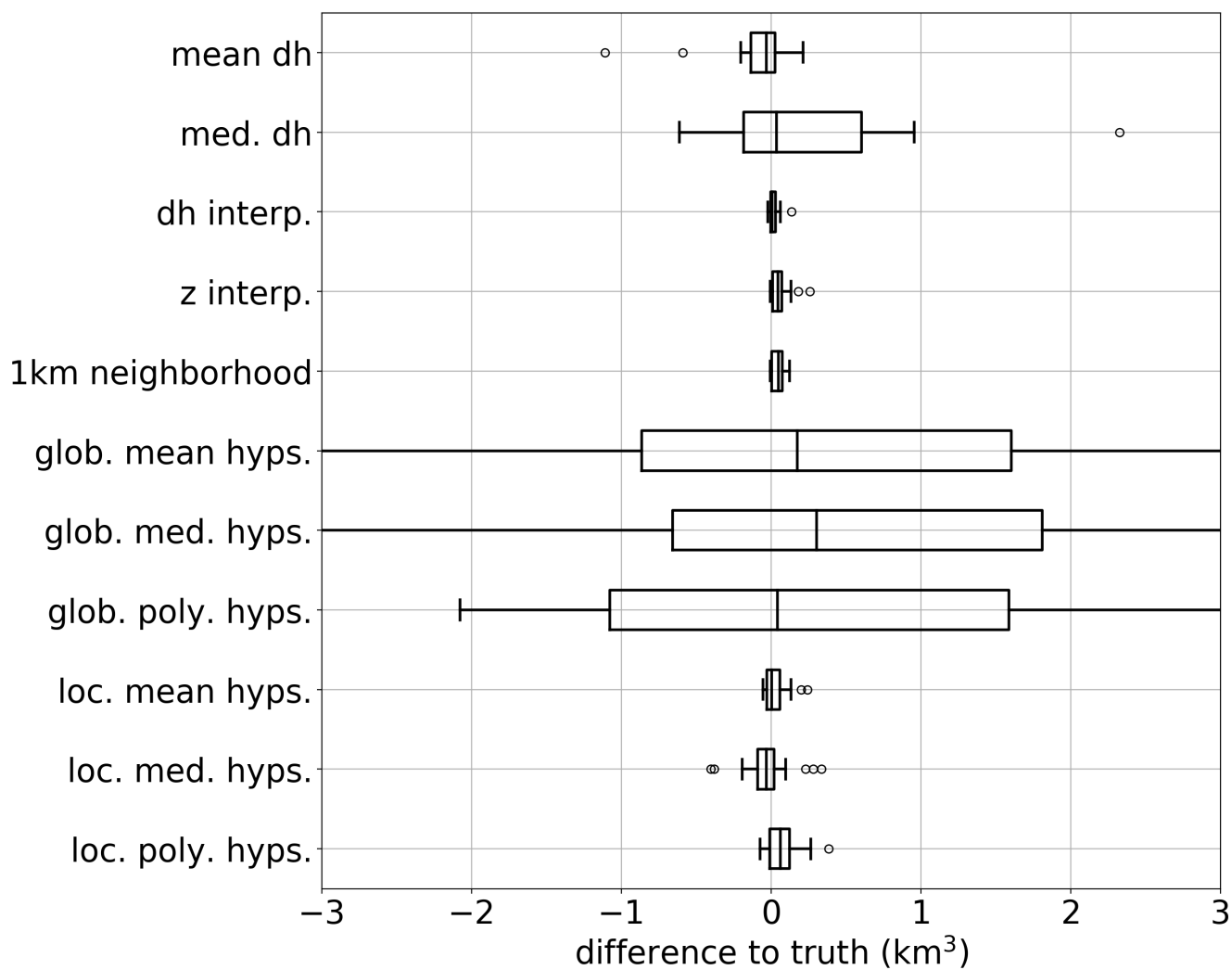
Figure 8. Difference to true volume change for each method tested, for glaciers larger than $100\,\mathrm{km}^2$.
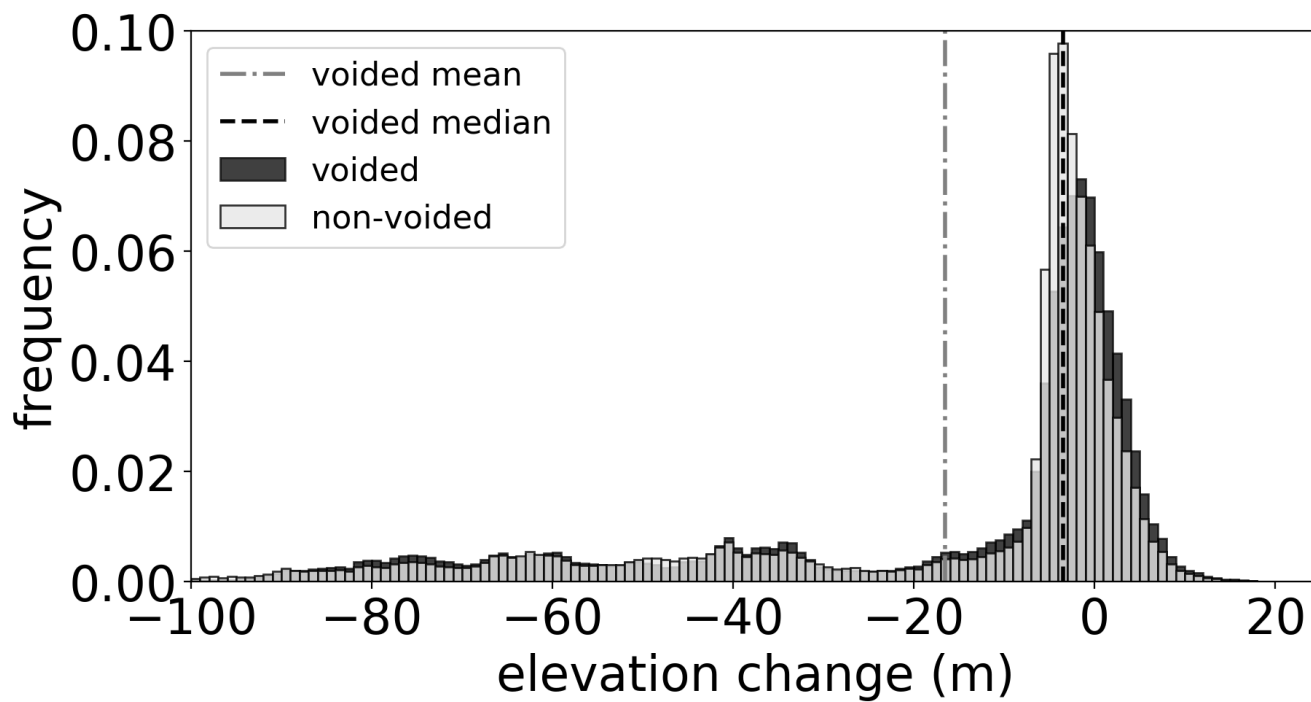
Figure 9. Distribution of elevation change values for voided and non-voided datasets over Field Glacier. Vertical lines indicate mean and median values for the voided dataset.
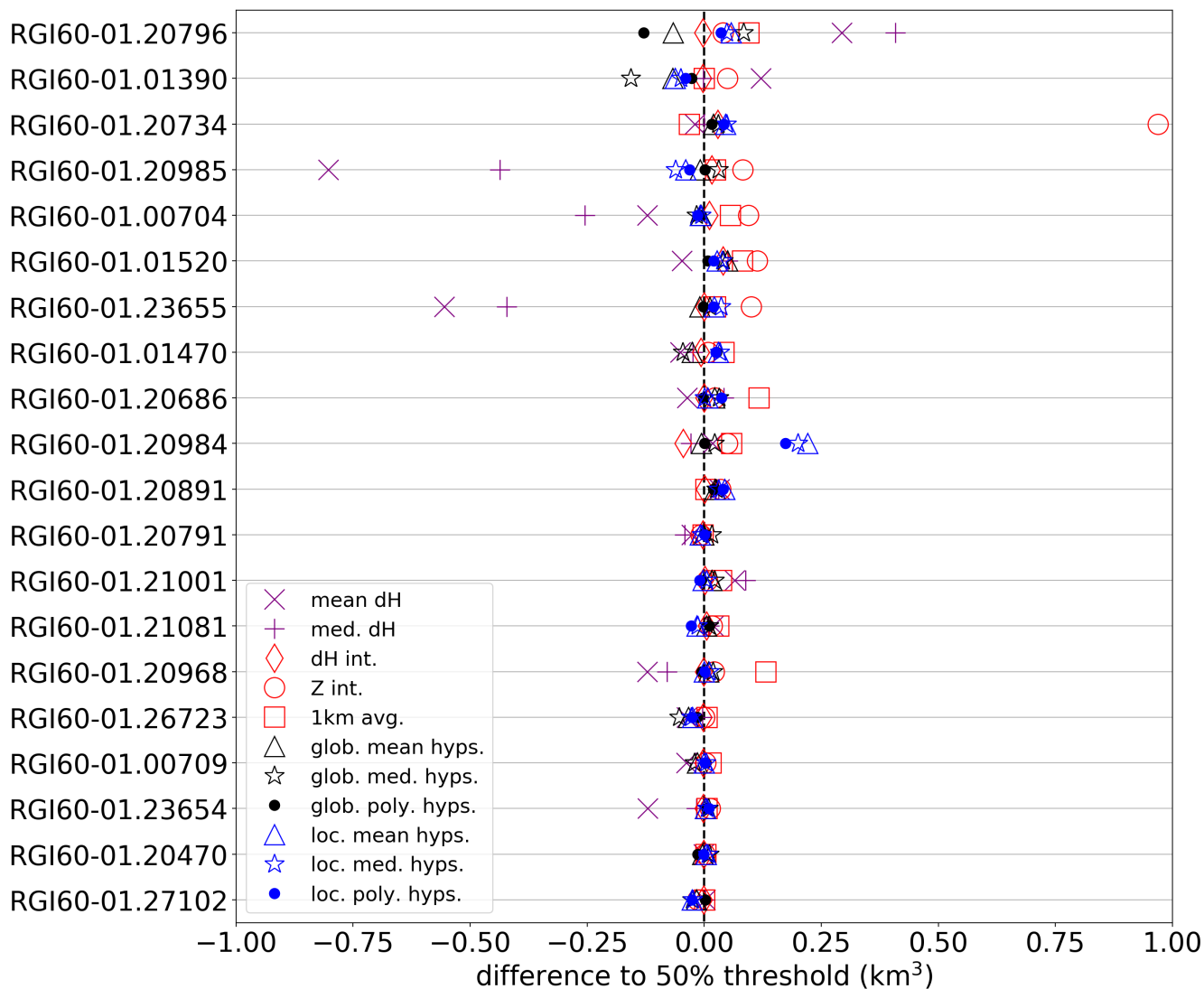
Figure 10. Difference in volume change estimate for each of the largest 20 glaciers seen by changing correlation threshold from 50% to 70%.
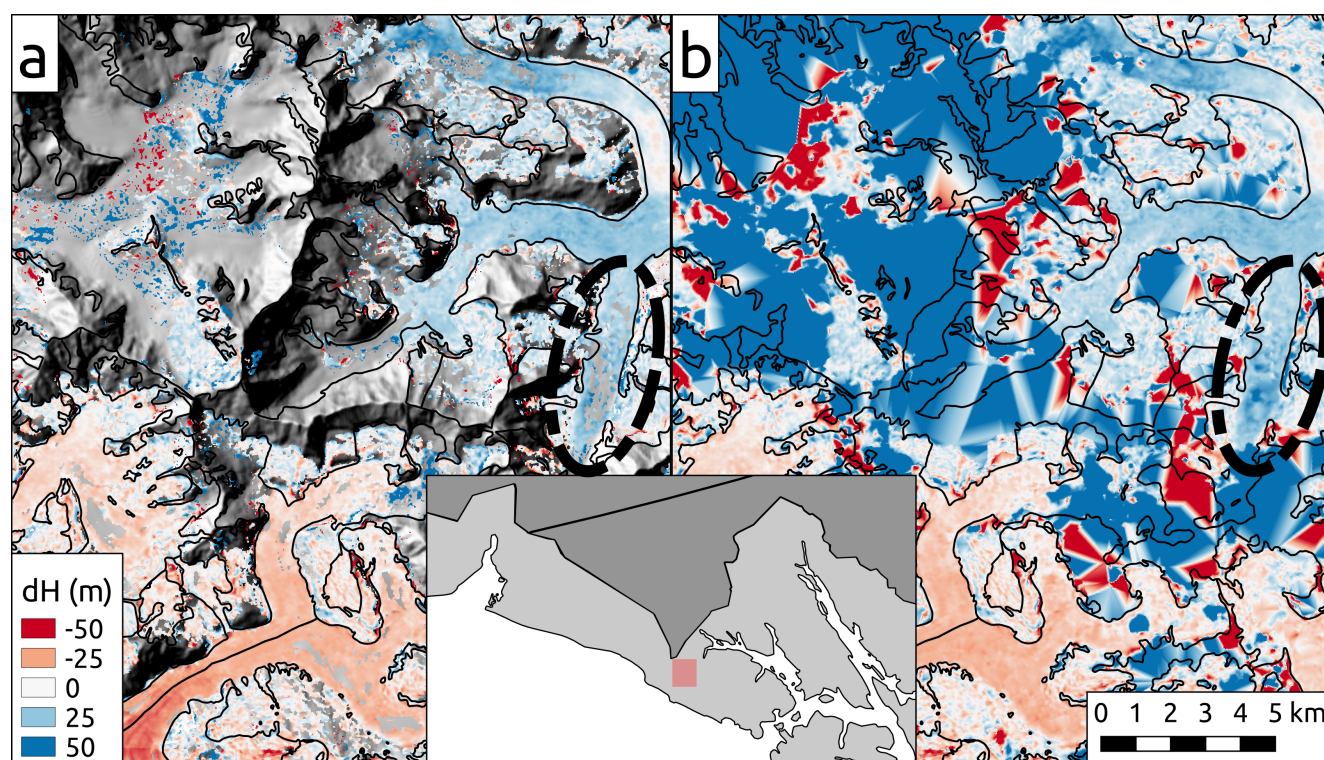
Figure 11. Elevation changes over the upper portion of Johns Hopkins Glacier, estimated by differencing an ASTER DEM acquired 13 August 2015 and the SRTM (a) with correlation-masked values left as nodata; (b) with voids filled using linear interpolation. Clear interpolation-related artefacts are seen in the sparsely-sampled accumulation area. Ellipses highlight an area over the glacier where linear interpolation performs well, with no obvious artefacts in the interpolated surface.

Table 1. Summary statistics for difference to true volume change for each method. All units in km^3, except for "pct. uncert.", which indicates the percentage of glaciers for which the interpolated dV was within the uncertainty of the true volume change.

method	mean $\pm$ std	median	max	min	rms diff	total diff	pct. uncert.
Mean dH	-0.01 $\pm$ 0.07	0.00	0.21	-1.11	0.07	-2.26	94.41
Median dH	0.02 $\pm$ 0.15	0.00	2.32	-0.61	0.15	8.30	77.85
dH interp.	0.00 $\pm$ 0.01	0.00	0.13	-0.04	0.01	0.39	97.99
Z interp.	0.00 $\pm$ 0.09	0.00	0.26	-1.25	0.09	-1.85	93.96
1km neighborhood	0.00 $\pm$ 0.02	0.00	0.12	-0.02	0.02	1.78	95.08
Glob. Mean Hyps.	0.00 $\pm$ 0.35	0.00	3.31	-4.16	0.35	-0.40	47.20
Glob. Median Hyps.	0.01 $\pm$ 0.35	0.00	3.65	-3.57	0.35	4.47	46.76
Glob. Polyfit Hyps.	-0.02 $\pm$ 0.40	-0.01	3.17	-5.38	0.40	-8.64	34.90
Loc. Mean Hyps.	0.00 $\pm$ 0.02	0.00	0.24	-0.17	0.02	0.09	96.20
Loc. Median Hyps.	0.00 $\pm$ 0.04	0.00	0.33	-0.41	0.04	-1.21	95.97
Loc. Polyfit Hyps.	0.00 $\pm$ 0.04	0.00	0.38	-0.17	0.04	1.74	92.84

Table 2. Difference to true volume change for the glaciers with the two largest changes. All units in km^3.

	Taku Glacier	Field Glacier
Mean dH	0.18	-0.02
Median dH	-0.22	2.32
dH interp.	0.01	0.00
Z interp.	0.02	0.01
1km neighborhood	0.00	0.11
Glob. Mean Hyps.	-4.16	1.59
Glob. Median Hyps.	-3.57	1.81
Glob. Polyfit Hyps.	-5.38	1.71
Loc. Mean Hyps.	-0.04	0.05
Loc. Median Hyps.	-0.03	0.00
Loc. Poly Hyps.	-0.01	0.38