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Dear Tobias,

Please, find enclosed a revised version of our manuscript (MS) entitled "Brief communication: Unabated wastage of the Juneau and Stikine icefields (southeast Alaska) in the early twenty-first century". To facilitate your assessment, we uploaded a track-change version of the revised MS.

We thank you for your careful reading of the paper and your comments. Find below a copy of them and, in bold/blue, a point-by-point response. The revised text is provided in italics.

We hope that these corrections/clarifications make our paper now suitable for publication in The Cryosphere.

Yours sincerely,

Etienne Berthier and co-authors

Reply to the Editor, Tobias Bolch

Dear Etienne, dear co-authors,

I carefully read the manuscript and your reply to the comments. The comments were mainly of minor nature. Most of them have been addressed, but I would have expected slightly more careful incorporation. Some sentences were added as a response to the comments, but they partly do not fit into the flow of the text, e.g. line 41: It is not clear to which statement you are referring to. Lemon Creek Glacier had a negative balance throughout while the balance for Taku Glacier was clearly positive for a period.

> **Reply: We changed "The statement is" to "***The trend toward enhanced mass loss***"**

L. 61: Be more specific about field observations. Which glacier(s) were observed? Entire Stikine icefield?

> **Reply: We changed the sentence to "***Field observations of the equilibrium line altitudes and surface mass balances on Lemon Creek and Taku glaciers (JIF) also do not support a slowdown (WGMS, 2017).***"**

L. 85 Images do not cover elevation data. One can guess what you mean, but it is not clear from the text.

> **Reply: "Images" replaced by "***DEMs***"**

Please check once again all added statements and sentences carefully.

> **Reply: Checked everywhere**

In addition, I do not agree to not consider a comment because it is not easy to understand. You can at least provide a guess or better write an email to the reviewer who provided his name to ask for clarification.

> **Reply: We assume that the editor refers here to the following comment "The linear correction used by Larsen et al (2007) would depend on the season of comparison". We contacted directly Mauri Pelto and he told us by email "This was more in support of what you were saying. The seasonal correction just adds an uncertainty/error to their determination that your methodology does not. I was suggesting, maybe not so clearly, that you could add this as a supportive/explaining comment. There was not a question to respond to."**
>
> **The linear correction was calculated between two dataset with a clear timestamp (February 2000 and August 2000) so it is not clear to us why the correction would depend on the season of comparison. It was an empirical way for Larsen et al. (2007) to make the data seasonally compatible by adjusting the SRTM DEM to a summer elevation dataset.**
>
> **No change was made to the manuscript.**

It is also a valid comment to mention that extensive thinning of some glaciers is due to calving events. In case you do not want to include a third study by the reviewer (which I would understand) you can refer the Larsen et al. (2015) as mention in the reply.

> **Reply: It is not a problem of adding another reference. It is simply that our study is not about understanding the cause of glacier loss in southeast Alaska and neither about the drivers of variability between individual glaciers. In fact, our results do not bring any new**

> **insights on the processes governing glacier mass loss so we strongly believe that there is no point in mentioning the extensive thinning at lake-terminating (not tidewater) glaciers. To avoid any ambiguity/disappointment for the reader, we clarify this by adding the statement: "***Understanding the pattern of dh/dt and its variability among glaciers is beyond the scope of this brief communication and the reader is referred to earlier publications on this topic (e.g., Larsen et al., 2015).*"**

In addition, I have two more substantial comments and several minor specific comments:

1. I asked you to provide more information about the utilized glacier outlines. Years were added, but ask you to carefully check once again. As I understood (not entirely clear from Kienholz et al. 2015) for some regions outlines from Bolch et al. (2010) were used and some images were not acquired in 2004/05. In addition, and as a good example as your papers are highly recognized, you should cite the original source of the outlines if possible.

> **Reply: we contacted Christian Kienholz who told us:**
>
> **"The Bolch et al. (2010) outlines were used for the Canadian/eastern part of the JIF, as stated in Figure 2c of the Kienholz et al. (2015) paper. However, the outlines may not be fully identical to the original outlines. For example, we used ALOS-derived streamlines to check/update the divides across the entire JIF (see Figure 3a in my 2015 paper). Adding a sentence that the RGI outlines are based on outlines compiled by Bolch et al. (2010) and Kienholz et al. (2015) may be good, as indicated by Tobias. Also, Figure 2 from my 2015 paper should be added to the next RGI technical guide to avoid confusion.**
>
> **2004/2005 is correct for the bulk of the glaciers across the Juneau and Stikine Icefields. A few glaciers were updated using imagery from 2010/2011."**
>
> **We also checked the RGI technical guide about recommandation for referencing RGI. The recommendation is that "The RGI may be used freely with due acknowledgement (by citing this note for technical details or Pfeffer et al. 2014 for scientific background)". Because we wanted to recognize the tedious work that accompanies the making of such a detail inventory in Alaska (in line with your comments), we made sure we cited the original reference. So we checked the Alaska chapter in the he RGI technical guide which mentions "Changes from Version 3.2 to 4.0. A new inventory compiled by C. Kienholz (Kienholz et al., submitted), including topographic and hypsometric attributes, replaces the former inventory of Alaska". Kienholz et al. was thus cited in our paper. Based on our personal communication with C. Kienholz, we now also cited the Bolch et al. 2010 study in our revised paper.**
>
> **You and Christian Kienholz were deeply involved in the RGI. If the recommendation provided on the technical guide (just citing the technical guide + Pfeffer et al. 2014) does not suit you, then I think there should be an open discussion among the RGI leaders about it. As users of these outlines, we are afraid that finding/citing all the sources that were compiled in the RGI would become a tedious work and we feel that it was not really the spirit of the RGI.**
>
> **We also checked again the dates of individual glacier outlines in the RGI attributes and found only image dates in 2004 and 2005. Despite the statement by C. Kienholz that a few glaciers were updated using more recent imagery. The revised text is:**
>
> *"The RGI v5.0 glacier outlines for both the JIF and SIF were mapped using imagery acquired in majority in August of 2004 and 2005 (Bolch et al., 2010; Kienholz et al., 2015). "*

But more important you are analysing the period 2000 – 2016, but the outlines are from 2004/05. Hence, a justification why you use outlines which do not match the investigation period is needed. Or were they adjusted?

> **Reply: The editor is right, glacier outlines were not adjusted to the start/end dates of your geodetic mass balance estimate. This important information was indeed missing in our paper. A statement is added in the revised text and the negligible effect on the mass balance is supported by a sensitivity analysis for the Northern Patagonia Icefield (3800 km²) in Dussaillant et al., 2018: "***No updated inventory is available or was produced in this study for the JIF and SIF. Therefore, we neglected changes in glacierized area between 2000 and 2016, and assumed that mass balance uncertainties linked to area changes are covered by our 5% area uncertainty (Paul et al., 2013; Dussaillant et al., 2018)*."**

2\. I agree that the comparison of DEM differencing results to repeat laser altimetry is not straight forward as you mention in L. 170. However, this is not only because of the different time periods. This is also due to different coverage. I did not read the paper in detail, but as I understood from Larson et al. (2015), mainly glacier centrelines were measured. Hence, the mass loss might be overestimated when scaling to the entire glacier in case no correction is included as mentioned by Berthier et al. (2010), NatGeo. This issue needs to be tackled and discussed.

> **Reply: Good point. We now added a paragraph about this in the comparison of the mass balances using the two techniques. "***A further complication for the comparison of our ASTER-based results to repeat laser altimetry arises from different spatial sampling: mostly continuous coverage from DEMs vs. centreline sampling from laser altimetry. Berthier et al. (2010) found that centreline sampling could lead to an overestimation of mass loss. In their study, two large and rapidly retreating glaciers (Bering and Columbia, outside of our study domain) were responsible for 92% of the overestimation of the mass loss from centreline profiling (Table S4 in Berthier et al., 2010). Overestimation was not obvious for other glaciers. More recently, Johnson et al. (2013) presented an improved treatment of laser altimetry data and found no such overestimation from centerline profiling over the Glacier Bay region (southeast Alaska). In their improved processing, each change in elevation (dz) is assigned to a mid-point between old and new elevations whereas in the original laser altimetry analysis (Arendt et al., 2002), dz were assigned to the old elevation..*"**
>
> **And also in the discussion: "***This agreement suggests that an appropriate analysis of centreline data may be sufficient to measure the glacier-wide mass balance of these glaciers as previously shown for the nearby Glacier Bay area (Johnson et al., 2013). .*"**

Specific comments:

L. 12/17. It is a matter of style, but I would not use abbreviations in the abstract, if not really needed to save words.

> **Reply: abbreviations removed. Good point.**

L. 16: remove ","

> **Reply: removed.**

L. 52: Where did you get the information about the mass balances from? Include a reference.

> **Reply: ref to (Larsen et al., 2015) repeated. It was not clear indeed.**

L. 62: I'd omit the word "further".

> **Reply: omitted.**

L. 66-70. This statement with more or less similar wording is repeated in L. 239ff. You may once again refer to the problem of the x-band radar penetration but with a different wording. But more important, you need to be more specific about the x-band penetration (under which conditions can the penetration be so high?) and not just provide a general statement. In case you are at the word limit avoid the repetition but provide this relevant information instead.

> **Reply: we find it difficult to avoid the repetition and think it is helpful for the reader to know right away in the introduction how Melkonian et al. addressed the penetration issue. It will help to understand how we designed our study and why revisiting the ASTER analysis is needed. It is maybe not so problematic to repeat twice that recent studies have found clear penetration of the X-Band signal into cold snow and firn at a time when many colleagues are using Tandem-X data for geodetic mass balance estimates? We fully agree with the editor that it is indeed important to add that such high penetration depth is observed under specific conditions and we now write: "***X-band penetration depth has recently been recognized to reach several meters in cold and dry snow/firn*****".**

L. 93: According to my knowledge the automatically generated ASTER DEMs which are available are called "AST14DEM". The "AST14DMO" includes both the DEM and the orthoimage generated using this DEM.

> **Reply: true. Thanks. Changed everywhere and also in the color code of Figure 2.**

L. 95: Co-registration is crucial. Hence include a short statement with reference regarding the co-registration.

> **Reply: We stated a few line above "Planimetric and altimetric offsets of each ASTER DEM were corrected using the SRTM DEM as a reference". We now added a reference to Nuth and Kääb (2011).**

L. 112: Include one/two sentences how the uncertainties where calculated and then refer to the reference for more details.

> **Reply: More details about this uncertainty assessment is given now.**

L. 192: Check sentence. Write glaciological mass balance (also L. 196), so that it fully clear that these are values are based on the glaciological method.

> **Reply: Sentence corrected.**

L. 196: write "was" instead of "is".

> **Reply: corrected.**

Table 1: Add uncertainty rages.

> **Reply: Added.**

L. 252: Repetition of "consider"

> **Reply: corrected.**

L. 294: I think you can make an even broader statement here as the penetration might also be underestimated in several other studies.

> **Reply: we followed this suggestion but the broader statement was included a few lines further down the text "***Caution should thus be used when deriving mass balance using SRTM and Tandem-X DEMs over time period of less than ~20 years in Alaska and elsewhere*****".**

L. 297: I think it is very crucial to be more precise of the x-band penetration. The penetration depth depends also on the depth of the snow and firn layers

Reply: we added "*under cold and dry conditions*".

L. 301: I'd move this important statement to the discussion and put slightly more emphasis on it.

Reply: we prefer to keep it here at the end of the conclusion as this is not a result from out study but a perspective on how to use more safely the tandem-X DEM.

I am looking forward to your revised version. Please include a reply to each comment and highlight the changes made in to manuscript.

Do not hesitate to ask in case you have a question.

Best regards,

Tobias - Editor TC

Brief communication: Unabated wastage of the Juneau and Stikine icefields (southeast Alaska) in the early ~~21st~~ twenty-first century

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Abstract. The large Juneau and Stikine icefields (Alaska~~, JIF and SIF~~) lost mass rapidly in the second part of the 20th century. Laser altimetry, gravimetry and ~~sparse~~ field measurements suggest continuing mass loss in the early 21st century. However, two recent studies based on time series of SRTM and ASTER digital elevation models (DEMs) indicate a slowdown in mass loss after 2000. Here, the ASTER-based geodetic mass balances ~~is~~ are recalculated~~,~~ carefully avoiding the use of the SRTM DEM because of the unknown penetration depth of the C-Band radar signal. We find strongly negative mass balances from 2000 to 2016 (-0.68±0.15 m w.e. a^{-1} for the ~~JIF~~ Juneau Icefield and -0.83±0.12 m w.e. a^{-1} for the ~~SIF~~Stikine Icefield), in agreement with laser altimetry, confirming that mass losses are continuing at unabated rates for both icefields. The SRTM DEM should be avoided or used very cautiously to estimate glacier volume change, especially in the North Hemisphere and over timescales of less than ~20 yrs.

1 Introduction

The Juneau Icefield (JIF) and Stikine Icefield (SIF) are ~~among~~ the ~~largest and~~ southernmost large icefields in Alaska (Figure 1). The JIF covers about 3800 km² and the SIF close to 6000 km² at the border between southeast Alaska and Canada (Kienholz et al., 2015). Together they account for roughly 10% of the total glacierized area in Alaska. Both icefields experienced rapid mass loss in the second part of the 20th century (Arendt et al., 2002; Berthier et al., 2010; Larsen et al., 2007). Spaceborne gravimetry and laser altimetry data ~~suggest~~ indicate continuing rapid mass loss in southeast Alaska between 2003 and 2009 (Arendt et al., 2013).

For the JIF, Larsen et al. (2007) found a negative mass balance of -0.62 m w.e. a^{-1} for a time interval starting in 1948/1982/1987 (depending on the map dates) and ending in 2000, the date of acquisition of the shuttle radar topographic mission (SRTM) digital elevation model (DEM). Berthier et al. (2010) found a slightly less negative multi-decadal mass balance (-0.53 ± 0.15 m w.e. a^{-1}) from the same starting dates as Larsen et al. (2007) to a final DEM acquired in 2007. Repeat airborne laser altimetry are available for nine glaciers of the JIF (Larsen et al., 2015) with a first survey performed in 1993 (2 glaciers), 1999 (1 glacier) and 2007 (6 glaciers). The last survey used in Larsen et al. (2015) was flown in 2012 for all glaciers. During these varying time intervals, nine glaciers experienced strongly negative mass balances (between -0.51 and -1.14 m w.e. a^{-1}) while Taku Glacier, which alone accounts for one fifth of the JIF area, experienced a slightly positive mass balance (+0.13 m w.e. a^{-1}). Further, the glaciological measurements performed on Lemon Creek Glacier, ~~(11.8 km^2 in 1998,~~ a world glacier monitoring service (WGMS) reference glacier covering 11.8 km^2 in 1998~~)~~, suggest accelerated mass loss since the mid-~~eighties~~1980s: the glacier-wide mass balance declined from -0.30 m w.e. a^{-1} ~~during~~ between 1953 and ~~-~~1985 to -0.60 m w.e. a^{-1} ~~during~~ between 1986 and ~~-~~2011 (Pelto et al., 2013). The trend toward enhanced mass loss is ~~statement is~~ also ~~valid~~ observed on~~for~~ Taku Glacier, for which the mass balance was positive (+0.42 m w.e. a^{-1}) from 1946 to 1988 and negative (-0.14 m w.e. a^{-1}) from 1988 to 2006 (Pelto et al., 2008). A modelling study also found a negative mass balance for the entire JIF (-0.33 m w.e. a^{-1}) for 1971-2010 (Ziemen et al., 2016). Their 40-year mass balance is a result of glacier mass stability until 1996 and rapid mass loss afterwards. Taken together, all these studies point toward rapid mass loss of the JIF and accelerated wastage during the last ~20 years. Conversely, a study based on the SRTM DEM and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) multi-temporal DEMs found a JIF mass balance only moderately negative at -0.13 ± 0.12 m w.e. a^{-1} from 2000 to 2009/2013 (Melkonian et al., 2014).

Only a few estimates of mass change are available on the larger and more remote SIF. Three of its glaciers were surveyed with airborne laser altimetry from 1996 to 2013 and all experienced rapid mass loss (Larsen et al., 2015). The glacier-wide mass balances were -0.71, -0.98 and -1.19 m w.e. a^{-1} for, respectively, Baird, Le Conte and Triumph glaciers (Figure 1) ~~(Larsen et al., 2015)~~. Based on DEM differencing over several decades, Larsen et al. (2007) and Berthier et al. (2010) found SIF-wide mass balance of, respectively, -1.48 and -0.76 ± 0.12 m w.e. a^{-1}. A recent estimate based on the SRTM and ASTER DEMs suggest a less negative icefield-wide mass balance of -0.57 ± 0.18 m w.e. a^{-1} from 2000 to 2014 (Melkonian et al., 2016).

If correct, Melkonian et al. (2014, 2016)'s estimates would imply a considerable slowdown of the mass loss of the Juneau and, to a smaller extent, Stikine icefields during the first decade of the 21st century. However, no clear trend in climate such as cooling or increased precipitation was found during this period to explain such a slow-down (Melkonian et al., 2014; Ziemen et al., 2016). Field observations of the equilibrium line altitudes and surface mass balances on Lemon Creek and Taku glaciers (JIF) also do not support a slow-down (WGMS, 2017). ~~Further,~~ Melkonian et al. (2014, 2016)'s estimates used as starting elevation measurement the C-Band SRTM DEM acquired in February 2000, the core of winter in Alaska. The C-Band radar signal is known to penetrate into the cold winter snow and firn such that SRTM maps a surface below the real glacier surface which can bias the elevation change measurements (e.g., Berthier et al., 2006; Rignot et al., 2001). Melkonian et al. (2014, 2016) accounted for this penetration by subtracting the simultaneous C-Band and X-Band SRTM DEMs, assuming no penetration of the X-Band DEM (Gardelle et al., 2012), the best available correction at the time of their study.

However, this strategy ~~is~~ may not be appropriate given that the X-band penetration depth has recently been recognized to reach several meters in cold and dry snow/firn (e.g., Dehecq et al., 2016; Round et al., 2017). In this context, the goal of this brief communication is to recalculate the early 21st century geodetic mass balances of the Juneau and Stikine icefields using multi-temporal ASTER DEMs, carefully excluding the SRTM DEM to avoid a likely penetration bias.

2 Data, methods and uncertainties

The data and methodology applied to the JIF and SIF were identical to the ones used in a recent study deriving region-wide glacier mass balances in High Mountain Asia (Brun et al., 2017). The reader is thus referred to the latter study for details. Only the main processing steps are briefly presented here.

ASTER DEMs were calculated using the open-source Ames Stereo Pipeline (ASP) (Shean et al., 2016) from 3N (nadir) and 3B (backward) images acquired between 2000 and 2016. ~~All i~~Images with cloud coverage lower than 80% were selected, resulting in 153 stereo pairs for the JIF and 368 stereo pairs for the SIF. ~~Images~~ DEMs in which valid elevation data covered less than 0.5% of the icefield areas were excluded, reducing the number of ~~stereo pairs~~DEMs to 114 for the JIF and 284 for the SIF. Planimetric and altimetric offsets of each ASTER DEM were corrected using the SRTM DEM as a reference (Nuth and Kääb, 2011). Offsets were determined on stable terrain, masking out glacierized areas using the Randolph Glacier Inventory v5.0 (Pfeffer et al., 2014). The RGI v5.0 glacier outlines for both the JIF and SIF were mapped using imagery acquired in majority in~~from~~ August of 2004 and 2005 (Bolch et al., 2010; Kienholz et al., 2015). No updated inventory is available or was produced during this study for the JIF and SIF. Therefore, we neglected changes in glacierized area between 2000 and 2016, and assumed that mass balance uncertainties linked to area changes are covered by our 5% area uncertainty (Paul et al., 2013, Dussaillant et al., 2018).

For the JIF only, we also downloaded directly the ASTER DEMs available online from the LPDAAC website (called ~~14DMO~~AST14DEM) because they were used in Melkonian et al. (2014, 2016). The goal is to test the sensitivity of the JIF-wide mass balance to the ASTER DEM generation software. 3D coregistration of the ~~14DMO~~AST14DEMs ~~DEMs~~ was performed using the same steps as the ASP DEMs. Unlike the ASP DEMs, the ~~14DMO~~AST14DEMs ~~DEMs~~ contain no data gaps, as they are filled by interpolation.

From the time series of 3D-coregistered ASTER DEMs, the rate of elevation changes (*dh/dt* in the following) was extracted for each pixel of our study domain in two steps (Berthier et al., 2016). The SRTM DEM was excluded when extracting the final *dh/dt*. *dh/dt* were calculated for the entire period (from 2000 to 2016) and also for different sub-periods for the sake of comparability to published mass balance estimates.

For both icefields and in each 50-m altitude interval, *dh/dt* lying outside of ±3 normalized median absolute deviations (NMAD) were considered as outliers. We further excluded all *dh/dt* measurements for which the error in the linear fit is larger than 2 m a^{-1}. The total volume change rate was calculated as the integral of the mean *dh/dt* over the area altitude distribution. The icefield-wide mass balances ~~was~~ were obtained using a volume-to-mass conversion factor of 850 ~~± 60~~ kg m^{-3} (Huss, 2013). The same procedure was followed to compute the glacier-wide mass balances of selected ~~individual~~ glaciers for which mass balances were estimated from repeat laser altimetry surveys (Larsen et al., 2015).

Uncertainties for *dh/dt* were computed using ~~the tile~~a method ~~as in Berthier et al. (2016).~~ which consists in s~~S~~plitting the off-glacier terrain in 4 by 4 tiles (Berthier et al., 2016).~~,~~ For each tile, the mean *dh/dt* off-glacier is computed. The uncertainty is then calculated ~~using~~as the mean absolute difference for these 16 tiles. W~~w~~e found uncertainties of 0.03 m a^{-1} for JIF and 0.04 m a^{-1} for SIF from 2000 to 2016. When data gaps occurred in the *dh/dt* map, we conservatively multiplied these uncertainties by a factor of five. A ± 5% uncertainty for glacier area (Paul et al., 2013) and ± 60 kg m^{-3} for the density conversion factor (Huss, 2013) were used.

3 Results

Rate of elevation changes for the two icefields from 2000 to 2016 are mapped in Figure 1. Most glaciers thinned rapidly in their lower parts and experienced limited elevation change in their upper reaches. Thinning rates as negative as 9 m a^{-1} are observed. Taku Glacier (southern outlet of the JIF) is an exception with thickening of up to 4 m a^{-1} at its glacier front. Understanding the pattern of *dh/dt* and its variability among glaciers is beyond the scope of this brief communication and the reader is referred to earlier publications on this topic (e.g., Larsen et al., 2015).

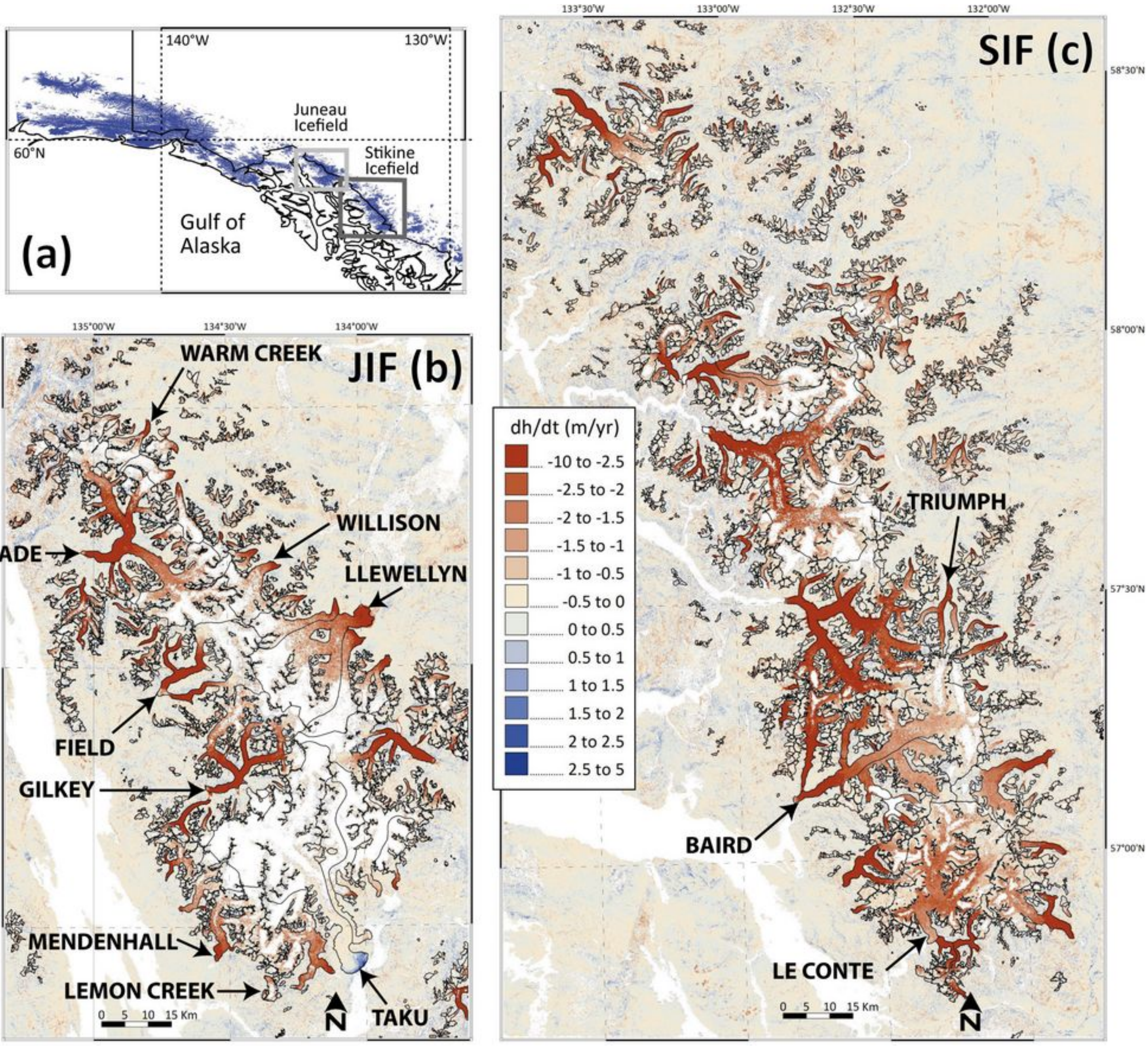

Figure 1: Rate of elevation changes for the Juneau and Stikine icefields from 2000 to 2016. (a) Location of the two icefields in southeast Alaska. Rate of elevation changes (*dh/dt*) for the JIF (b) and (c) for the SIF. Glacier outlines are from RGI v5.0. Glaciers surveyed by airborne laser altimetry are labelled. The horizontal scale and the color code are the same for the two maps. Areas in white correspond to data gaps.

The 2000-2016 mass balances are clearly negative for both icefields at -0.68±0.15 m w.e. a^{-1} for JIF (59% coverage with valid data) and -0.83±0.12 m w.e. a^{-1} for SIF (81% coverage with valid data). Our values are 0.51±0.18 m w.e. a^{-1} (JIF) and 0.21±0.25 m w.e. a^{-1} (SIF) more negative than in Melkonian et al. (2014, 2016) and statistically different for the JIF, i.e. the JIF mass balances do not overlap given the error bars. If we apply the linear regression analysis to a subset of the ASTER DEMs to match the time periods studied by Melkonian et al. (2014, 2016), the icefield-wide mass balances remain mostly unchanged: -0.64±0.14 m w.e. a^{-1} for JIF from 2000 to 2013, 44% coverage with valid data; -0.78±0.17 m w.e. a^{-1} for SIF from 2000 to 2014, 55% coverage with valid data.

The coverage with valid *dh/dt* data drops rapidly for both icefields when shorter time periods are considered, especially at high elevation. For example, the percentage of valid data is reduced to only 8% (respectively 25%) ~~only~~ on the JIF when the 2000-2008 (respectively 2008-2016) period is analyzed. Thus, the ASTER multi-temporal analysis is not appropriate to measure mass balance over periods shorter than 10 years for these two Alaskan icefields. This is due to the presence of many cloudy images and, for cloud-free scenes, to a large percentage of data gaps in individual ASTER DEMs over the accumulation areas of the icefields, a direct result of the limited contrast in the ASTER stereo-images over textureless snow fields.

In Figure 2, *dh/dt* are plotted as a function of altitude and compared to the values in Melkonian et al. (2014, 2016). To enable a more direct comparison, we applied the same criteria to average their *dh/dt* in 50-m altitude bands and exclude outliers. We also considered the same periods, from 2000 to 2013 for the JIF and from 2000 to 2014 for the SIF. In the case of the SIF (Figure 2b), we also added the *dh/dt* obtained by applying our method to the ~~14DMO~~AST14DEMs~~ DEMs~~.

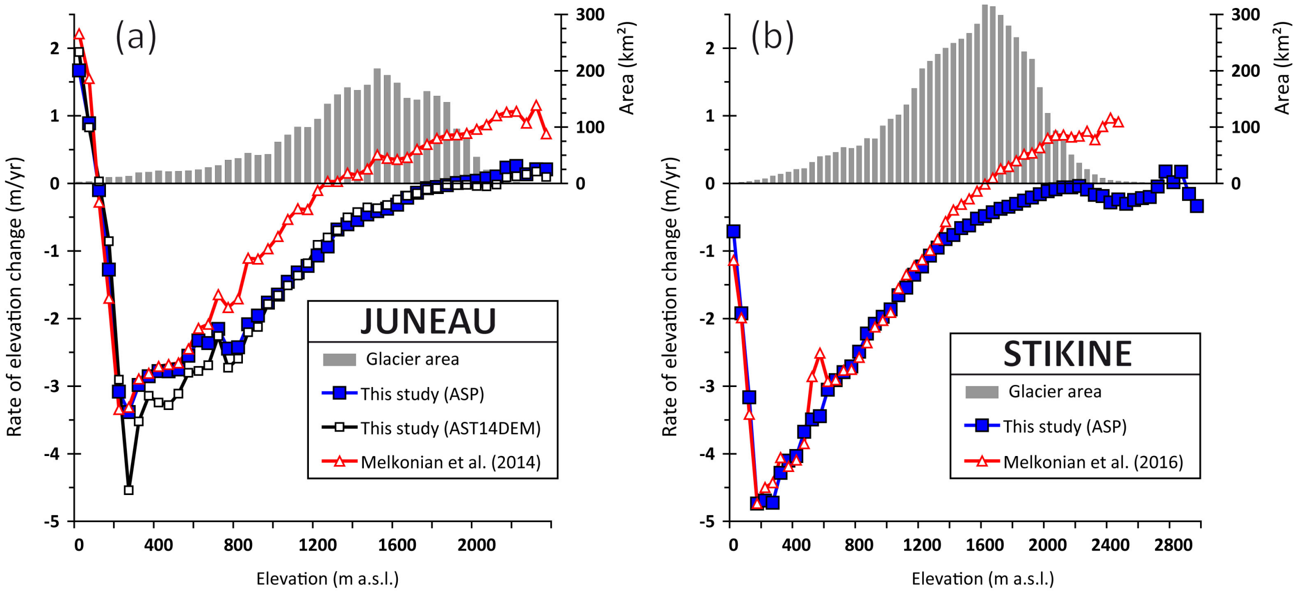

Figure 2: Rates of elevation change vs. elevation for the JIF from 2000 to 2013 (a) and for the SIF from 2000 to 2014 (b). Results from this study are compared to the *dh/dt* values obtained in two earlier studies using a similar method (Melkonian et al., 2014, 2016). The grey histograms show the area-altitude distribution.

For the JIF, an excellent agreement is found between the *dh/dt* values obtained in this study using the ASP DEMs and- the ~~14DMO~~AST14DEMs~~ DEMs~~, except ~~maybe~~ between 250 and 600 m a.s.l. (5% of the icefield area) where the thinning rates are about 0.5 m a^{-1} more negative using the ~~14DMO~~AST14DEMs~~ DEMs~~. The area-weighted mean absolute difference between these two curves (ASP and ~~14DMO~~AST14DEM) is 0.09 m a^{-1}. The Melkonian et al. (2014)'s *dh/dt* generally agree with ours below 600 m a.s.l. Above this elevation, their values are systematically more positive. The difference reaches 0.7 m a^{-1} at 800 m a.s.l. and then remains more or less stable, around 0.7-0.9 m a^{-1}. Melkonian et al. (2014) data suggests thickening of the areas above 1350 m a.s.l. where 62% of the JIF area is located.

For SIF, a good agreement is found between ours and Melkonian et al. (2016)'s *dh/dt* below an elevation of 1300 m a.s.l. Above 1300 m the two curves diverge. Our *dh/dt* are becoming less negative until 2100 m a.s.l. where they become indistinguishable from 0 m a^{-1} up to the SIF highest elevation band. Conversely, in the Melkonian et al. (2016) dataset, *dh/dt* increases rapidly, crossing 0 m a^{-1} at ~1650 m a.s.l., finally arriving at a thickening rate of > 0.7 m a^{-1} above 2000 m a.s.l. Thus the difference in SIF-wide mass balance between the two datasets is due to difference in *dh/dt* above 1300 m a.s.l., where 66% of the SIF icefield area is found.

Comparison of our *dh/dt* estimates to the ones derived from repeat laser altimetry data is not straightforward because the survey periods differ. For example, for the JIF, six out of nine glaciers were sampled for the first time in 2007. In most cases, it would be technically possible to use a temporal subset of the ASTER DEMs to match the time period of altimetry surveys but, as said above, this would be at the cost of the coverage in our *dh/dt* maps and would lead to much more uncertain mass balance estimates. Consequently, we preferred to extract *dh/dt* and the individual glacier mass balance for the longest available time period in the ASTER series (from 2000 to 2016) in order to maximize coverage and thus minimize uncertainties. ~~Another~~A further complication for the comparison of our ASTER-based results to repeat laser altimetry arises from ~~the~~ different spatial sampling: ~~generally~~mostly continuous coverage from DEMs vs. centreline sampling ~~only~~ from laser altimetry. Berthier et al. (2010) found that centreline sampling could lead to an overestimation of ~~the~~ mass loss. In ~~fact~~their study, two large and rapidly retreating glaciers (Bering and Columbia, outside of our study domain) ~~alone~~ were responsible for 92% of the overestimation of the mass loss from centreline profiling (Table S4 in Berthier et al., 2010). ~~while the o~~Overestimation was not obvious for other glaciers ~~(their Table S4)~~. More recently, Johnson et al. (2013) ~~developed~~presented an improved ~~methodology~~treatment of laser altimetry data and found no such overestimation from centerline profiling ~~for~~over the ~~nearby~~ Glacier Bay region ~~of~~(~~s~~Southeast Alaska). In their ~~revised~~improved processing ~~analysis~~, each change in elevation (*dz*) is assigned to a mid-point between old and new elevations whereas in the original laser altimetry analysis (Arendt et al., 2002), *dz* were assigned to the old elevation.

The pattern of *dh/dt* with altitude for individual glaciers is in broad agreement between laser altimetry and our ASTER-based results (Supplementary Figure S1). Importantly, for both datasets, no clear thickening was observed in the accumulation areas of glaciers. When individual elevation bins of 50 m are considered, averaged differences between *dh/dt* from laser altimetry and the ASTER DEMs are typically 0.2 to 0.3 m a^{-1} for individual glaciers. This level of error is similar to the one found previously for the ASTER method in the Mont-Blanc area (Berthier et al., 2016).

Glacier-wide mass balances for individual glaciers match well (Table 1, Supplementary Figure S2).

The mean mass balance of these 12 glaciers is nearly the same (-0.73 and -0.74 m w.e. a^{-1}) using the two techniques. The standard deviation of the mass balance difference is 0.18 m w.e. a^{-1} (n=12). For 60 individual glaciers larger than 2 km² in High Mountain Asia, Brun et al. (2017) also found a standard deviation of 0.17 m w.e. a^{-1} between the ASTER-based and published glacier-wide mass balance estimates. In the very different geographic context of large maritime glaciers of southeast Alaska, we confirm here their uncertainty estimate for individual glaciers in High Mountain Asia.

Our results are also in good agreement with ~~field (~~glaciological~~)~~ measurements on Taku and Lemon Creek glaciers. For Taku Glacier, ~~found ~~the mass balance was -0.01 m w.e. a^{-1} between September 2000 and September 2011 (Pelto et al., 2013) and -0.08 m w.e. a^{-1} between September 2000 and September 2016 (WGMS, 2017). We derived a very similar glacier-wide mass balance (-0.01 ± 0.16 m w.e. a^{-1}) from ASTER DEMs acquired between 2000 and 2016. Conversely, Melkonian et al. (2014)'s mass balance for Taku Glacier was strongly positive at +0.44 ± 0.15 m w.e. a^{-1}. The 2000-2016 mass balance for Lemon Creek Glacier ~~is ~~was -0.56 m w.e. a^{-1} (WGMS, 2017) while our ASTER-based mass balance is just slightly more negative at **-0.78 ± 0.14** m w.e. a^{-1}.

Table 1. Glacier-wide mass balances (B_a) of 12 individual glaciers of the JIF and SIF derived from airborne laser altimetry for different periods (Larsen et al., 2015) and calculated in this study using ASTER DEMs from 2000 to 2016. Uncertainties for the mean mass balances of 9 (JIF) and 3 (SIF) and 12 (JIF and SIF) glaciers are calculated as the area-weighed mean of uncertainties for individual glaciers.

Icefield/Glacier	Area km²	Laser period	B_a Laser m w.e. a^{-1} (Larsen et al., 2015)	B_a ASTER m w.e. a^{-1} (this study)
Juneau	**3398**			**-0.68 ± 0.15**
Field	187	2007-2012	-0.94 ± 0.26	-0.93 ± 0.16
Gilkey	223	2007-2012	-0.75 ± 0.23	-0.99 ± 0.14
Lemon Creek	9	1993-2012	-0.91 ± 0.48	-0.78 ± 0.14
Llewellyn	435	2007-2012	-0.61 ± 0.15	-0.70 ± 0.17
Meade	446	2007-2012	-1.03 ± 0.26	-0.88 ± 0.15
Mendenhall	106	1999-2012	-0.57 ± 0.87	-0.73 ± 0.13
Taku	711	1993-2012	0.13 ± 0.10	-0.01 ± 0.16
Warm Creek	39	2007-2012	-0.67 ± 0.31	-0.71 ± 0.16
Willison	79	2007-2012	-0.51 ± 0.38	-0.69 ± 0.15
Sum/Mean 9 glaciers	**2234**		**-0.65 ± 0.22**	**-0.71 ± 0.16**
Stikine	**5805**			**-0.83 ± 0.12**
LeConte	56	1996-2013	-0.98 ± 0.31	-0.93 ± 0.13
Baird	435	1996-2013	-0.71 ± 0.12	-0.70 ± 0.12
Triumph	356	1996-2013	-1.19 ± 0.48	-0.86 ± 0.10
Sum/Mean 3 glaciers	**847**		**-0.96 ± 0.28**	**-0.83 ± 0.12**
Mean all 12 Glaciers			**-0.73 ± 0.24**	**-0.74 ± 0.15**

4 Discussion

We find an excellent agreement between repeat laser altimetry survey and our multi-temporal analysis of ASTER DEMs both in term of mass balances and pattern of *dh/dt* with altitude for the JIF and SIF since 2000 (Supplementary Figure S1-S2). This agreement suggests that an appropriate analysis of centreline data may be ~~appropriate~~sufficient to ~~study~~measure the glacier-wide mass balance of these glaciers as~~,~~ previously ~~also ~~shown for the nearby Glacier Bay area (Johnson et al., 2013). Our results also suggest that the limited number of glaciers sampled using laser altimetry are representative of the icefields as a whole. This is rather expected for the JIF because 9 glaciers covering a large fraction of the icefield (66%) were monitored using airborne data but not straightforward for the SIF where only 3 glaciers, accounting for 15% of the total icefield area, were surveyed.

This agreement between our ASTER results and airborne laser altimetry, together with the fact that most studies point toward steady or accelerating mass losses in southeast Alaska (see introduction), suggest that the mass balance is overestimated in Melkonian et al. (2014, 2016). There are two main differences between Melkonian et al. (2014, 2016)'s method and ours that could explain these contending mass balances: (i) they did not generate the DEM themselves but directly download the ~~14DMO~~AST14DEM product from the LPDAAC website and (ii) they used the SRTM DEM as a starting elevation in their regression analysis to compute *dh/dt*.

To test the sensitivity of our results to the ASTER DEM generation software, we applied our processing chain (in particular, excluding the SRTM DEM to infer the final *dh/dt*) to the ~~14DMO~~AST14DEMs ~~DEMs~~. From 2000 to 2016, we found a JIF-wide mass balance of -0.67±0.27 m w.e. a^{-1}, in striking agreement with the value derived from ASP DEMs (-0.68±0.15 m w.e. a^{-1}). The pattern of *dh/dt* with elevation is also in excellent agreement (Figure 2a). Uncertainties are nearly doubled when applying our method to the ~~14DMO~~ AST14DEMs~~DEMs~~: this is explained by larger errors of *dh/dt* off glacier (0.06 m a^{-1} for AST14DEMs ~~14DMO DEMs~~ vs. 0.03 m a^{-1} for ASP DEMs) and a lower coverage of the JIF with valid *dh/dt* data (49% for AST14DEMs ~~14DMO DEMs~~ vs. 59% for ASP DEMs). The latter may appear counter-intuitive as the AST14DEMs~~14DMO DEMs~~ are delivered with no data gaps. The larger percentage of data gaps in the final AST14DEMs~~14DMO~~ *dh/dt* maps results from the higher noise level of the individual AST14DEMs ~~14DMO DEMs~~ and demonstrate the efficiency of our filters to exclude unreliable *dh/dt* values.

Thus, we conclude that ~~a likely explanation why~~ Melkonian et al. (2014, 2016) found too positive mass balance for the JIF and, to a lesser extent, for the SIF ~~is~~ because of~~associated with~~ ~~the SRTM DEM and in particular~~ the penetration of the SRTM C-Band radar signal into cold winter snow and firn. This interpretation is further supported by the fact that *dh/dt* curves nicely agree in the ablation areas where SRTM penetration depth is negligible and diverge in the colder and drier accumulation areas where ~~the~~ larger~~st~~ penetration depths are expected (Figure 2). As noted in the introduction, Melkonian et al. (2014, 2016) ~~attempted to~~ accounted for this by subtracting the C-Band and X-Band SRTM DEM, assuming no penetration of the X-Band DEM (Gardelle et al., 2012). However, ~~studies have measured~~ X-band penetration ~~depth~~ can reach~~of~~ several meters into cold snow and firn (e.g., Dehecq et al., 2016; Round et al., 2017). In the case of the SIF, Melkonian et al. (2016) assumed no penetration below 1000 m a.s.l. and 2 m for elevations above 1000 m. Aware of how uncertain this correction was, these authors also proposed (their supplementary material section 6.3 and, Table S4) a different correction with no penetration below 1000 m a.s.l. and a linear increase from 2 to 8 m from 1000-2500 m a.s.l. Using this alternative scenario, they found an icefield-wide mass balance of -0.85 m w.e. a^{-1}, in better agreement with our value of -0.78±0.17 m w.e. a^{-1} from 2000 to 2014. Their 2 to 8 m penetration depth is consistent with the penetration gradient we inferred here by subtracting the SRTM DEM from a reconstructed DEM, obtained by extrapolating *dh/dt* to the time of acquisition of the SRTM as proposed in Wang and Kääb (2015). This is also consistent with a first-order estimate of the penetration depth inferred from the elevation difference between the SRTM DEM and laser altimetry profiles acquired in late August 1999 and May 2000 over Baird and Taku glaciers. However, the latter estimates should be considered with care ~~considering~~ given the complexity to account simultaneously for seasonal elevation changes, long term elevation changes and the difficulty to estimate the vertical offset between the two elevation datasets on ice-free terrain.

The fact that the positive bias in Melkonian et al. (2014, 2016) mass balances was larger for the JIF ~~and~~ than for the SIF suggests a larger SRTM penetration depth for the JIF. It indicates that this~~e~~ penetration is probably spatially variable (depending on the firn conditions in February 2000) such that a correction determined on a single icefield (or worse a single glacier) may not apply to neighbouring glacier areas.

Larsen et al. (2007) used the SRTM DEM as their final topography after applying a linear correction of SRTM with altitude (2.6 m per 1000 m elevation, with a -2.5 offset at 0 elevation) determined by comparing SRTM to August 2000 laser altimetry data. Such a correction would correspond to a maximum SRTM penetration of ~1.5-2 m above 1500 m a.s.l., much smaller than what we found here. Thus, the fact that SRTM penetration depth is larger than previously thought over southeast Alaska icefields may explain why Larsen et al. (2007) found larger mass losses than Arendt et al. (2002) and Berthier et al. (2010) who both used only non-penetrating optical ~~(Lidar or stereo-imagery)~~ data (lidar or stereo-imagery).

An uneven seasonal distribution of the ASTER DEMs could bias the multi-annual mass balances derived using the ASTER method (Berthier et al., 2016). This is especially crucial in maritime environment such as southeast Alaska where large seasonal height variations are expected. As in the case of the Mont-Blanc area (Figure 6 in Berthier et al., 2016), we sampled an hypothetic seasonal cycle in surface elevation changes at the time of acquisition of all ASTER DEMs over the JIF and fitted a linear regression to the elevation change time series. Assuming a seasonal amplitude as large as 10 m (a value in agreement with field measurements of the Juneau Icefield Mass Balance Program, Pelto et al., 2013), the slope of the regression line is very close to 0 (-0.007 m a^{-1}) suggesting no seasonal bias in the dates of the ASTER DEMs. To confirm the lack of seasonal bias and because the majority of the ASTER images were acquired close to accumulation peak, we also calculated a mass balance for the JIF considering only the 61 ASTER DEMs acquired in March, April and May between 2000 and 2016. For this alternative mass balance estimate, the coverage with valid data is reduced to 38%. At -0.58±0.18 m w.e. a^{-1}, the JIF-wide mass balance is slightly less negative but not statistically different from the "all seasons" value (-0.68±0.15 m w.e. a^{-1}, 59% of valid data). The pattern of *dh/dt* with altitude is also very similar.

5 Conclusion

Our ASTER-based analysis~~In this study, we~~ shows that the Juneau and Stikine icefields continued to lose mass rapidly from 2000 to 2016, ~~which~~ a finding~~is~~ in agreement with the repeat laser altimetry and field based ~~assessments~~measurements~~ on a smaller sample of these glaciers~~. The mass balances from repeat airborne laser altimetry and multi-temporal ASTER DEMs are reconciled if the SRTM DEM is discarded when extracting the rate of elevation change on glaciers from the elevation time series. Multi-temporal analysis of DEMs derived from medium resolution satellite optical stereo-imagery is thus a powerful method to estimate geodetic region-wide mass balances over time intervals of, typically, more than 10 years. Shorter time intervals can now be measured using very high resolution imagery (e.g., Worldview and Pléiades). The strength of the ASTER method lies in the fact that it is based on an homogeneous and continuous archive of imagery built since 2000 using the same sensor. Maintaining openly available medium- to high-resolution stereo capabilities should be a high priority among space agencies in the future.

Previously published mass balances for these Alaska icefields using SRTM and ASTER DEMs were likely biased positively because of the strong penetration of the C-Band and X-Band radar signal into the cold winter snow and firn in February, when the SRTM was flown. Accounting for this penetration by subtracting the C-Band and X-Band SRTM DEMs (as often done before) is not appropriate because the X-Band penetration depth can also sometimes reach several meters if radar images are acquired under cold and dry conditions~~, except if water is present in the snow and firn upper layers at the time of acquisition of the radar images~~. Under wet conditions, when water is present in the snow and firn upper layers, this penetration is reduced. Even so, c~~C~~aution should thus be used when deriving mass balance using SRTM and Tandem-X DEMs over time period of less than ~20 years in Alaska and elsewhere. Comparing DEMs acquired at the same time of the year using the same radar wavelength ~~(e.g., Neckel et al., 2013)~~ is one promising strategy to limit the bias due to differential radar penetration (e.g., Neckel et al., 2013).

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Author contributions

E.B. designed the study, made the data analysis and lead the writing. C.L. provided the laser altimetry data. W.D., M.W. and M.P. provided unpublished results. All authors discussed the results and wrote the paper.

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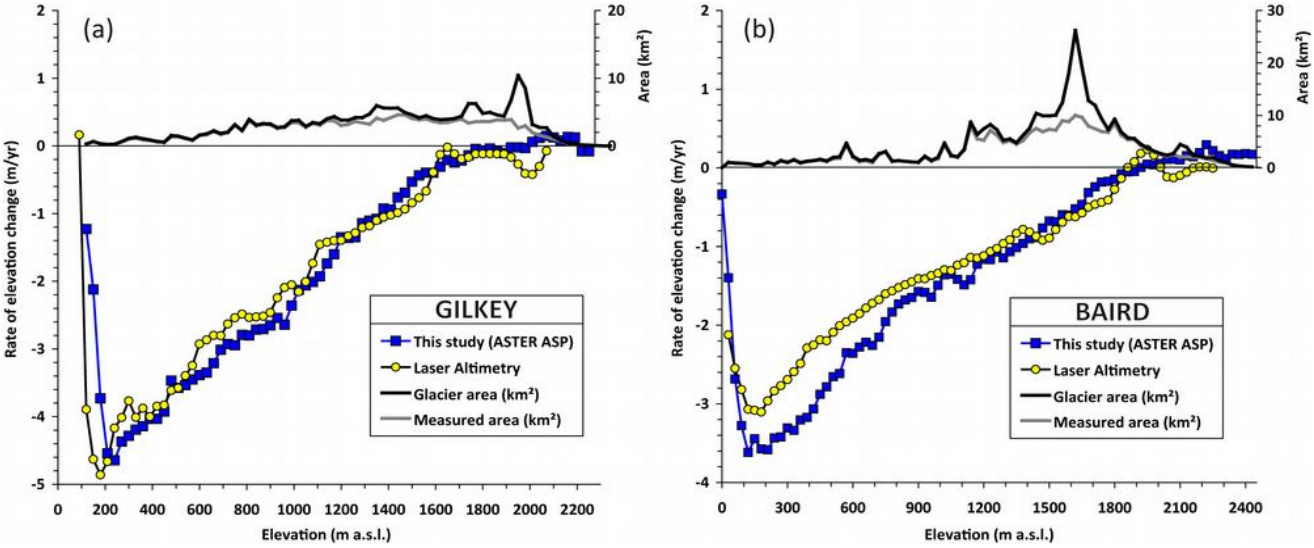
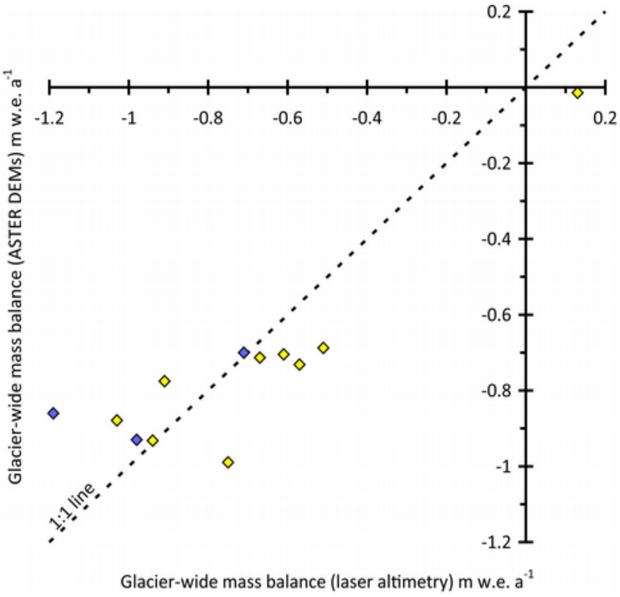
Supplement



Supplementary Figure S1: Rates of elevation change vs. elevation for (a) Gilkey Glacier (Juneau Icefield) and (b) Baird Glacier (Stikine Icefield) measured from ASTER DEMs (blue curve, 2000-2016) and airborne laser altimetry data (2007-2012 for Gilkey and 1996-2013 for Stikine). The upper curve (right Y-axis) show the total area altitude distribution (black) and the glacier area effectively sampled using in the ASTER DEMs~~dh/dt~~ (grey).



Supplementary Figure S2: Glacier-wide mass balances (Ba) of individual glaciers of the JIF (yellow, 9 glaciers) and SIF (blue, 3 glaciers) calculated in this study using ASTER DEMs from 2000 to 2016 and derived from airborne laser altimetry for different periods (Larsen et al., 2015). The dashed line is the 1:1 line.