12th May 2018

Centre for Polar Observation and Modelling

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Dear Prof. Vieli,

"Ice velocity of Jakobshavn Isbræ, Petermann Glacier, Nioghalvfjerdsfjorden and Zachariæ Isstrøm, 2015-2017, from Sentinel 1-a/b SAR imagery"

Thank you for considering the above manuscript for publication in The Cryosphere. We have submitted a revised manuscript that addresses each of the issues raised by the reviewers, and accompanying documents that describe these changes in detail.

We have given particular attention to the major issues raised by Reviewer 1, and full details of the changes and our response to these points are given below. In summary, we have (1) added more glaciological interpretation of the data focused on the capability offered by the high temporal sampling rate, namely to resolve the magnitude and duration of summer speed up at each glacier, (2) added further discussion relating to the glaciological interpretation of the data, (3) revised and expanded the introduction, including adding relevant references, and (4) clarified our method for estimating uncertainty.

We are grateful for the comments provided by yourself and the reviewers, as they have helped to substantially improve the manuscript, and we hope that the changes are to your satisfaction. We look forward to your reply.

Yours faithfully

Adriano Lemos

(corresponding author)

INTERACTIVE COMMENTS

The responses (A) to the referees' comments are shown in blue below.

ANONYMOUS REFEREE #1

We thank the anonymous referee for the comments and suggestions, which have significantly improved the manuscript.

GENERAL COMMENTS:

R#1: 1: The paper could be significantly improved by expanding on the implications of observations for better understanding ice dynamics. Right now, to me it reads as a lot of results without much discussion of significance or implications. For this work to be published in The Cryosphere, it seems it should increase our understanding of glacier mechanics/dynamics, not just describing what we see. For example, why has Jakobshavn Isbrae (JI) begun slowing? Why did the amplitude of seasonal velocity change increase on JI at the same time?

A: We have modified the abstract and discussions to make clear the scope of the paper, and to add some preliminary discussion relating to the origin of the JI slowdown. However, we emphasise that the purpose of this study was to develop and report new observations of glaciological change, rather than to provide a detailed process-orientated investigation. The former in itself, we believe, is a significant body of work, which reports new and important findings that will be of interest to a broad spectrum of the cryospheric community, and is therefore relevant for publication in The Cryosphere. The slowdown of JI, for example, is an important new finding and we have extended our discussion of the possible cause within the revised manuscript (P5L35-40). However, a full process-based investigation of the associated forcing mechanisms is, we believe, well beyond the scope of this current study.

R#1: 2: It seems to me that you could better exploit the novelty of this high temporal resolution dataset to investigate processes at "the timescales over which glacier dynamics evolve". Resolving multi-annual trends in velocity doesn't require 6 or 12 day repeat times. But investigating seasonal dynamics hugely benefits from this increased temporal resolution. I believe your paper could be strengthened (in its ability to demonstrate capability of new generation radar satellites) by digging in deeper to these processes that are more difficult to resolve with existing datasets.

A: Thanks for the suggestion. We have added new analysis of the 6 day dataset to quantify the relative magnitude and duration of the seasonal velocity acceleration for all glaciers. We now add these results (table 1) as one of the main conclusions of the paper, and report these findings in the abstract and the discussion section.

R#1: 3: The introduction could use more substance by referencing relevant existing work. See "specific comments" for some suggested references.

A: Thank you for the comments and the extras references suggested. We have rewritten unclear points and added more references. Further details are provided in the responses to specific comments below.

R#1: 4: I wonder if your method for characterizing uncertainty may overestimate your error. It seems that by using SNR (where SNR =(mean velocity)/(standard deviation of velocity) within your window, correct?) would be higher where velocity is spatially variable. In this case, SNR would be high, but not because of bad data – because of physically meaningful velocity variation. It seems like the margins/shear zones typically have high uncertainty – could this just be because there are very different (physically meaningful) velocities across these regions?

A: The signal to noise ratio (SNR) used in this work is a relation between the cross-correlation function peak (Cp) and the average correlation level (CL) on the tracking window used to estimate the velocity (SNR=Cp/CL). We clarify this point on lines P4L16-17. The shear margins have high uncertainties because they are challenging areas to track velocity due to the non-uniform flow, lack of stable features and geometry distortion even after the terrain correction (P4L19-21).

SPECIFIC COMENTS:

R#1: P1L28: Your definition of mass balance appears to ignore negative terms in SMB (i.e., only mentions mass input)

A: Done (P1L27-28).

R#1: P1L39: See below for relevant papers for this idea that should be cited – e.g.,

Felikson, D., Bartholomaus, T. C., Catania, G. A., Korsgaard, N. J., Kjær, K. H., Morlighem, M., . . . Nash, J. D. (2017). Inland thinning on the Greenland ice sheet controlled by outlet glacier geometry. Nature Geoscience, 10, 366–369. https://doi.org/10.1038/ngeo2934

Durkin, W. J., Bartholomaus, T. C., Willis, M. J., Pritchard, M. E. (2017). Dynamic changes at Yahtse Glacier, the most rapidly advancing tidewater glacier in Alaska. Frontiers in Earth Science, 5(March), 1–13. https://doi.org/10.3389/feart.2017.00021

A: We added additional references as showed in P1L39-40.

R#1: P2L7: Should cite modern Landsat efforts mapping glacier velocity changes at large scale – e.g.,

Armstrong, W. H., Anderson, R. S., Fahnestock, M. A. (2017). Spatial patterns of summer speedup on south central Alaska glaciers. Geophysical Research Letters, 44. https://doi.org/10.1002/2017GL074370

Burgess, E. W., Forster, R. R., Larsen, C. F. (2013a). Flow velocities of Alaskan glaciers. Nature Communications, 4, 2146. https://doi.org/10.1038/ncomms3146

Dehecq, A., Gourmelen, N., Trouve, E. (2015). Deriving large-scale glacier velocities from a complete satellite archive: Application to the Pamir-Karakoram-Himalaya. Remote Sensing of Environment, 162, 55–66. https://doi.org/10.1016/j.rse.2015.01.031

Fahnestock, M., Scambos, T., Moon, T., Gardner, A., Haran, T., Klinger, M. (2016). Rapid large-area mapping of ice flow using Landsat 8. Remote Sensing of Environment, 185, 84–94. https://doi.org/10.1016/j.rse.2015.11.023

Jeong, S., Howat, I. M. (2015). Performance of Landsat 8 Operational Land Imager for mapping ice sheet velocity. Remote Sensing of Environment, 170(8), 90–101. https://doi.org/10.1016/j.rse.2015.08.023

A: Done (P2L7-8).

R#1: P2L27-28: Many authors have shown that high melt years actually correspond with smaller net annual displacements – e.g.,

Burgess, E. W., Larsen, C. F., Forster, R. R. (2013b). Summer melt regulates winter glacier flow speeds throughout Alaska. Geophysical Research Letters, 40, 6160–6164. https://doi.org/10.1002/2013GL058228

Tedstone AJ and 6 others (2013) Greenland ice sheet motion insensitive to exceptional meltwater forcing. Proc.Natl. Acad. Sci.U. S. A., 110(49), 19719–19724 (doi: 10.1073/pnas.1315843110)

Van De Wal, R. S. W., Smeets, C. J. P. P., Boot, W., Stoffelen, M., Van Kampen, R., Doyle, S., Hubbard, A. (2015). Self-regulation of ice flow varies across the ablation area in south-west Greenland. Cryosphere, 9(2), 603–611. https://doi.org/10.5194/tc-9-603-2015

A: We rephrase the sentence and added one of the references (P2L29-31).

R#1: P3L35: I believe you are talking about 5 cm position uncertainty in the satellite. What is your uncertainty in the ground coordinates of each pixel?

A: We modified the text, making clear that the precise orbit establishes a 5 cm 3D 1-sigma co-registration accuracy requirement.

R#1: P3L36-37: I am not a SAR person – do you have to model or account for atmospheric delays? Seems like you would have to do that before isolating glacier displacement.

A: Our uncertainty estimates account other error's resources including the atmospheric delay due to ionospheric disturbances and/or tropospheric water vapour.

R#1: P3L41-42: What year was the data used for the GIMP DEM collected? How would error in the GIMP DEM (or elevation change between its acquisition and your time series) affect your velocity estimates?

A: Please find more information about GIMP digital elevation model in Howat et al. (2014). We discuss the elevation change variation influence in P4L15-19 and supplementary table 2.

R#1: P4L4-6: What labelling algorithm do you use? This bit is unclear and would be difficult to repeat.

A: In order to filter the final products, we group the image in patches with similar values based on the histogram and reject loose regions with area smaller than 1/1000 of the image size.

R#1: P4L10-13: It seems like this approach would lump actual physical spatial velocity variability with spurious non-physical velocities. Could this be why your glacier margins/shear zones on Figure 3 are always high uncertainty? There actually is high spatial variability in velocity there, so SNR would be low, but not because of bad data. It seems like this method may overestimate error in some regions.

A: As addressed in the major comments, the signal to noise ratio (SNR) used in this work is a relation between the cross-correlation function peak (Cp) and the average correlation level (C_L) on the tracking window used to estimate the velocity (SNR=Cp/C_L). The shear margins have high uncertainties because they are challenge areas to track velocity due to the non-uniform flow, lack of stable features and geometry distortion even after the terrain correction.

R#1: P4L17: What is your "airborne estimate of elevation change"? What constitutes an "extreme case" (i.e., what is the magnitude "large" of surface lowering? Needs more detail.

A: Done (P4L22-24).

R#1: P4L15-24: Are these errors systematic or random? Seems like tidal forcing may be random (sometimes surface is higher, other times surface is lower than you think) but thinning would be systematic (always lower than you think).

A: The errors are systematic and now we made this clearer in the text.

R#1: P4L26-27: It seems that using one SAR estimate of velocity to check another SAR estimate of velocity is vulnerable to errors that would effect both in the same way. Do you have any known velocities from GPS or optical image correlation to compare against?

A: We chose TSX due to its long time series and overlap estimates. The use of GPS velocities to validate our estimates would be a better alternative instead of other SAR estimate, however we don't have any known of overlap measurements.

R#1: P4L26-27: Should also specify that TSX is based off phase change (InSAR) and you are using feature tracking of SAR imagery (amplitude based) if that is indeed the case. This provides more evidence that using it is a robust check on your data because it is a different method.

A: Done (P4L35).

R#1: P5L7-9: How does this “highlight the importance of resolving glacier velocities within their near terminus regions”? And resolve for what purposes?

A: We rephrase the sentence making it clearer (P5L15-17).

R#1: P5L25: What station is this 5 year speed change calculated at? Jif? Looks like JI1/2 are relatively stable over this time. What would magnitude be if calculated there?

A: We indicated which point (Jif) we referred to and included the figures that shows it. J1 and J2 have also a negative trend, however gentler (~40 and ~8 m yr^{-2}) due to their distance from the ice front (P5L34-35).

R#1: P6L1 - This is interesting that you find different relationship between speedup and retreat at different glaciers. But seems similar to findings by Moon et al., that find some glaciers terminus-forced, others see more land-terminating style of meltwater-forced. If dL = uice −ucalve, then would expect lengthening if calving can't keep up with faster ice flow in summer.

A: Our dataset shows that for this period of time, PG speedup and underwent an ice front advancing.

R#1: P6L20-24 – How could Münchon et al. [2016] have used data from 2016/2017? And seems like comparing apples to oranges to compare speedup calculated over different time spans. That seems to tell more about glacier dynamical change than measurement accuracy.

A: We agree this was poorly worded. We have modified the text to explain more clearly the time period used for the inter-comparison. Moreover, we rewrote the text to specify that we assessed the level of stability and not the accuracy of the dataset.

FIGURES

R#1: Figure 1 – difficult to see lines. Please thicken all lines, but especially green. I also think the overlay makes the image harder to interpret. Maybe just overlay on a grayscale hill-shaded DEM that would provide topographic data but not confuse velocity information.

A: Done. However, instead of adding the hill-shaded DEM, we added contour lines with elevation information.

R#1: Figure 2 – This figure would be clearer to me if you labelled the lines in at least panel a.

A: Done.

R#1: Figure 5 – Could you show earlier data (from a different source) to put this plot in context of longer-term JI velocity evolution?

A: Due to the focus of the study which is on short-term velocity variations, we prefer to concentrate only on the period after 2009 when sampling is frequent, as we do not aim to analyse long term variations.

R#1: Figure 6 – How are portions of data for fitting red and black lines decided? Don't think either is the 2009-2011 or 2012-2017 fit lines mentioned in the text?

A: The portions are defined by the slowing down period. The fitting lines were mentioned in the text however, it was missing a reference. The reference is included now. (P5L38-40)

TECHNICAL CORRECTIONS – TYPOGRAPHICAL ERRORS:

R#1: P1L33: language is a little sloppy/unclear – marine terminating glaciers still have SMB – should specify this 30

A: Done.

R#1: P1L34-35: "erosion of their termini" → replace with "terminus retreat" or "submarine melting"; I can't tell what you mean and "erosion" could be confused for subglacial bedrock lowering.

A: Done.

R#1: P1L38: "high frequency variability" → "high spatial variability" if this is what you mean

A: Done.

R#1: P2L8: "Polar Regions" → "polar regions".

A: Done.

R#1: P2L26: "over the past few years" implies the JI speedup is ongoing (which you show it is not).

A: Done.

R#1: P2L33-35: Sentence starting with "Therefore. . ." is confusing. You are saying -10 km2/a is not a big area change? Could just reword this sentence to be positive (e.g., "glacier area has remained relatively constant") instead of negative (e.g., "glacier area has not changed an unusually large amount")

A: Done.

R#1: P3L1: migration of what? Would call this "terminus retreat rate" if that is indeed what it is.

A: Done.

R#1: P3L8: Sentence starting with "Although located. . ." could be reworded to use fewer commas.

A: Done.

J.R. CARR (REFEREE #2)

R#2: This paper uses new, high-resolution satellite imagery to assess velocity variations on four large Greenlandic outlet glaciers. Overall, it is very well written, clear and topical. It makes a useful contribution to the field and presents interesting results. It also nicely illustrates the usefulness of these datasets. It is concise but addresses the questions it sets out to answer. I have a few minor comments below, which are noting places where things could be clarified or expressed more clearly. Overall, however, I think it is a really good paper in its present form. Nice to see such a well-put together and concise paper.

A: We would like to thank J.R. Carr for the suggestions and positive comments, which have significantly improved the manuscript. We made all the modifications suggested and we addressed the minor comments as follow below.

MINOR COMMENTS

R#2: P1L13: Indicate temporal resolution in brackets.

A: Done.

R#2: P1L19: Give date.

A: Done.

R#2: P1L30: Sentence is a bit hard to follow. Consider splitting.

A: We reworded the sentence (P1L30-33).

R#2: P1L34: Specify the time period as 'last years' will date with the paper.

A: Done (P1L34).

R#2: P1L37: There are other references that are relevant here, e.g. Jensen et al., 2016, Carr et al., 2017 (J Glac). There are a couple of places in the intro where only one or two refs are given, but there are clearly more. Please add a selection of relevant ones and add 'e.g.' to indicate awareness of the others you don't list. Also need a couple of references for the statement about glacier specific and climatic controls.

A: Done (P1L39-40).

R#2: P2L3: ...ice sheet dynamics AND ice discharge, and for assessing....

A: Done.

R#2: P2 L14: Why these glaciers. I'd add a sentence of two. This is sort of given in the next sentence, but it feels like it needs a clear justification at this point.

A: Done. We complemented the paragraph on the "Study areas" (P2L22-23)

R#2: P2L33: Seems odd to switch to area change here, after discussing retreat. I know this paper does look at area change, so I'd work on improving the flow of the argument here.

A: We changed the linking word, showing additional information (P2L36).

R#2: P3L21: Is this the maximum data range? Worth stating for clarity.

A: Done (P3L22-24).

R#2: P3L26: Might be useful to have graph showing image availability for each glacier over time. E.g. you could have a bar graph, with number of images on the Y axis, then time on the X axis, at monthly intervals. You'd then have a different coloured bar for each of the four glaciers. I'm suggesting this so that the reader can get a better handle on how these 187 velocity maps are distributed over the glaciers and over time.

A: Done. We added the figure as a supplementary figure (Figure S2).

R#2: P3L40: Why was this value used?

A: This means values under 5 % from the maximum normalised cross-correlation peak were rejected (P4L1).

R#2: P4L2: Why was this spacing used? Was it because of the GIMP resolution?

A: We use the GIMP for the terrain correction, which the spatial resolution is 90m.

R#2: P4L14: Please state what these higher errors were in a separate sentence.

A: Done.

R#2: P4L43: What period were these means taken over? Or do you mean the maximum value of the means across the whole glacier? Generally this is done well, but make sure you give the time period / spatial extent of your averages, as it's sometimes hard to follow which average/period you are discussing.

A: We meant the mean speeds along the stacked dataset (P5L7).

R#2: P4L44: Do you mean velocity MAXIMA (not magnitude)?

A: Done.

R#2: P5: On this page, there are several points were it would be useful to refer back to the relevant figures, e.g. L2, L24, L26. Please update throughout, as it helps guide the reader quickly to the relevant figures.

A: Done.

R#2: P5L2: I'm not clear what '46 km extension' refers to. Please revise this description so it's clear.

A: Done (P5L11).

R#2: P5L7: I find this hard to follow. Please re-phrase.

A: Done (P5L15-16).

R#2: P5L12: ...scale variability, which continues....

A: Done.

R#2: P5L14: Helpful to repeat the time period these values relate to.

A: Done.

R#2: P5L34: starts IN early 2015.

A: Done.

R#2: P6L10: Please state whether or not this relationship is statistically significant, then have the explanation of why it is not significant (i.e. lack of data).

A: We explain it is difficult to assess due to the limited dataset (P6L26).

R#2: P6L27: I think it would help to add a summary sentence or two. I'd definitely add one to sum up the key message of this paragraph (i.e. your data agree pretty well), and maybe add another, more general summary sentence to reflect on the usefulness of the data for this purpose. At the moment, it feels like the paper ends abruptly, even if you do say this in the conclusion.

A: Done (P6-43-P7L2).

R#2: P6L31: Be specific about what you mean by 'important', I.e. high flow, large discharge.

A: Done (P7L3).

R#2: P6L32: I'd just give the date, as 'the present day' dates.

A: Done (P7L6).

FIGURES

R#2: Figure 1 & 3: The labels on these maps need to be much bigger, especially the locations of the extracted velocities. I find it really difficult to see these, but they're important for the context of the paper. I also think the three Greenland overviews are too small and don't work. Instead, please add one Greenland overview, with the sites marked, but which is a reasonable size. It's a shame to have nice figures like these when the reader can't read them properly.

A: Done.

R#2: Figure 2: As with the other figures, this needs to be bigger, especially the text, as I can barely read it, especially the axes labels.

A: Done.

R#2:Figure 3: The grounding line needs to be much more obvious, as do the lines for the termini. I really struggle to see them. Same for figure 1 Particularly for A), it would be useful to have a land mask to orientate people.

A: Done.

R#2:Figure 4: make the line stronger ad markers larger. Add the p-value and R2 for this regression.

A: We added R2 values to the regression.

R#2:Figure 5: The text is much easier to read on this, but some of the points are hard to see, e.g. the green dots in A. I know it's difficult given the data density, but think how you can back the points easier to see throughout this figure (e.g. through increasing size or changing the colours).

A: Done.

R#2:Figure 6: Add p-values for the regression lines.

A: We include the correlation coefficients to the regression lines.

R#2:Figure 7: Might be clearer with slightly large points.

A: Done.

Ice velocity of Jakobshavn Isbræ, Petermann Glacier, Nioghalvfjerdsfjorden and Zachariæ Isstrøm, 2015-2017, from Sentinel 1-a/b SAR imagery

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Abstract

Systematically monitoring Greenland's outlet glaciers is central to understanding the timescales over which their flow and sea level contributions evolve. In this study we use data from the new Sentinel-1a/b satellite constellation to generate 187 velocity maps, covering 4 key outlet glaciers in Greenland; Jakobshavn Isbræ, Petermann Glacier, Nioghalvfjerdsfjorden and Zachariæ Isstrøm. These data provide a new high temporal resolution record (6 days) of each glacier's evolution since 2014, and resolve recent seasonal and inter-annual changes in Greenland outlet glacier speed with an estimated certainty of 10 %. We find that since 2012, Jakobshavn Isbræ has been decelerating, and now flows approximately 1250 m yr^{-1} (10 %) slower than 5 years previously, thus reversing an increasing trend in ice velocity that has persisted during the last decade. Despite this, we show that seasonal variability in ice velocity remains significant; up to 750 m yr^{-1} (14 %) at a distance of 12 km inland of the terminus. We also use our new dataset to estimate the duration of speedup periods (80-95 days), and to demonstrate a strong relationship between ice front position and ice flow at Jakobshavn Isbræ, with increases in speed of ~1800 m yr^{-1} in response to 1 km of retreat. Elsewhere, we record significant seasonal changes in flow of up to 25 % (2015) and 18 % (2016) at Petermann Glacier and Zachariæ Isstrøm, respectively. This study provides a first demonstration of the capacity of a new era of operational radar satellites to provide frequent, and timely, monitoring of ice sheet flow, and to better resolve the timescales over which glacier dynamics evolve.

1. Introduction

Between 1992 and 2011, the Greenland Ice Sheet lost mass at an average rate of 142±49 Gt yr^{-1} [Shepherd et al., 2012], increasing to 269±51 Gt yr^{-1} between 2011 and 2014 [McMillan et al., 2016]. Ice sheet mass balance is determined from the ~~ratio of~~ surface mass ~~input~~ balance and ice discharge exported from the ice sheet [van den Broeke et al., 2009]. In 2005, dynamic imbalance was responsible for roughly two-thirds of Greenland's total mass balance, making an important contribution to freshwater input into the ocean and 0.34 mm yr^{-1} to the global sea level rise at that time [Rignot & Kanagaratnam, 2006]. Despite the anomalous atmospheric warming events, especially ~~during~~ in 2012 [Tedesco et al., 2013], ~~and therefore~~presenting a more spatially extensive and longer lasting surface melt during this period, marine-terminating outlet glaciers in Greenland still contribute~~s~~d with roughly 30 % (2000–2012) of total mass loss [Enderlin et al., 2014]. The observed acceleration of many marine-based glaciers in the western and northern regions of Greenland over the last ~~years~~ decade may have been driven by rises in air and adjacent ocean temperatures, which enhanced the surface melting and ~~erosion of their termini~~terminus retreat [Holland et al., 2008; Moon et al, 2014; Moon et al., 2015]. The associated increases in basal sliding and calving of their ice fronts in turn produce enhanced discharge, leading to dynamical imbalance and additional ice loss [Joughin et al., 2010; Joughin et al., 2014]. Acceleration of marine-terminating glaciers is, however, highly variable in space and time [Howat et al., 2010; Moon et al., 2012; Enderlin et al., 2014], due to the geometry of individual glaciers (Felikson et al., 2017), and the high spatial~~frequency~~ variability in the forcing mechanisms (Jensen et al., 2016; Carr et al., 2017). This complexity in glacier response challenges efforts to model their future evolution [Joughin et al., 2012;

Bondzio et al., 2017] and, therefore, frequent and systematic monitoring is essential to understand the processes governing their dynamic stability and contribution so future mean sea level rise [Joughin et al., 2010; Shepherd et al., 2012].

Ice motion measurements are essential for monitoring ice sheet dynamics~~,~~ and ice discharge, and for assessing an ice sheet's mass budget [Joughin et al., 1995]. At present, the only way to monitor ice velocity at a continental scale is through satellite imagery. Glacier velocities were first measured using Landsat satellite data acquired during the 1970s through digital optical image comparison [Lucchitta & Ferguson, 1986]. Currently, optical images are still largely used for mapping glaciers velocity at large scale (e.g. Dehecq et al., 2015; Fahnestock et al., 2016; Armstrong et al., 2017). However, due to the dependency upon daylight conditions and the limited acquisitions across the ~~P~~polar Regions, the use of Synthetic Aperture Radar (SAR) images has become common since the launch of ERS-1 in 1991. In the following decades, these data have been used to monitor dynamic processes occurring across remote areas such as the Greenland and Antarctic ice sheets [Joughin et al., 2010; Rignot & Mouginot, 2012; Nagler et al., 2015 Mouginot et al., 2017]. More recently, after the launch by the European Space Agency (ESA) of the Sentinel 1-a and 1-b satellites, in April 2014 and April 2016 respectively, many key ice margin areas are systematically monitored every 6 to 12 days. This novel dataset provides the opportunity to systematically monitor the dynamical process driving glacier ice velocity over periodic and short temporal scales. Here we use the Sentinel SAR archive to investigate the temporal variation in ice flow since October 2014 at four large outlet glaciers of the Greenland ice sheet.

2. Study areas

In this study, we map ice velocity of the Jakobshavn Isbræ (JI), Petermann Glacier (PG), Nioghalvfjerdsfjorden (79-G) and Zachariæ Isstrøm (ZI), which are four of the largest marine-based ice streams in Greenland. ~~and c~~Combined they contain ice equivalent to 1.8 m of global sea-level rise [Mouginot et al., 2015; Jensen et al., 2016], and drain ~21.5 % of Greenland's ice [Rignot & Kanagaratnam, 2006; Rignot & Mouginot, 2012; Münchow et al, 2014].

Jakobshavn Isbræ terminates in the Ilulissat Icefjord in western Greenland (Figure 1a), and is the fastest glacier draining the ice sheet [Enderlin et al., 2014; Joughin et al., 2014]. During the late 1990s, the ice tongue experienced successive break up events and the glacier began to speedup, exhibiting annual increases in speed of 7 % per year from 2004 and 2007 [Joughin et al., 2008a; Joughin et al., 2012; Joughin et al., 2014]. Until 2012 and 2013~~Over the last few years~~, the speed up has continued, reaching maximum velocities in excess of 17 km yr^{-1} ~~during 2012 and 2013~~ [Joughin et al., 2012; Joughin et al., 2014]. It has been suggested [~~Tedesco et al., 2013~~van de Wal et al., 2015] that the speedup over this period in the southwest of Greenland ~~was~~ might enhanced by anomalously high melting across the ice sheet surface [Tedesco et al., 2013]. Jakobshavn Isbræ is susceptible to changes in the adjacent ocean and Holland et al. [2008] have shown that warm water originating in the Irminger Sea likely enhanced basal melting and weakened the floating ice tongue, triggering its break up in 1997. Furthermore, Gladish et al. [2015] showed that subsequent changes which, occurred between 2001–2014, were mainly triggered by changes in Ilulissat Icefjord water temperatures adjacent to the glacier. At present, JI is a tidewater glacier and has a bimodal behaviour, retreating by ~3 km during summer and advancing by a similar amount during winter seasons [Cassotto et al., 2016]. ~~Therefore~~Moreover, as showed by Jensen et al. [2016] through analysis of optical images from 1999 to 2013, it has not exhibited an unusually large change in area (-10.3 km^2 yr^{-1}).

Petermann Glacier flows into the Hall Basin in the Nares Strait in Northwest Greenland (Figure 1b), and has a perennial floating ice tongue of 1280 km^2 in area [Hogg et al, 2016]. PG is grounded on bedrock ~300 m below sea level and, therefore, is also influenced by the adjacent ocean [Münchow et al, 2014; Hogg et al., 2016]. The retreat of the ice stream calving front led to an area decrease of 352 km^2 from 1959 to 2008, 270 km^2 in 2010 and 130 km^2 in 2012 [Johannessen et al., 2013]. It is considered a dynamically stable marine-terminating glacier despite several grounding line advancing and retreating events between 1992 and 2011, with a ~~migration~~terminus retreat rate of 25.2 m a^{-1} [Hogg et al., 2016]. PG has an average velocity of ~1100 m yr^{-1} at its grounding line since the 1990s [Rignot, 1996; Rignot & Steffen, 2008] and a multi-annual trend (2006–2010) in flow speed of 30 m yr^{-2} [Nick et al., 2012]. The ice shelf is thicker than 100 m and it is 15 km wide, with low resistive stresses along flow due to the limited attachment to the fjord walls, diminishing the velocity response after calving events [Nick et al., 2012].

Nioghalvfjerdsfjorden and Zachariæ Isstrøm are situated in the northeast of Greenland (Figure 1c and Figure 1d respectively). The two glaciers together drain more than 10 % of the Greenland Ice Sheet [Rignot & Mouginot, 2012], and their maximum velocities are found near the grounding line. They have exhibited different behaviour in recent years, ~~A~~although located in the same region ~~they have, in recent years, exhibited different behaviour~~. 79-G underwent a modest velocity increase of ~150 m yr^{-1} between 2001 and 2011 at the grounding line [Khan et al., 2014]. In contrast, during the same period, ZI exhibited a much larger increase in speed greater than 600 m yr^{-1} [Khan et al., 2014]. The ice thinning rates above the grounding line varies from 5.1 m yr^{-1} in ZI (2010–2014) to 1.4 m yr^{-1} in 79-G (2012–2014) [Mouginot et al., 2015]. Between 1999 and 2013, ZI has undergone an average area change of -26.0 km^2 yr^{-1}, due to break off of the ice tongue and is now a tidewater glacier [Khan et al., 2014; Jensen et al., 2016]. In contrast, 79-G had a much lower average area change during the same period of -4.7 km^2 yr^{-1} and still retains a small ice shelf [Jensen et al., 2016], although recent ice shelf thinning [Mouginot et al., 2015] may increase vulnerability to break up in the future.

3. Data and Methodology

To map ice velocity, we used Single Look Complex (SLC) Synthetic Aperture Radar images acquired in the Interferometric Wide swath (IW) mode from the Sentinel-1a and Sentinel-1b satellites. Data used in this study were acquired in the period spanning from October 2014 to February 2017 and from October 2016 to February 2017, for Sentinel-1a and Sentinel-1b respectively (Figure S2 and Table S1). Each satellite has a repeat cycle of 12 days and 180 degrees orbital phasing difference, resulting in a revisit time of 6 days over the same area after the Sentinel-1b launch. The Sentinel SAR instruments operate at C-Band, with a centre frequency of 5.405 GHz, corresponding to a wavelength of 5.55 cm. The IW mode has a 250 km swath and spatial resolution of 5 m in ground range and 20 m in azimuth. It has burst synchronization for interferometry and acquires data in 3 sub-swaths, each containing a series of bursts, which are acquired using the Terrain Observation with Progressive Scans SAR (TOPSAR) imaging technique [Yague-Martinez et al., 2016]. We followed the workflow described below to derive 187 ice velocity maps from pairs of Sentinel-1a/b SAR images over Jakobshavn Isbræ, Petermann Glacier, Nioghalvfjerdsfjorden and Zachariæ Isstrøm, using the GAMMA-SAR software [Gamma Remote Sensing, 2016].

We used the SAR intensity tracking technique [Strozzi et al., 2002] to estimate surface ice velocities due to glacier flow, assuming that the ice flow occurs parallel to the surface. This method uses a cross correlation algorithm applied to image patches [Strozzi et al. 2002; Pritchard et al. 2005, Paul et al. 2015] to estimate offsets between similar features, such as crevasses and radar speckle patterns, in two co-registered SAR images (Table S1). Images were co-registered using the precise orbit information, available 20 days after the image acquisition, establishing a ~~position~~ co-registration accuracy of 5 cm 3D 1-sigma [Sentinels POD team, 2013]. The elimination of the orbital offsets isolates displacement due to the glacier movement [Strozzi et al., 2002]. To estimate ice flow, we then used windows sizes of 350 pixels in ground range (~ 1.7 km) and 75 pixels in azimuth (~1.5 km) for each glacier, to produce a series of velocity maps with spatial resolution of 388 m in ground range and 320 m in azimuth.

Image matches with low certainty, defined as returning a normalised cross-correlation of less than ~~0.0~~5 % of its maximum peak , were rejected and the results were then converted into displacement in ground range coordinates using the Greenland Ice Mapping Project (GIMP) digital elevation model (DEM) posted on a 90 m grid [Howat, 2014]. Along- and across- track displacement components were combined to determine the displacement magnitude, which was then converted to an estimate of annual velocity using the temporal baseline of each image pair. Final velocity products were posted on 100 m by 100 m grids. Post-processing of ice velocity data reduces noise and removes outliers [Paul et al., 2015], so we applied a low-pass filter (moving mean) twice to the data, using a kernel of 1 km by 1 km, and we reject values where the deviation between the unfiltered and filtered velocity magnitude exceeds 30 %. We apply a labelling algorithm, based on the image histogram, to identify and classify regions with similar values, excluding isolated pixels with a non-coherent area of velocity values, or where the area of the classified region was smaller than 1/1000th of the processed image size.

Errors in our velocity estimates arise primarily through inexact co-registration of the SAR images, uncertainties in the digital elevation model used in the terrain correction, and fluctuations in ionospheric activity and tropospheric water vapour [Nagler et al., 2015; Hogg et al., 2017]. To estimate the accuracy of our Sentinel-1 average velocity data (Figure 1 and Figure 3) we computed pixel-by-pixel errors based on the signal to noise ratio (SNR) of the cross correlation function [Hogg et al., 2017]. The SNR is the ratio between the cross-correlation function peak (C_p) and the average correlation level (C_l) on the tracking window used to estimate the velocities (Lange et al., 2007). We then averaged these estimates across all images in our temporal stack to determine the percentage errors associated with our mean velocity maps (Figure 3). Although in isolated areas the error exceeds 30 %, the mean error across the whole imaged area were approximately 10 % for JI, 7 % for PG, and 8 % for 79G and ZI. ~~, with all~~Due to the non-uniform flow, lack of stable features and remaining geometry distortions, the four glaciers ~~exhibiting~~exhibit higher errors across their faster flowing and steeper areas, and along the shear margins. Where localised rates of surface elevation change are high, the surface slope may have evolved away from that of the GIMP DEM used in our processing. To assess the sensitivity of our velocity estimates to this effect, we selected the JI site where thinning is most pronounced, and used airborne estimates of elevation change from IceBridge and Pre-Icebridge data acquired from the NASA Airborne Topographic Mapper (ATM) [Studinger, 2014] to update the DEM. We find that in this extreme case, the large thinning rates (~12 m yr^{-1}) may introduce an additional uncertainty of 200-300 m yr^{-1} ~~within individual pixels of our velocity estimates~~which may bias the velocity estimates in this region, albeit limited to the first 10 km upstream of the grounding line (Table S2). Over floating ice tongues, uncompensated vertical tidal displacement may also introduce additional uncertainty into our velocity fields. The sensitivity of our results to this effect was assessed based upon a net 50 cm tidal displacement over 6-12 day repeat period and a centre swath incidence angle of 35 degrees. We estimate that such a tidal signal would introduce ~20–40 m yr^{-1} additional uncertainty into the ground range component of our velocity fields. In the context of this study, this uncertainty does not affect the results at JI or ZI, and it is limited only to the floating sections of PG and 79G.

To provide an independent evaluation of our ice velocity dataset, we finally compared them (Table S1) to independent estimates derived from TerraSAR-X (TSX) SAR imagery through the speckle tracking technique (Joughin, 2002), which has a repeat period acquisition of 11 days and spatial resolution up to 3 m [Joughin et al., 2016]. The TSX data consist of 444 image pairs covering Jakobshavn Isbræ over the period January 2009 to January 2017, 18 pairs at Petermann Glacier over the period November 2010 to December 2016, and 17 pairs at Nioghalvfjerdsfjorden over the period March 2011 to December 2016. In general, the temporal evolution of the S1-a/b measurements matches very closely with the TSX estimates. At JI, we are able to compare S1 and TSX datasets at three different locations to assess their consistency (Figure 4). Even though the flow speed at these sites is high, which typically proves more challenging for feature tracking techniques, we find good agreement between the two datasets, especially at the J1 and J2 sites, with mean differences of 40 m yr^{-1} and 76 m yr^{-1} respectively. However, nearer to the calving front (site Jif), the S1-a/b measurements tend to give significantly higher velocities than TSX with a mean difference of 489 m yr^{-1} (5 % of the mean velocity) between the two datasets.

4. Results and Discussion

We used our complete Sentinel-1a/b dataset (Table S1) to generate contemporary, time-averaged velocity fields at each of our study sites (Figure 1). To investigate spatial and temporal variations in ice velocity, we then extracted profiles in the along- and across-flow directions, together with time series at fixed glacier locations (Figure 1). Our velocity profiles in Jakobshavn Isbræ, Petermann Glacier, Nioghalvfjerdsfjorden and Zachariæ Isstrøm reached maximum mean speeds, along the stacked dataset, of approximately 9 km yr^{-1}, 1.2 km yr^{-1}, 1.4 km yr^{-1}, 2.7 km yr^{-1}, respectively. The location of the velocity ~~magnitude~~ maxima varied between glaciers, as a result of their differing geometries. For JI and ZI, neither of which have a significant floating tongue, we find a progressive increase in ice velocity towards the calving front (Figures 2a and 2d). For PG, the maximum velocity is reached at the grounding line and remains steady along the ~46 km of ice tongue (~~~46 km extension in~~ Figure 2b). In contrast, although 79G also reaches its maximum velocity close to the grounding line, its speed then diminishes by ~ 50 % (Figure 2c) near the ice front location where the ice flow divides into two main portions before it reaches several islands and ice rises (Figure S1b). Furthermore, it is interesting to note that, despite being located in the same region, the adjacent glacier ZI flows ~60 % faster in comparison. JI, PG and ZI glaciers show velocity increases progressively downstream across the transverse profiles. The four glaciers, JI, PG, 79G and ZI respectively reduce ~~in speed to half of~~ their maximum velocity to half at distances of 12 km, 22 km, 18 km, and 12 km inland of their grounding lines, highlighting the importance of resolving glacier velocities within their near terminus regions.

Next, we used the Sentinel-1a/b and TerraSAR-X velocities to assess the seasonal and longer-term variations in Jakobshavn Isbræ ice velocity over the period 2009–2017. Our Sentinel-1a/b velocity estimates at JI resolve clear seasonal velocity fluctuations, superimposed upon longer term decadal scale variability, which continues~~ing~~ observations made by previous satellite instruments [Joughin et al., 2012; Joughin et al., 2014]. At site J1 we find an average seasonal ~~summer~~ change~~increase~~ in speed of 750 m yr^{-1}, or 14 % between 2014 and 2015 and a speedup persistence of 80-95 days, being twice longer than the other three glaciers (Table 1). Inland, the amplitude of seasonal variability diminishes, to an average of 300 m yr^{-1} (8 %) at J2. Our near-continuous, decadal-scale record clearly shows that the amplitude of the seasonal signal has evolved through time. At J1, for example, the average seasonal variability in ice speed was 400 m yr^{-1} during 2009-2011, increasing by more than a factor of 3, to 1400 m yr^{-1} between 2012 and 2013 and then diminishing to 750 m yr^{-1} between 2015–2017.

Turning to the longer term evolution of JI (Figure 5; time series location shown in Figure 1), fitting a linear trend to the data suggests an annual acceleration since 2009 of ~218 m yr^{-1} at Jif, diminishing inland to ~128 m yr^{-2} at J1, and ~102 m yr^{-2} at J2. Although this provides a simple characterisation of the longer-term evolution in ice speed, it is clear from our time series that computing a linear trend does not capture the full decadal scale variability in ice velocity. In particular, we note that much of the acceleration occurred between 2011 and 2013 (Figures 5b and 5c), and since then there has been a notable absence of multi-annual acceleration as earlier records suggest [Joughin et al., 2014]. Computing trends in ice velocity since 2012 near the glacier terminus (Jif), for example, shows a modest decline in speed of 321 m yr^{-2} over the 5-year period (Figure 5b). The calving front migration has been suggested as the trigger to the stresses regimes variations and consequently the main driver to the JI velocity fluctuations [Joughin et al., 2008a; 2008b; 2012; 2014; Bondzio et al., 2017]. After successive and gradually increased rate of the ice front retreat until 2012 (Figure 5a), the JI grounding line is now located on a higher bed location (Joughin et al., 2012; An et al., 2017). This may be acting to stabilise the grounding line, and in turn contribute to the glacier deceleration, although the main cause remains to be determined and further investigations is necessary. We used our observations of calving front position to assess the correlation between ice speed and calving front location, relative to their respective long term means (Figure 6). Based on the linear regression (Figure 6), our dataset indicates correlation coefficients (R^2) of 0.62 (2009–2011) and 0.79 (2012–2017), and velocity changes by 1100 and 1600 m yr^{-1} per kilometre of calving front retreat, respectively.

At Petermann Glacier we extracted two velocity time series at P1, located ~45 km downstream of the grounding line and close to the calving front of the ice tongue; and P2, ~10 km upstream of the grounding line. These locations were chosen to examine any differences in velocity evolution over the grounded and floating portions of the glacier. Our P1 time series starts in early 2015 because it is not covered by the TerraSAR-X dataset (Figure 7a). We observe that, in general, ice at P1 flows ~400 m yr^{-1} faster than P2. Fitting a linear trend to the longer P2 dataset indicates no significant trend in ice velocity since 2011, although the precision of this trend is hampered by the sparse data coverage during the early part of this period. Continued monitoring by Sentinel-1 will improve our confidence in resolving any decadal scale variability. The improvement in temporal sampling provided by Sentinel-1 at this site is clear (Figure 7a)~~, and~~ allows us to resolve the seasonal cycle in velocity since 2015 and helps to delimit the duration of the speedup period. At P1, we detect a seasonal change in speed of ~ 300 m yr^{-1}, equivalent to a 25 % increase relative to its winter velocity (Table 1). Despite the high seasonal change, the relation between P1's annual mean and winter velocity is 0 %, likely due to the short speedup period (25 days - Table 1) This provides further evidence of a seasonal velocity cycle which has been observed at both Petermann and other glaciers in this region, and is understood to be predominantly controlled by changes in basal traction, induced by penetration of surface melt water to the bed [Nick et al., 2012; Moon et al., 2014; Moon et al., 2015]. This is further supported by our analysis of changes in calving front position (Figure S1a) which shows that, in contrast to JI, seasonal acceleration does not coincide with ice front retreat. Specifically, we found that during the summers of 2015 and 2016, the calving front of PG advanced ~1 km during the speedup (Figure S1a). These observations are consistent with previous modelling results, which did not find evidence of acceleration driven by large calving events in 2010 and 2012 [Nick et al., 2012; Münchon et al., 2014], suggesting that the ice shelf exerts low backstress on the glacier. More recently, we note that since September 2016 PG has developed a new crack near the ice front, which has continued to grow in length up to the present day.

At 79-G, we again extracted velocity time series over the ice shelf (F1, ~20 km downstream of the grounding line) and at the grounding line (F2). In contrast to PG and due to the steeper surface gradient upstream of the grounding line (Figure 2c), ice flow is slower on the floating tongue than at the grounding line location (Figure 7b). We observe a seasonal speed up of ~10 % at F2 during summer 2016 (Table 1), although evidence of the same acceleration on the ice shelf is not clear given the magnitude of the signal and the precision of our data. Fitting a linear trend to our data returns an annual change in velocity of 15 m yr^{-2} since 2011, although assessing the significance of this result is difficult given the limited data sampling early in the period. Turning to Zachariæ Isstrøm, we extract time series at two locations slightly upstream of the grounding line in order to observe different temporal responses between them (Figure 7c). At this glacier, no observations are available within the TSX dataset and so our time series is limited to the period December 2015 to January 2017. Nonetheless, like its neighbour ZI, we again find evidence of a summer speed up during 2016, equating to around 400 m yr^{-1}, or 18 % (Table 1). Given the short period of observations we do not attempt to derive a longer-term trend in ice velocity at this site.

We compared our estimates to the results of previous studies to assess the level of ~~agreement~~ stability relative to past work. At Petermann, we have observed increases in ice velocity of ~10 % at P1 and ~8 % at P2 between the 2015/2016 and 2016/2017 winters, matching in percentage with the observations made ~~during the same period~~ by Münchon et al. [2016] between 2013/14 and 2015/16. Furthermore, the Sentinel-1a/b dataset indicates a multi-annual acceleration of ~32 m/yr^2 between 2015-2017 at P1, which is similar to the ~30 m/yr^2 reported by Nick et al. [2012] based upon observational measurements over a longer period, from 2006 to 2010. The same authors also show seasonal variations of ~20–25 % over the same location, similar to the ~22 % shown by the Sentinel-1 dataset. At 79-G, Mouginot et al. [2015] showed a speedup of 8 % from 1976 to 2014 with the main changes occurring after 2006, similar to our estimates which also suggest a slight multi-year trend of ~16 m yr^{-2} (~8 %) for F2 between 2015 and 2017. Zachariæ Isstrøm shows seasonal variation up to 15 % between 2015 and 2017 in the Sentinel-1 dataset, agreeing with seasonal variation up to 20 % estimated by Mouginot et al. [2017] using Landsat-8 optical images during 2014–2016. Overall, our Sentinel

1 results shows a close agreement with previous studies using different techniques and demonstrated to be a powerful tool for monitoring the cryosphere.

6 Conclusions

We have presented a new, high temporal resolution record of ice velocity evolution for four important, and with high discharge, marine based glaciers in Greenland, updated to the present day (October 2014 to February 2017). Using SAR data acquired by the Sentinel-1a/b constellation, with its 250 km wide swath and frequent revisit time, we have produced 187 velocity maps, which, in combination with 479 maps from the TerraSAR-X satellite, provide detailed spatial and temporal coverage of these key sites. Importantly, the systematic acquisition cycle of Sentinel-1a/b, which now provides measurements of all of these sites every 6 days allows for detailed monitoring of both seasonal and multi-annual velocity fluctuations, and allow us to demonstrate the speedup persistence in a higher resolution. The short revisit time of 6 days, made possible since the launch of Sentinel-1b in April 2016, particularly benefits the retrieval of velocity signals across fast flowing regions close to the ice front, due to a reduction in the decorrelation occurring between image pairs. Using this new dataset, we confirm evidence of intra-annual variations in ice velocity and clear seasonal cycles occurring over the past few years at JI, PG, 79G and ZI. Of the sites studied here, JI exhibits the largest velocity variations, as demonstrated in other studies, which we show are strongly correlated with the evolution of the position of its calving front. Notably, however, in the last 5 years the longer-term ice speed has started to decrease (321 m yr^{-2}). This study demonstrates the utility of a new era of operational SAR imaging satellites for building systematic records of ice sheet outlet glacier velocity and its good agreement with TerraSAR-X products, which indicates Sentinel-1 can confidently extend the times series that began with other sensors. Looking to the future, these datasets are key for the timely identification of emerging signals of dynamic imbalance, and for understanding the processes driving ice velocity change.

Competing interests. The authors declare that they have no conflicts of interest.

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7 Figures and Captions

- Figure 1. Time-averaged ice velocity magnitude maps for the period Oct/2014–Feb/2017 (a) Jakobshavn Isbræ (JI; 69°N, 50°W), (b) Petermann Glacier (PG; 81°N, 62°W), (c) Nioghalvfjerdsfjorden (79G; 79°N, 20°W) and Zachariæ Isstrøm (ZI; 78°N, 20°W) glaciers, derived from Sentinel-1 SAR images. Velocities are shown on a logarithm scale and overlaid on a SAR backscatter intensity image and thin grey lines represent elevation. The along-flow profiles are indicated by solid green lines scaled in kilometres, the solid ~~white~~ black lines show the across-flow transects, the red triangles represent the locations at which velocity time series are extracted and the thick solid and dashed black lines represent the ice front locations (IF) and the grounding lines (GL), respectively. The inset figures show the location of each glacier.

- Figure 2. Average velocities extracted from along- and across-flow profiles of Jakobshavn Isbræ, Petermann Glacier, Nioghalvfjerdsfjorden and Zachariæ Isstrøm. Figures a–d present along-flow profiles of ice velocity (solid black lines), surface elevation from the GIMP DEM [Howat et al., 2014; dashed blue lines] and bed elevation from the IceBridge BedMachine Greenland V2 product [Morlighem et al., 2015; dashed yellow lines]. The location of each profile is shown in Figure 1 (green lines). The grey shaded area represents the floating regions, and the light grey dashed line the ice front positions. The blue, black and red markers represent the locations of the across-flow profiles. Figures e–h show the across-flow velocity profiles (solid white lines in Fig.1), centred on the main profile (solid green line).

- Figure 3. Time-averaged uncertainty in ice velocity at each site expressed in percentage, based on the signal to noise ratio (SNR) for (a) JI, (b) PG, and (c) 79G and ZI.

- Figure 4. Comparison between co-located and contemporaneous Sentinel 1-a/b and TerraSAR-X Jakobshavn Isbræ velocity measurements at Jif, J1 and J2 locations (blue, black and red dots respectively), together with root mean square (rms) and correlation coefficients (R^2).

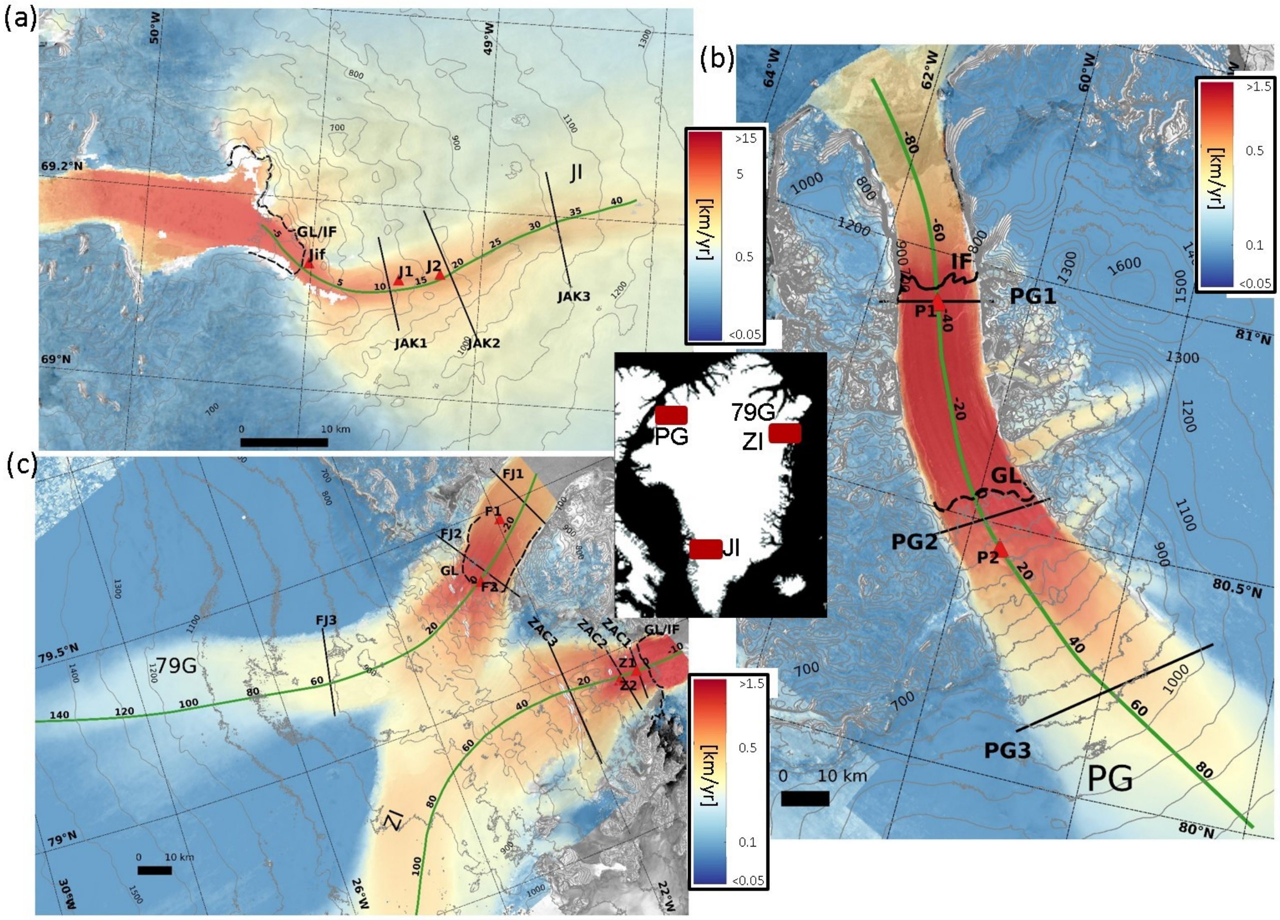
- Figure 5. Temporal evolution of Jakobshavn Isbræ (a) ice front position extracted from Joughin et al. [2014], ESA Greenland Ice Sheet Climate Change Initiative (CCI) project [2017], and Sentinel-1a/b SAR images represented in blue, black and magenta dots respectively, where higher values correspond to ice front retreat. Changes in ice velocity through time is also shown (b, c), extracted at the locations indicated in Figure 1. The velocity data derived from TerraSAR-X (Joughin et al., 2016) are shown as grey squares, and the data from Sentinel 1-a/b as coloured triangles.

- Figure 6. Comparison between Jakobshavn Isbræ ice velocity and calving front anomalies at the Jif site, 0.8 km upstream of the calving front, between 2009 and early 2017. Positive values correspond to ice front retreat and speed up respectively. The red and black lines represent the linear regression through the 2009-2011 and 2012-2017 periods, respectively, together with the correlation coefficients (R^2).

- Figure 7. Temporal evolution of ice velocity at the locations indicated in Figure 1 over (a) Petermann Glacier, (b) Nioghalvfjerdsfjorden and (c) Zachariæ Isstrøm. The data derived from TerraSAR-X [Joughin et al., 2016] and Sentinel 1-a/b are represented as grey squares and coloured triangles, respectively.

- Table 1: Speedup Persistence and seasonal percentage increase in speed relative to winter and annual background for each glacier for the Sentinel 1 dataset. Speedup persistence has an uncertainty of ± 12 days due to the image acquisition interval of Sentinel 1a.

Figure 1



(a)
(b)
(c)
JI
GL/IF
Jif
J1
J2
JAK1
JAK2
JAK3
[km/yr]
PG
79G
ZI
IF
GL
P1
P2
PG1
PG2
PG3
FJ1
FJ2
FJ3
F1
F2
ZAC1
ZAC2
ZAC3
Z1
Z2
10 km

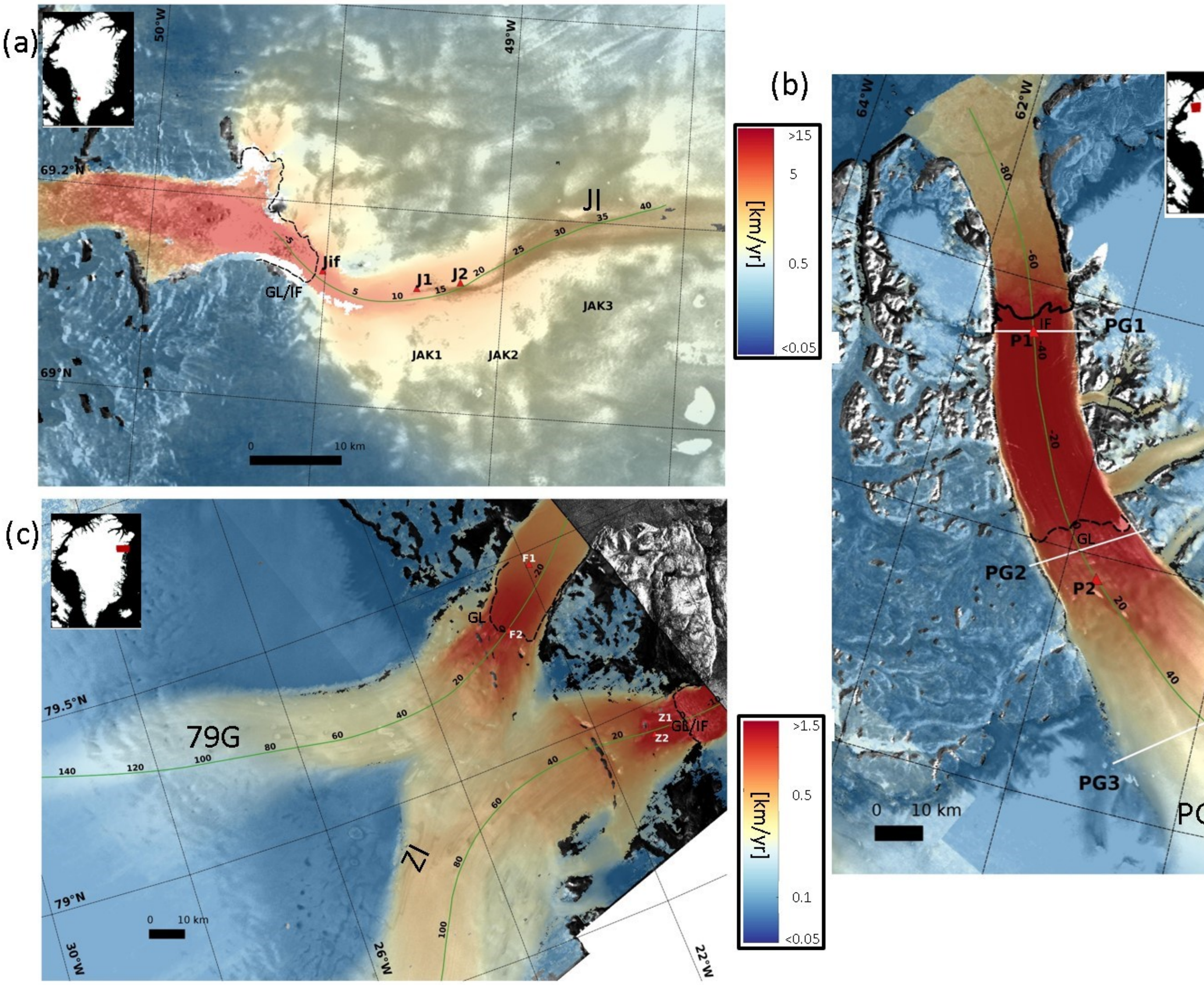
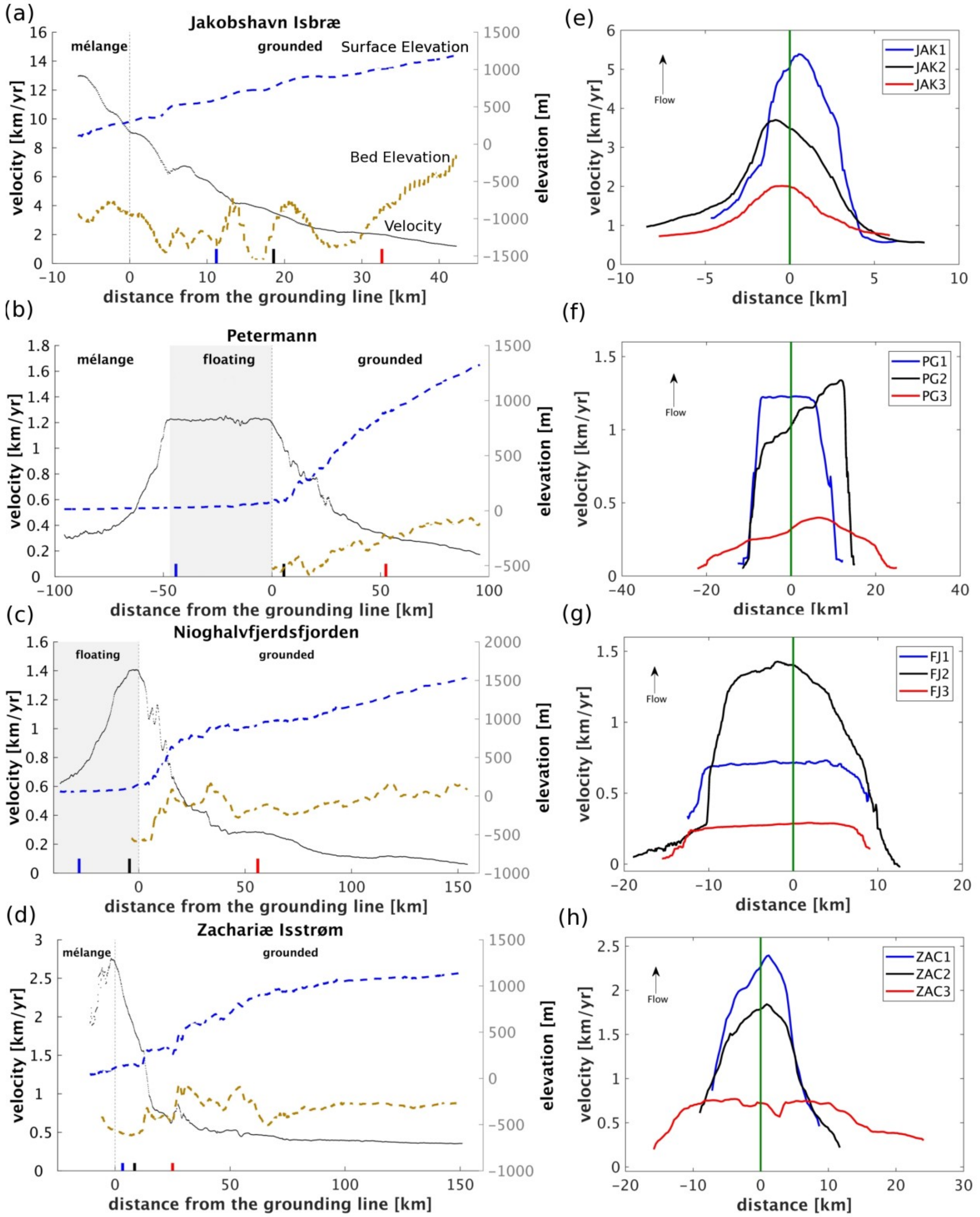
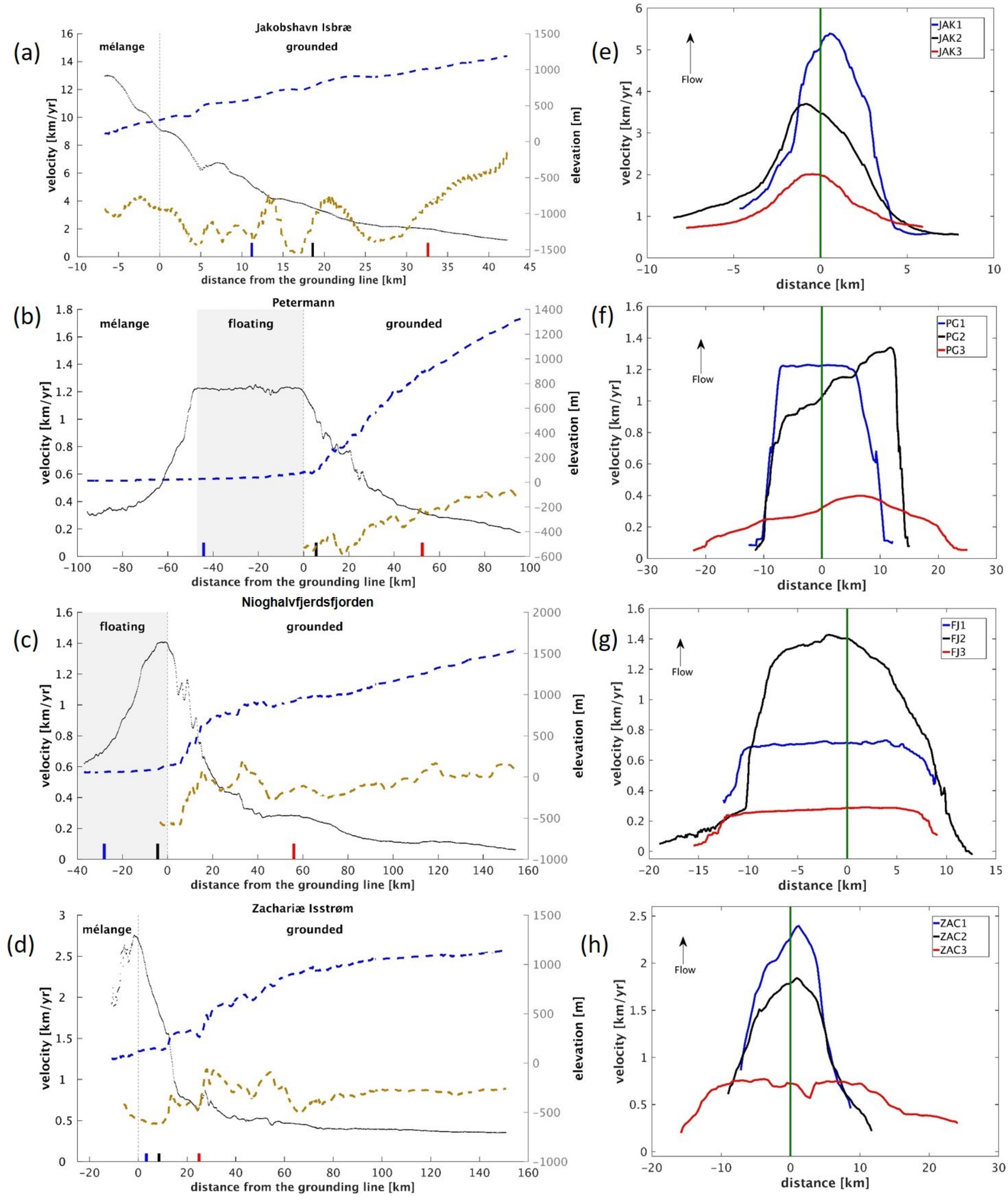

(a)
50°W
49°W
69.2°N
69°N
JI
Jif
J1
J2
GL/IF
JAK1
JAK2
JAK3
0 10 km
(b)
64°W
62°W
[km/yr]
>15
5
0.5
<0.05
IF
P1
PG1
GL
PG2
P2
PG3
0 10 km
(c)
GL
F1
F2
79.5°N
79G
Z1
Z2
GL/IF
ZI
79°N
30°W
26°W
22°W
0 10 km
[km/yr]
>1.5
0.5
0.1
<0.05

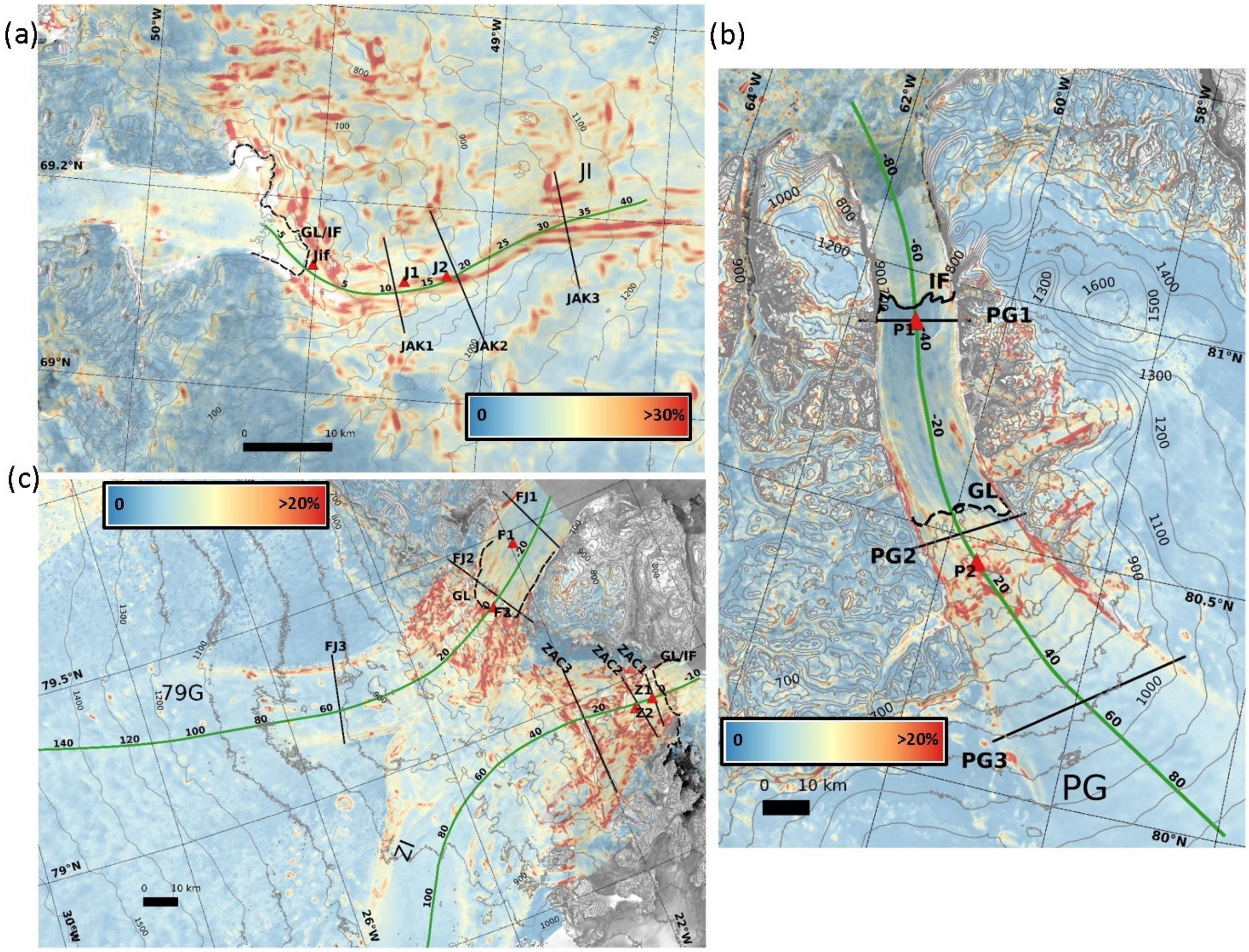
Figure 2


(a)
Jakobshavn Isbræ
mélange
grounded
Surface Elevation
Bed Elevation
Velocity
velocity [km/yr]
elevation [m]
distance from the grounding line [km]
(b)
Petermann
mélange
floating
grounded
velocity [km/yr]
elevation [m]
distance from the grounding line [km]
(c)
Nioghalvfjerdsfjorden
floating
grounded
velocity [km/yr]
elevation [m]
distance from the grounding line [km]
(d)
Zachariæ Isstrøm
mélange
grounded
velocity [km/yr]
elevation [m]
distance from the grounding line [km]
(e)
Flow
JAK1
JAK2
JAK3
velocity [km/yr]
distance [km]
(f)
Flow
PG1
PG2
PG3
velocity [km/yr]
distance [km]
(g)
Flow
FJ1
FJ2
FJ3
velocity [km/yr]
distance [km]
(h)
Flow
ZAC1
ZAC2
ZAC3
velocity [km/yr]
distance [km]



(a)
Jakobshavn Isbræ
mélange
grounded
velocity [km/yr]
elevation [m]
distance from the grounding line [km]
(b)
Petermann
mélange
floating
grounded
velocity [km/yr]
elevation [m]
distance from the grounding line [km]
(c)
Nioghalvfjerdsfjorden
floating
grounded
velocity [km/yr]
elevation [m]
distance from the grounding line [km]
(d)
Zachariæ Isstrøm
mélange
grounded
velocity [km/yr]
elevation [m]
distance from the grounding line [km]
(e)
Flow
JAK1
JAK2
JAK3
velocity [km/yr]
distance [km]
(f)
Flow
PG1
PG2
PG3
velocity [km/yr]
distance [km]
(g)
Flow
FJ1
FJ2
FJ3
velocity [km/yr]
distance [km]
(h)
Flow
ZAC1
ZAC2
ZAC3
velocity [km/yr]
distance [km]

Figure 3



(a)
50°W
49°W
69.2°N
69°N
JI
GL/IF
Jif
J1
J2
JAK1
JAK2
JAK3
0
>30%
0 10 km
(b)
64°W
62°W
60°W
58°W
IF
P1
PG1
81°N
GL
PG2
P2
80.5°N
PG3
PG
80°N
0
>20%
0 10 km
(c)
0
>20%
FJ1
F1
FJ2
GL
F2
FJ3
79G
ZAC3
ZAC2
ZAC1
GL/IF
Z1
Z2
79.5°N
ZI
79°N
30°W
26°W
22°W
0 10 km

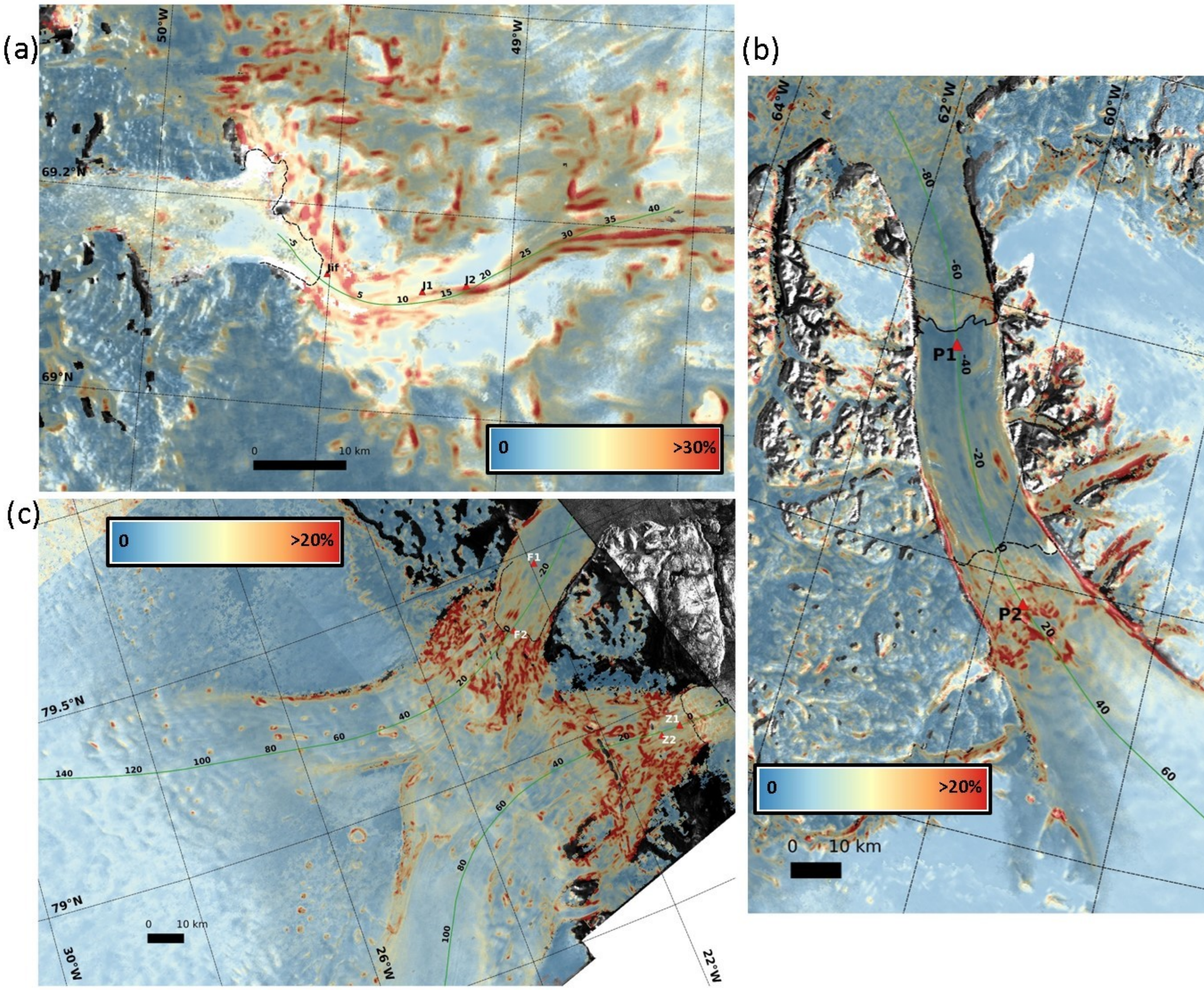
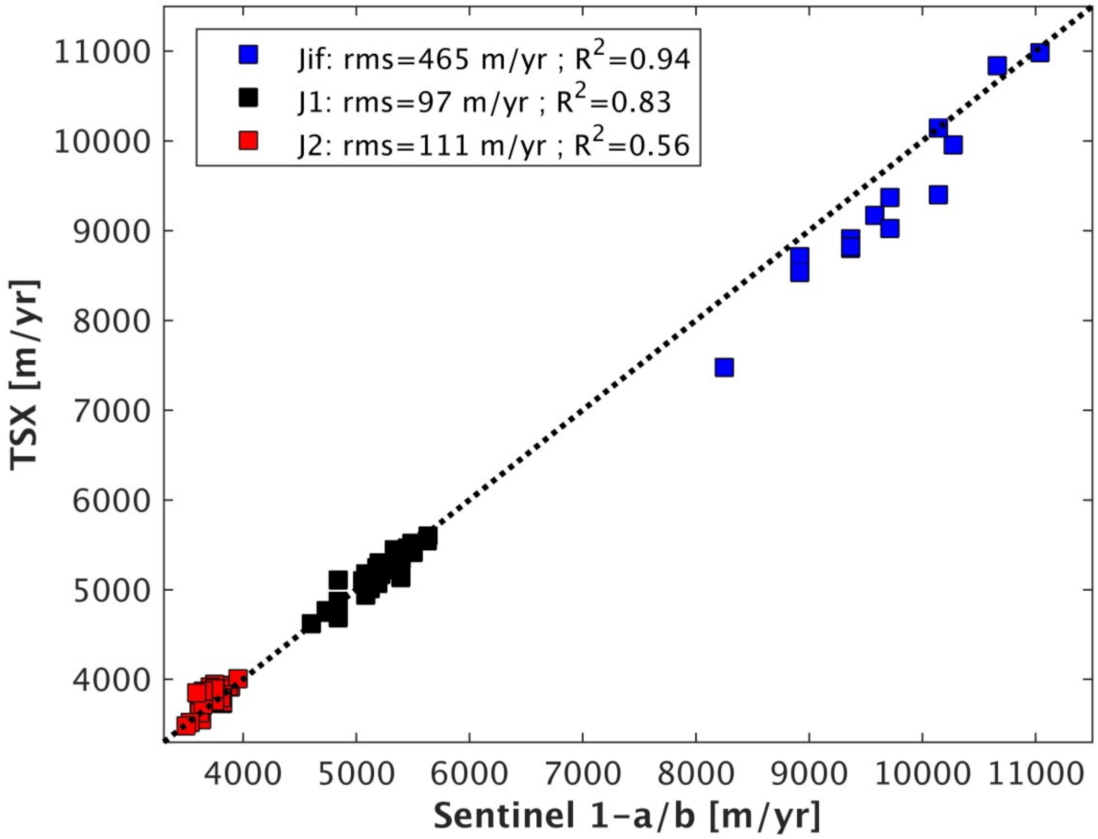

(a)
50°W
49°W
69.2°N
69°N
Jif
J1
J2
0
10 km
0
>30%
(b)
64°W
62°W
60°W
P1
P2
0
>20%
0
10 km
(c)
0
>20%
F1
F2
Z1
Z2
79.5°N
79°N
0
10 km
30°W
26°W
22°W

Figure 4


Jif: rms=465 m/yr ; R^2=0.94
J1: rms=97 m/yr ; R^2=0.83
J2: rms=111 m/yr ; R^2=0.56
TSX [m/yr]
Sentinel 1-a/b [m/yr]

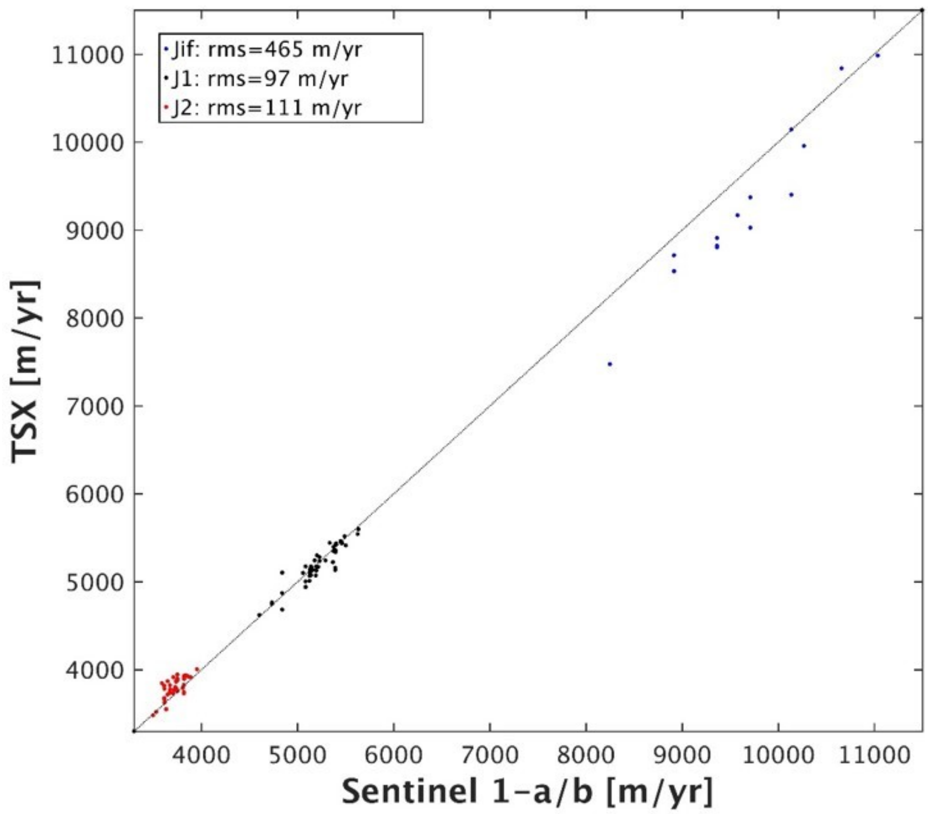
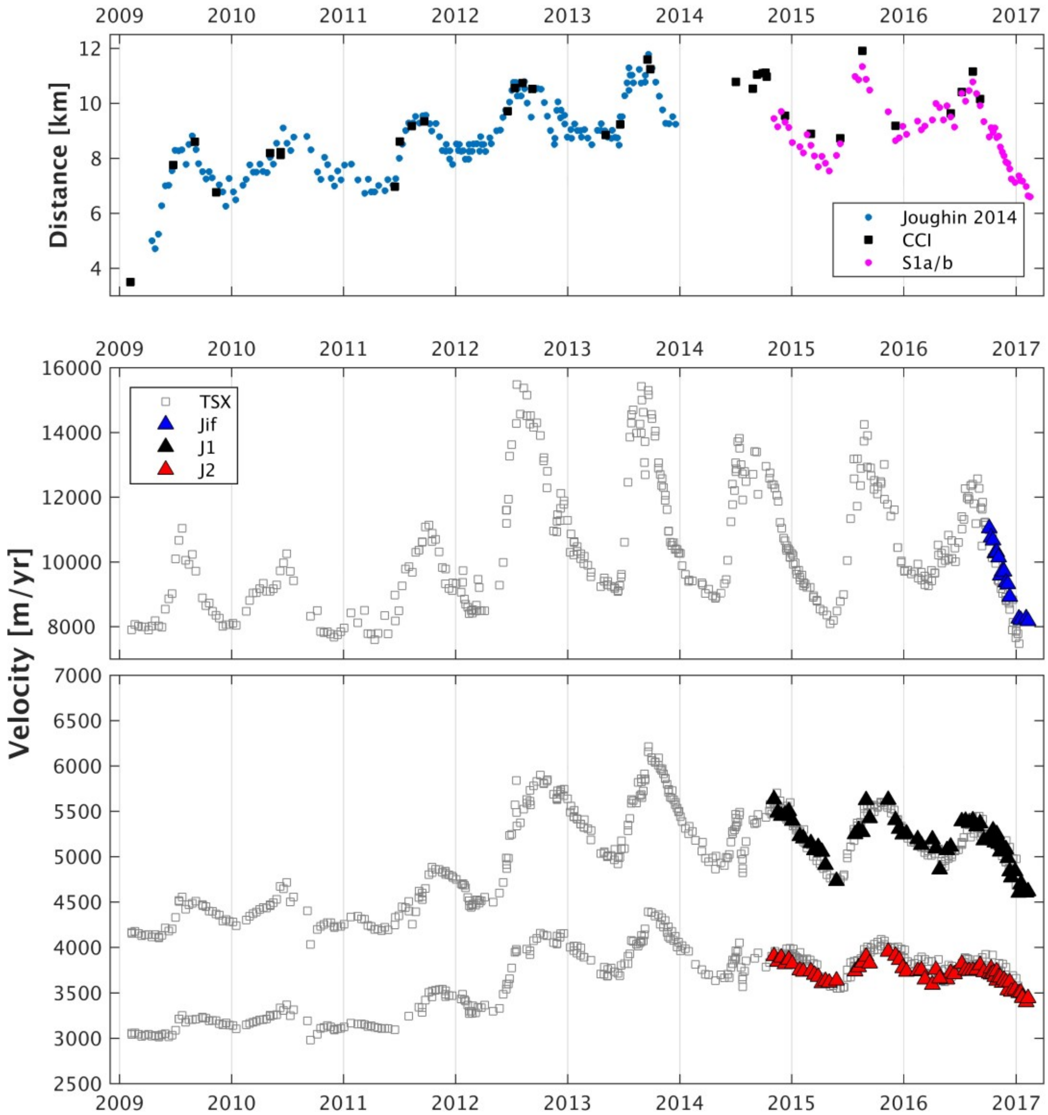
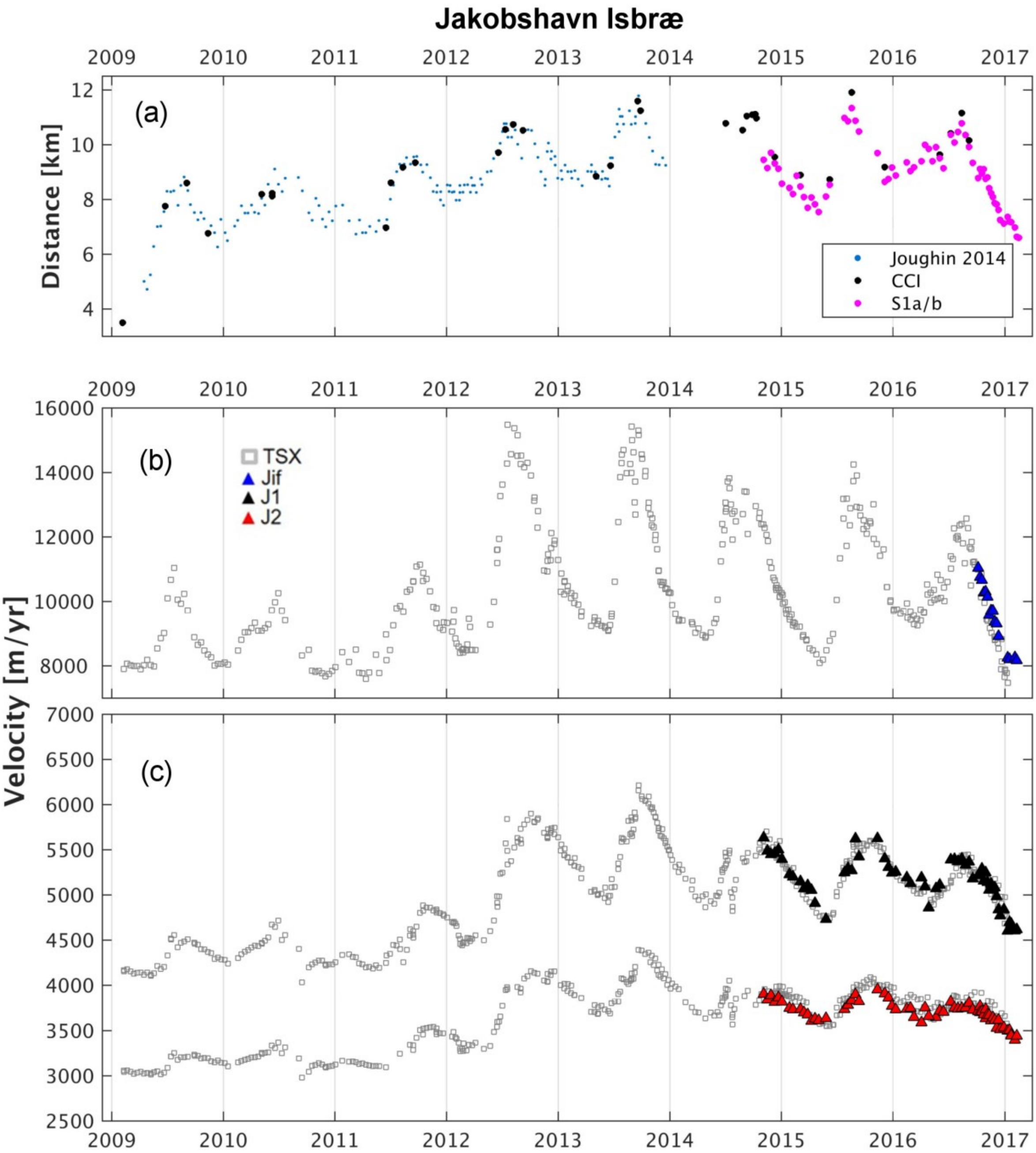

Jif: rms=465 m/yr
J1: rms=97 m/yr
J2: rms=111 m/yr
TSX [m/yr]
Sentinel 1-a/b [m/yr]

Figure 5

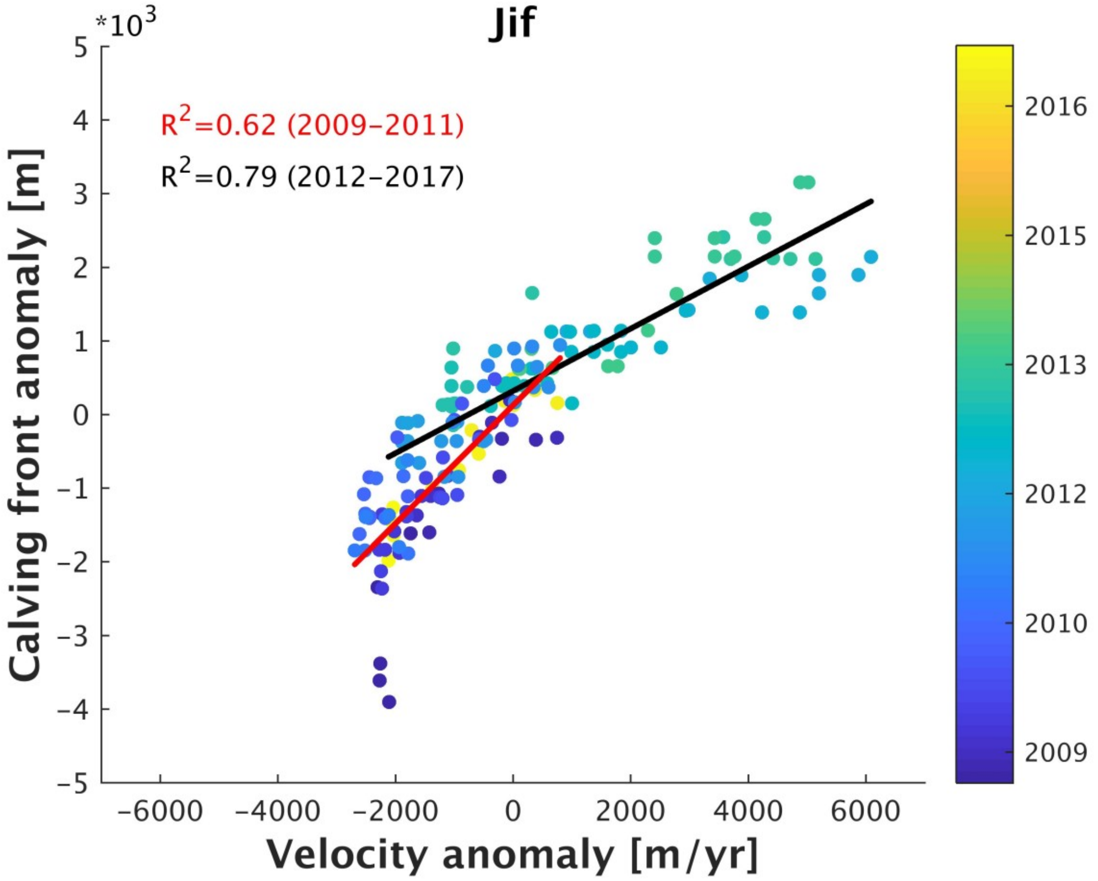


2009
2010
2011
2012
2013
2014
2015
2016
2017
Distance [km]
Joughin 2014
CCI
S1a/b
TSX
Jif
J1
J2
Velocity [m/yr]



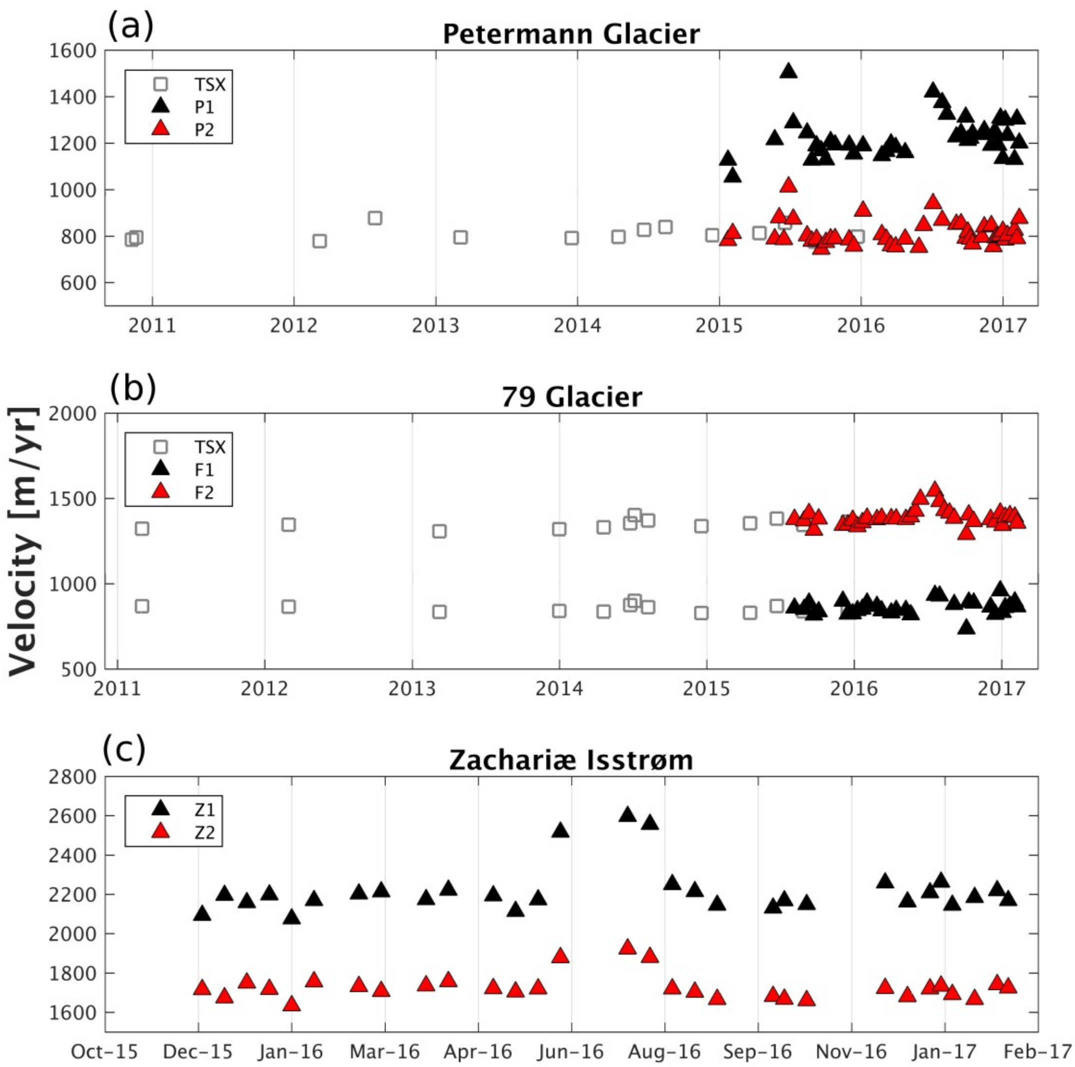
Jakobshavn Isbræ
(a)
Distance [km]
Joughin 2014
CCI
S1a/b
(b)
TSX
Jif
J1
J2
(c)
Velocity [m/yr]

Figure 6

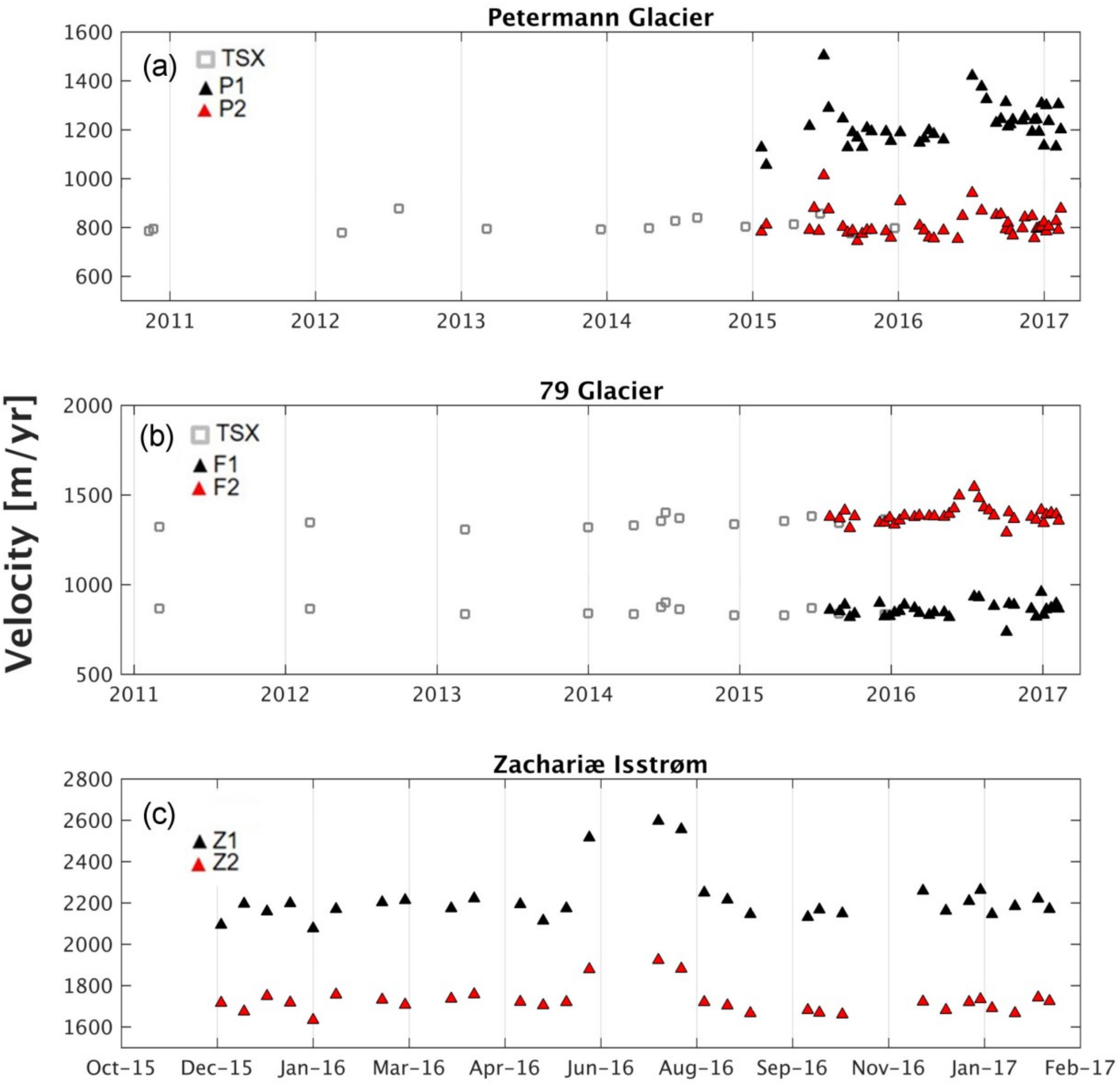


Jif
*10^3
R^2=0.62 (2009-2011)
R^2=0.79 (2012-2017)
Calving front anomaly [m]
Velocity anomaly [m/yr]
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6000
−4000
−2000
0
2000
4000
6000
2016
2015
2013
2012
2010
2009

Figure 7



(a)
Petermann Glacier
TSX
P1
P2
1600
1400
1200
1000
800
600
2011
2012
2013
2014
2015
2016
2017
(b)
79 Glacier
Velocity [m/yr]
TSX
F1
F2
2000
1500
1000
500
2011
2012
2013
2014
2015
2016
2017
(c)
Zachariæ Isstrøm
Z1
Z2
2800
2600
2400
2200
2000
1800
1600
Oct-15
Dec-15
Jan-16
Mar-16
Apr-16
Jun-16
Aug-16
Sep-16
Nov-16
Jan-17
Feb-17



Petermann Glacier
(a)
TSX
P1
P2
1600
1400
1200
1000
800
600
2011
2012
2013
2014
2015
2016
2017
Velocity [m/yr]
79 Glacier
(b)
TSX
F1
F2
2000
1500
1000
500
2011
2012
2013
2014
2015
2016
2017
Zachariæ Isstrøm
(c)
Z1
Z2
2800
2600
2400
2200
2000
1800
1600
Oct–15
Dec–15
Jan–16
Mar–16
Apr–16
Jun–16
Aug–16
Sep–16
Nov–16
Jan–17
Feb–17

Table 1

	Speedup Persistence	Summer speedup (%)	V_{annual}/V_{winter}(%)
JI (J1)	95 days (2015) 80 days (2016)	14% 9%	6% 4%
PG (P1)	25 days (2015) 55 days (2016)	25% 17%	0% 6%
79G (F2)	45 days (2016)	10%	1%
ZI (Z1)	45 days (2016)	18%	3%

Supplementary Material

Figure S1: Ice front location extracted from Sentinel-1 images on (b) Petermann Glacier and (b) Nioghalvfjerdsfjorden.

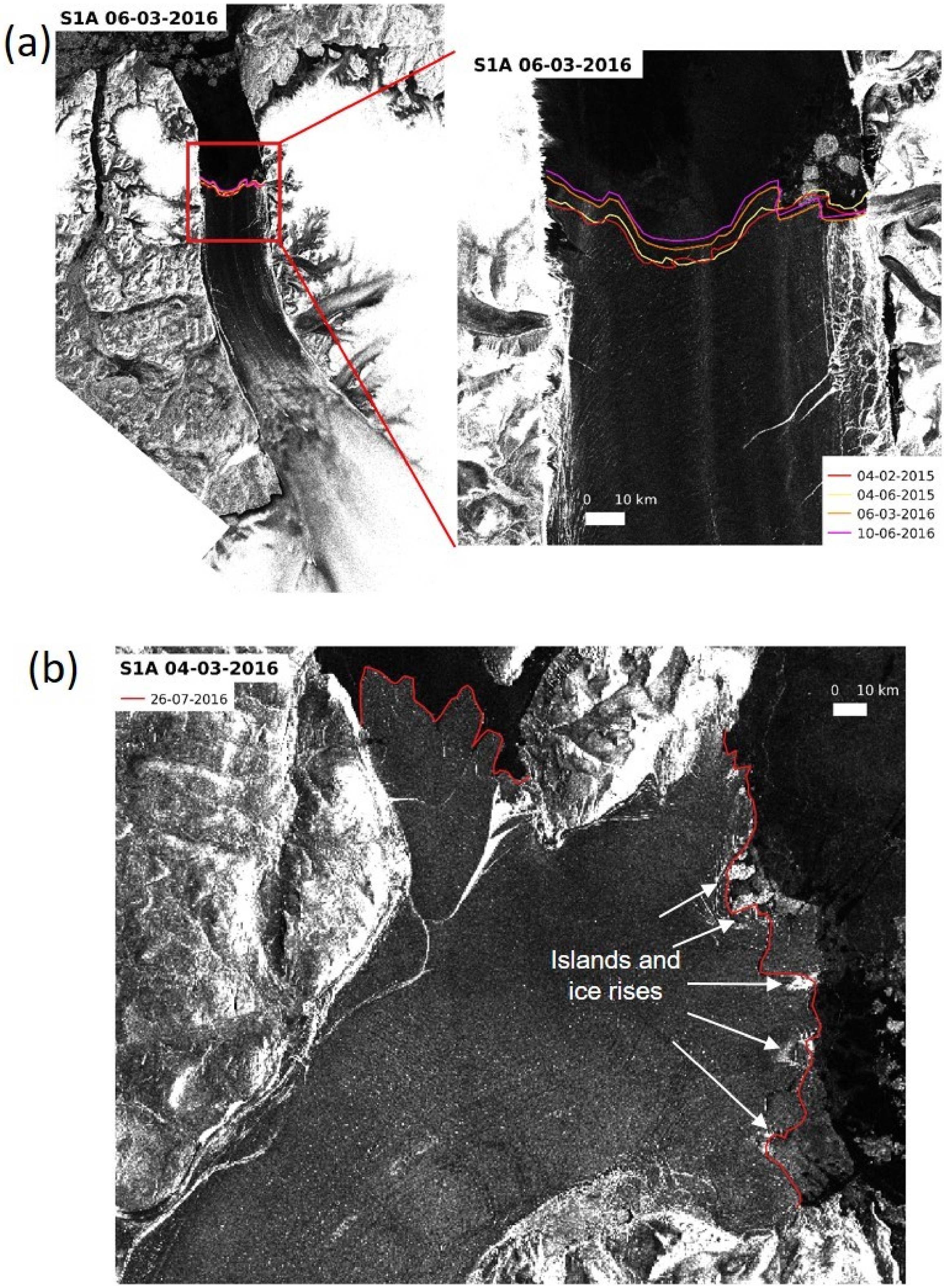


Figure S2: Number of images used separated per month.

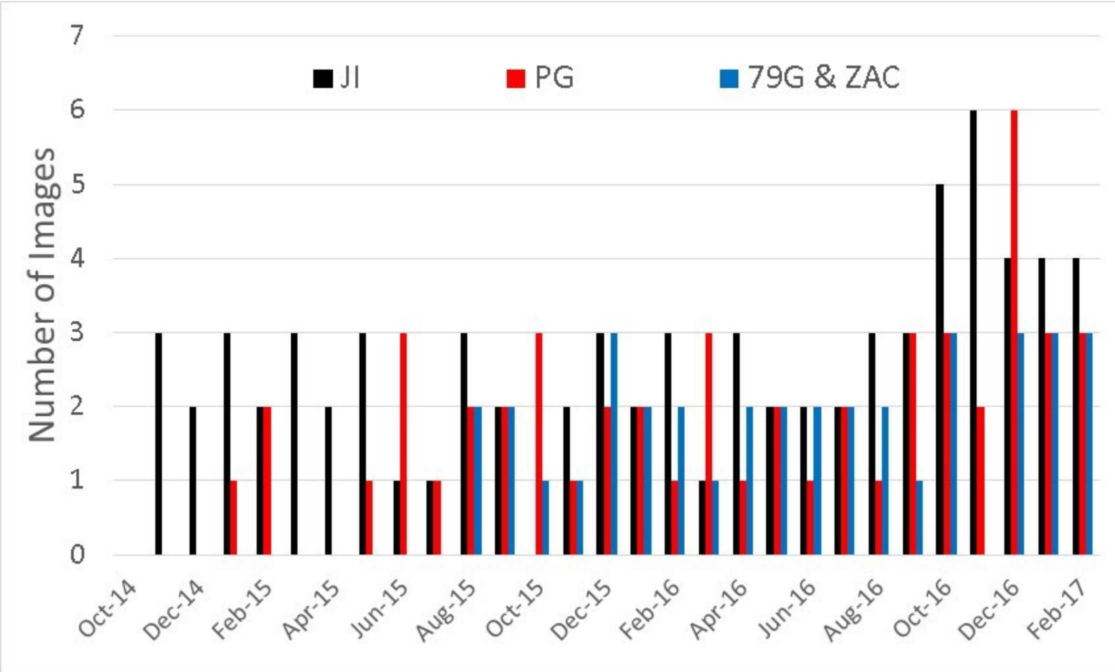


Table S1: List of Sentinel-1 images used.

Glacier	Scene 1				Scene 2			
	Satellite	day	month	year	Satellite	day	month	year
JI	S1A	4	Nov	14	S1A	16	Nov	14
	S1A	16	Nov	14	S1A	28	Nov	14
	S1A	28	Nov	14	S1A	10	Dec	14
	S1A	10	Dec	14	S1A	22	Dec	14
	S1A	22	Dec	14	S1A	3	Jan	15
	S1A	3	Jan	15	S1A	15	Jan	15
	S1A	27	Jan	15	S1A	8	Feb	15
	S1A	8	Feb	15	S1A	20	Feb	15
	S1A	20	Feb	15	S1A	4	Mar	15
	S1A	4	Mar	15	S1A	16	Mar	15
	S1A	16	Mar	15	S1A	28	Mar	15
	S1A	28	Mar	15	S1A	9	Apr	15
	S1A	9	Apr	15	S1A	21	Apr	15
	S1A	21	Apr	15	S1A	3	May	15
	S1A	3	May	15	S1A	15	May	15
	S1A	27	May	15	S1A	8	Jun	15
	S1A	8	Jun	15	S1A	26	Jul	15
	S1A	26	Jul	15	S1A	7	Aug	15
	S1A	7	Aug	15	S1A	19	Aug	15
	S1A	19	Aug	15	S1A	31	Aug	15
	S1A	31	Aug	15	S1A	12	Sep	15
	S1A	12	Sep	15	S1A	24	Sep	15

	S1A	11	Nov	15	S1A	23	Nov	15
	S1A	5	Dec	15	S1A	17	Dec	15
	S1A	17	Dec	15	S1A	29	Dec	15
	S1A	29	Dec	15	S1A	10	Jan	16
	S1A	10	Jan	16	S1A	22	Jan	16
	S1A	22	Jan	16	S1A	3	Feb	16
	S1A	3	Feb	16	S1A	27	Feb	16
	S1A	15	Feb	16	S1A	27	Feb	16
	S1A	27	Feb	16	S1A	10	Mar	16
	S1A	10	Mar	16	S1A	3	Apr	16
	S1A	3	Apr	16	S1A	15	Apr	16
	S1A	15	Apr	16	S1A	27	Apr	16
	S1A	27	Apr	16	S1A	9	May	16
	S1A	27	Apr	16	S1A	21	May	16
	S1A	9	May	16	S1A	21	May	16
	S1A	21	May	16	S1A	2	Jun	16
	S1A	2	Jun	16	S1A	14	Jun	16
	S1A	14	Jun	16	S1A	8	Jul	16
	S1A	14	Jun	16	S1A	1	Aug	16
	S1A	20	Jul	16	S1A	1	Aug	16
	S1A	1	Aug	16	S1A	13	Aug	16
	S1A	13	Aug	16	S1A	25	Aug	16
	S1A	25	Aug	16	S1A	6	Sep	16
	S1A	6	Sep	16	S1A	18	Sep	16
	S1A	18	Sep	16	S1A	30	Sep	16
	S1A	30	Sep	16	S1B	6	Oct	16
	S1B	6	Oct	16	S1A	12	Oct	16
	S1A	12	Oct	16	S1B	18	Oct	16
	S1B	18	Oct	16	S1A	24	Oct	16
	S1A	12	Oct	16	S1B	30	Oct	16
	S1A	24	Oct	16	S1B	30	Oct	16
	S1B	30	Oct	16	S1A	5	Nov	16
	S1B	30	Oct	16	S1B	23	Nov	16
	S1A	5	Nov	16	S1B	11	Nov	16
	S1B	11	Nov	16	S1A	17	Nov	16
	S1A	17	Nov	16	S1B	23	Nov	16
	S1B	23	Nov	16	S1A	29	Nov	16
	S1A	29	Nov	16	S1B	5	Dec	16
	S1B	5	Dec	16	S1A	11	Dec	16
	S1A	11	Dec	16	S1B	17	Dec	16
	S1B	17	Dec	16	S1A	23	Dec	16
	S1B	10	Jan	17	S1A	16	Jan	17
	S1A	16	Jan	17	S1B	22	Jan	17
	S1B	22	Jan	17	S1A	28	Jan	17
	S1A	28	Jan	17	S1B	3	Feb	17
	S1B	3	Feb	17	S1A	9	Feb	17
	S1A	9	Feb	17	S1B	15	Feb	17
	S1B	15	Feb	17	S1A	21	Feb	17
PG	S1A	23	Jan	15	S1A	4	Feb	15
	S1A	4	Feb	15	S1A	16	Feb	15
	S1A	23	May	15	S1A	4	Jun	15
	S1A	4	Jun	15	S1A	16	Jun	15
	S1A	16	Jun	15	S1A	28	Jun	15
	S1A	28	Jun	15	S1A	10	Jul	15

	S1A	10	Jul	15	S1A	15	Aug	15
	S1A	15	Aug	15	S1A	27	Aug	15
	S1A	27	Aug	15	S1A	8	Sep	15
	S1A	8	Sep	15	S1A	20	Sep	15
	S1A	20	Sep	15	S1A	2	Oct	15
	S1A	2	Oct	15	S1A	14	Oct	15
	S1A	14	Oct	15	S1A	26	Oct	15
	S1A	26	Oct	15	S1A	7	Nov	15
	S1A	1	Dec	15	S1A	13	Dec	15
	S1A	13	Dec	15	S1A	6	Jan	16
	S1A	6	Jan	16	S1A	18	Jan	16
	S1A	23	Feb	16	S1A	6	Mar	16
	S1A	6	Mar	16	S1A	18	Mar	16
	S1A	18	Mar	16	S1A	30	Mar	16
	S1A	30	Mar	16	S1A	23	Apr	16
	S1A	23	Apr	16	S1A	5	May	16
	S1A	29	May	16	S1A	10	Jun	16
	S1A	10	Jun	16	S1A	4	Jul	16
	S1A	4	Jul	16	S1A	28	Jul	16
	S1A	28	Jul	16	S1A	9	Aug	16
	S1A	9	Aug	16	S1A	2	Sep	16
	S1A	2	Sep	16	S1A	14	Sep	16
	S1A	14	Sep	16	S1A	26	Sep	16
	S1A	26	Sep	16	S1B	2	Oct	16
	S1B	2	Oct	16	S1A	8	Oct	16
	S1A	8	Oct	16	S1B	14	Oct	16
	S1B	14	Oct	16	S1B	7	Nov	16
	S1B	7	Nov	16	S1A	13	Nov	16
	S1A	13	Nov	16	S1B	1	Dec	16
	S1B	1	Dec	16	S1A	7	Dec	16
	S1A	7	Dec	16	S1B	13	Dec	16
	S1B	13	Dec	16	S1A	19	Dec	16
	S1A	19	Dec	16	S1B	25	Dec	16
	S1B	25	Dec	16	S1A	31	Dec	16
	S1A	31	Dec	16	S1B	6	Jan	17
	S1B	6	Jan	17	S1A	12	Jan	17
	S1A	12	Jan	17	S1B	30	Jan	17
	S1B	30	Jan	17	S1A	5	Feb	17
	S1A	5	Feb	17	S1B	11	Feb	17
	S1B	11	Feb	17	S1A	17	Feb	17

	S1A	6	Aug	15	S1A	30	Aug	15
	S1A	30	Aug	15	S1A	11	Sep	15
	S1A	11	Sep	15	S1A	23	Sep	15
	S1A	23	Sep	15	S1A	5	Oct	15
	S1A	5	Oct	15	S1A	10	Nov	15
	S1A	4	Dec	15	S1A	16	Dec	15
79-G and ZI	S1A	16	Dec	15	S1A	28	Dec	15
	S1A	28	Dec	15	S1A	9	Jan	16
	S1A	9	Jan	16	S1A	21	Jan	16
	S1A	21	Jan	16	S1A	2	Feb	16
	S1A	2	Feb	16	S1A	26	Feb	16
	S1A	26	Feb	16	S1A	9	Mar	16
	S1A	9	Mar	16	S1A	2	Apr	16
	S1A	2	Apr	16	S1A	14	Apr	16

S1A	14	Apr	16	S1A	8	May	16
S1A	8	May	16	S1A	20	May	16
S1A	20	May	16	S1A	1	Jun	16
S1A	1	Jun	16	S1A	13	Jun	16
S1A	13	Jun	16	S1A	19	Jul	16
S1A	19	Jul	16	S1A	31	Jul	16
S1A	31	Jul	16	S1A	12	Aug	16
S1A	12	Aug	16	S1A	24	Aug	16
S1A	24	Aug	16	S1A	5	Sep	16
S1A	5	Sep	16	S1B	5	Oct	16
S1B	5	Oct	16	S1A	11	Oct	16
S1A	11	Oct	16	S1A	23	Oct	16
S1A	23	Oct	16	S1B	4	Dec	16
S1B	4	Dec	16	S1B	16	Dec	16
S1B	16	Dec	16	S1B	28	Dec	16
S1B	28	Dec	16	S1A	3	Jan	17
S1A	3	Jan	17	S1B	9	Jan	17
S1B	9	Jan	17	S1B	21	Jan	17
S1B	21	Jan	17	S1B	2	Feb	17
S1B	2	Feb	17	S1A	8	Feb	17
S1A	8	Feb	17	S1B	14	Feb	17

- Table S2: Velocity magnitude differences of JI using surface elevation rate of change information derived from IceBridge and Pre-Icebridge data acquired from the NASA Airborne Topographic Mapper (ATM) [Studinger, 2014] for terrain correction, and velocity magnitude without using thinning correction.

Difference [m/yr]	**Distance along the profile from the grounding line [km]**								
	0 - 5	**5 - 10**	**10 - 15**	**15 - 20**	**20 - 25**	**25 - 30**	**30 - 35**	**35 - 40**	**40 - 45**
Mean	-65.7	-18.1	-12.4	-2.9	3.0	-3.8	0.9	1.9	1.9
Max	55.8	58.6	33.2	9.9	37.6	36.9	13.1	16.0	20.2
Min	-277.3	-160.4	-75.3	-17.2	-32.8	-39.3	-11.8	-6.0	-6.6