Response to Anonymous Referee #1

Our response to the Referee #1 comments are given below and appropriate changes to the paper have been included in the new version of the manuscript. A "Track Changes" version and a "clean" version of the revised manuscript were prepared.

Strozzi et al. presents their study about the dynamic changes of Stonebreen located in the southeast of the Svalbard archipelago. Using remote sensing (mostly SAR), they have reconstructed the surface ice velocity since 1994. The glacier shows a strong acceleration from 1994 to 2016 superimposed with very strong seasonal variations (<0.5 km/yr in winter to >2 km/yr at the end of summer). The authors discuss the different causes for the glacier destabilization. They conclude that surface melt-water and/or warm ocean water could be the cause of such changes.

I do not see any issues with the processing and analysis of the different remote sensing data sets (surface ice velocity changes). The results shown here are solid and should be published.

Thank you very much for this encouraging remark and the constructive review given below that helped us to revise the paper.

On the other hand, the discussion about the potential causes for the glacier acceleration is not well supported due to the lack of other external data (bathymetry, ice thickness, ocean water temperature).

Yes, we fully agree. Unfortunately, these other external data are not available for our analysis, and, to our best knowledge, they do not actually exist at all. By necessity our discussion of potential reasons becomes thus open. Still, we believe it is important to publish information about these processes and make them thus more widely known.

The authors are seeing strong seasonal variations of the ice speed and mention the frontal ablation as a cause for the observed changes. To better prove this interaction, I think it would be interesting to show the seasonal position of the terminus corresponding to Figure 9 and Figure 10 and see if they are linked to seasonal speed changes.

In order to map the position of the terminus in correspondence to Fig. 9 and Fig. 10 we have to use Radarsat-2 and Sentinel-1 data, the only data set that are available a high temporal sampling throughout the year. However, the spatial resolution of Radarsat-2 and Sentinel-1 is not very high (on the order of 10 to 20 m) and the peculiar properties of the SAR sensors (side-locking, radar speckle) make it even more difficult to map the glacier's frontal position. By applying a certain multi-looking to the Sentinel-1 SAR data (e.g. 20 in slant-range and 4 in azimuth) we can reduce to a certain level the speckle, but at the end the terminus position cannot be identified with an accuracy better than 100 m. Considering also that calving happens along different positions of the front at different times, the resulting plot of the terminus position determined with Radarsat-2 in 2013 and 2014 at 24 days temporal sampling and with Sentinel-1 in 2015 and 2016 at 12 days temporal sampling is very noisy and not helpful for our discussion.

Although the authors rule out ice thickness changes as the cause of the recent speed fluctuations, I still believe that the combination of higher input of melt-water and ice thickness reduction could have triggered this surge-type behavior.

As written at lines 1 and 2 of page 3, we are actually not ruling out this cause but state that it could be a cause: "This suggests that reduction of ice thickness is not a result of the increase in flow and discharge to the ocean, but rather an independent process or cause." We now expanded and clarified this sentence.

The glacier shows similar behavior that other "surge-type" glacier such as Pío XI in Patagonia (see Fig. 2c in Mouginot and Rignot 2015), which presents similar features such as shallow bed below sea level at the terminus, large thickness changes, strong seasonal and annual variations, and large melt water production. I believe a comparison with other glaciers in the region or elsewhere would be interesting. In other words, is the behavior of Stonebreen glacier unique, and if yes, in what sense?

According to the extensive comments of Referee #2, we revised the discussion to put the frontal destabilization of Stonebreen more in the general context of surges over Svalbard and elsewhere. We refer therefore to the response to Referee #2 for more information on this topic.

Below are the minor comments on the document:

Page 1
L10 don't -> do not
Done.

Page 2
L1,2 : unclear. If at steady state, calving fluxes are always the same order of magnitude than surface mass balance. The authors probably meant that mass fluctuation in Svalbard is similarly controlled by both dynamic and SMB changes.
Agreed, this sentence was reformulated. "For Svalbard, calving fluxes are assumed to be on a similar order of magnitude than the surface mass balance, making glacier dynamics an important factor of glacier's mass turnover and change."

Page 5
The authors mention ERS data with 3-day repeat cycle are not suitable for speckle tracking. I wonder if the authors looked at longer repeats (6 to 36 days). I know in Greenland such pairs are sometimes available, is it the case over Svalbard?
We tracked ERS and ENVISAT data over 35 days over Nordaustlandet in the past, but the results were of low quality and limited to the very crevassed fronts of the large active glaciers. The southern lobe of Stonebreen was not crevassed during the 1990's, though.

Page 6
The authors did not mention ionosphere noise in your ALOS error estimation. It is probably very small (not visible in Fig. 5a) or is it a source of error here?
Indeed ionospheric artifacts are not a source of visible error in Fig. 5a.

Page 7
I think a reference would be needed for the computation of speed changes from increase in slope.
Done.

Page 11
L21: "Total contribution to sea level..." sentence is not clear as described here. If the authors look at the calving flux, they have to compare to the surface mass balance. They could assume that surface mass balance was equal to zero (no discharge and glacier in balance), but if they do so, they should state it. In conclusion, more details on contribution to sea level needed here.
Agreed, "This total sea level contribution ..." was modified to "This value ...".

Page 12 or 13

I think the derived data sets should be made available to the scientific community. A sentence in the conclusion or acknowledgments where to find them would be great.
Agreed, we have now included in the Acknowledgments the server database addresses of the ESA Glacier_CCI and FP7 SEN3APP projects, where ALOS PALSAR and Sentinel-1 ice surface velocity data are available. Radarsat-2 Wide data can eventually be made available at a later point as the University of Oslo currently has no facilities to provide that kind of service.

Table 2 could be added as supplemental material.
Agreed, this could be added as supplemental material.

I see that Landsat-8 pairs are not a factor of 16 days (nominal repeat cycle), which means that the authors used different path/row to compute ice speed. It is a potential large source of error due to topographic effects (even with the orthorectification from USGS). I would recommend using only identical orbits as done for SAR sensors.
Indeed, Landsat-8 image pairs are not always the optimal factor of 16 days nominal repeat cycle, this depended on the availability of cloud-free summer images. However, we think that topographic effects are marginal. We have now included this aspect in the revised version of the manuscript and extended the last paragraph of Section 3.3 substantially in this respect

Figures should be vector graphic rather than raster.
Figures were prepared in a GIS using a combination of vector and raster layers, then exported to be included in the manuscript.

Fig. 1
If Stonebreen glacier is the glacier shown in Fig.1c-d, I think the label Stonebreen in Fig.1b should be placed differently. Perhaps an arrow pointing to glacier would do.
The following changes were included in the revised version of this figure:
- the glacier's basin delineation from the RGI is included in Fig.1b;
- the label “Stonebreen” was placed more to the centre of the whole basin;
- the size of the north arrows and that of the font of the scale bars were increased;
- the specifications “southern lobe” and “northern lobe” are now included Fig.1b;
- the name of the ice cap (“Edgeøyjøkulen”) is now included Fig.1b.

Fig. 2
The background is not contrasted enough, which makes the map difficult to read .
The following changes were included in the new version of this figure:
- the background image is now a panchromatic one;
- the color scheme of the glacier outlines is now following a blue-to-red graded colour scheme with time;
- a scale bar was added;
- an inset map was added to show the frontal retreat and advance of the southern lobe of Stonebreen with more details.

Fig. 5-8
These figures could be combined in one figure.
We think that how these figures are combined depends on the way the paper is read. If a printed version is considered, then we agree that having all the images in one page would be an advantage. But if a digital version of the pdf is considered on a computer screen, then we think that having only two large images side by side on the same position on every page that can be alternatively viewed with PgUp and PgDn is of great advantage for understanding how velocity changes are happening in time and space and how this is related to height changes (Fig. 3).

Fig. 10
Although obvious, blue and red dots should be explained in caption. Corresponding terminus position would be a must.
Done, the colours of the dots are now explained in the caption. For the terminus positions see reply above.

Response to Anonymous Referee #2

Our response to the Referee #2 comments are given below and appropriate changes to the paper have been included in the new version of the manuscript. A "Track Changes" version and a "clean" version of the revised manuscript were prepared.

General Description:
Strozzi et al., [2016] use optical and SAR datasets to observe the dynamic evolution of the Stonebreen Glacier of Edgeøyjøkulen Ice Cap (Svalbard) in 1994, and more frequently from 2011-2016. They combine the observed pattern of velocity fluctuation with glacier geometry evolution (determined from DEM differencing) and terminus position change, in order to speculate at the mechanisms causing the observed fluctuations in surface motion. A secondary stated goal is to evaluate the potential of frequent standard coverage acquisitions from recent earth observation missions (such as Landsat-8 and Sentinel-1) in order to analyze temporal variability in ice motion. The authors draw upon well used methods, and although there is little novel with regard to the methodology, they are nevertheless suitable for this type of work and reasonable uncertainty levels are provided. For the most part, the paper is well written and easy to follow, although in some places small typos need to be corrected and some modified work choice would help improve clarity. The tables are generally well done and complete, although some of the figures may be combined to improve clarity. At present, the discussion section of the paper is a bit too brief. I suggest that the section begin with a short paragraph which outlines how the velocity variability observed here differs significantly from glacier surging (which is observed in other basins of Edgeøyjøkulen Ice Cap), once the distinction from surging is made clear, then the other mechanisms that may be causing the variability in ice motion and the reasons for and against each of these mechanisms from the observations, can be described. I suggest that the authors also look at the "pulse" mechanism described by Van Wychen et al., [2016] for the Canadian Arctic as another mechanism that may be inducing fluctuations in ice motion. Finally, given that a major goal of this work is to assess the importance of frequent standard coverages of earth observation data for glacier velocity monitoring, there needs to a portion of the discussion devoted to this topic and more than a single sentence regarding this topic in the concluding remarks. Despite these comments, the authors now provide a much more comprehensive record of ice velocities for Stonebreen than was previously available and the dynamic behaviour observed here may apply to other glaciers in Svalbard (and other Arctic regions). I have provided a number of points below for the authors to address.

Thank you for pointing out that we are now providing a much more comprehensive record of ice velocities for Stonebreen than was previously available and that the dynamic behaviour observed here may apply to other glaciers in Svalbard. The fact that with Landsat-8 and Sentinel-1 it is now possible to observe ice surface velocities of many Arctic glaciers at high temporal sampling is one of the major considerations we wanted to raise up with our paper. As suggested, we will make more clear in the revised version of the paper the importance of frequent standard coverages of earth observation data for glacier velocity monitoring. We will also revise the discussion following the suggestions given above - and repeated below where we will summarize the changes we have been making - to put the frontal destabilization of Stonebreen more in the general context of surges over Svalbard.

Specific Comments
Minor Changes
PAGE 1
L6: Please provide a reference for the warming trend observed since the 1990s.
This is part of the Abstract, references are usually not included here. In addition, because the 20th-century warming trend in air temperature in the Arctic has been published in the IPCC and largely reported in the news, we think that it is not necessary to provide a reference for this as it somehow

represent common knowledge.

L7: “ice mass loss” -> “mass loss”
Done.

L11: “glacier’s” -> “glacier”
Done.

L12: suggest changing “speed increases” to “velocity increases”
Done.

L13: Please provide references.
Again, this is the Abstract, where references are usually not included. For references see page 2, line 16.

L14-15: “from 1971 until 2011 followed since 2012 by a strong increase in ice surface velocity along with a decrease of volume and an advance in frontal extension” -> “from 1971 until 2011, followed by (since 2012), a strong increase in ice surface velocity along with a decrease of volume and frontal extension”.
Done.

PAGE 2
L3: “The total calving flux of Svalbard is dominated by a few large and fast-flowing glaciers” please provide a reference.
Done, Dowdeswell et al. (2008).

L4: “So, far” -> “So far,”
Done.

L5: “A few glaciers” -> “A few glaciers,” add comma
Done.

L9: “overdeepenings in the glacier bad” -> “overdeepenings of the glacier bed”
Done.

L10: “reduced buttressing” and “changes in the back-stressing sea ice cover in front of the glaciers” are these differing mechanisms? If so, please clarify the distinction.
Yes, these are two differing mechanisms. One one hand, warm ocean water is reaching the fronts of the glaciers and is causing their retreat. On the other hand, sea ice cover in front of the glaciers is changing. In both cases, we have as a consequence changes in the back-stressing, i.e. reduced butressing.

L11-12: Please provide a reference or example to back up the statement.
References are provided just above, see Dunse et al. (2012) and Schellenberger et al. (2015), we don't want to repeat this just after one line.

L14: “of Svalbard” -> “of the ice masses of the Svalbard Archipelago”
Done.

L22: “seem possible” -> “seems possible”
Done.

L24: “data a” -> “data, a” (add comma)
Done.

PAGE 3:
L4: Please provide a lat/long coordinate for Stonebreen.
Done.

L6-7: “new missions” -> “new earth observation missions” such as Sentinel-1 (SAR) and Landsat 8 (optical) to detect. . .”
Done.

L10: “5,073 km2” -> “5,073 km2” change to superscript.
Done.

L11: “The eastern side of Edgeøya is covered by the Edgeøyjøkulen Ice Cap, which had an area of 1365 km2 in 1985”. . . (also note the superscript) –> please modify text.
Done.

L12-13: “is among the least well” -> “are among the least well”, also please add the (Dowdeswell and Bamber, 1995) reference to this statement.
Done.

L19: “extension” -> “area”
Done.

L20: Mark the northern lobe of Stonebreen with an “” and the southern lobe of Stonebreen with an “#” on Figure 1 to make it clear to the reader exactly where you are referring to. Also suggest making all the glaciers previously identified as surge-type (e.g. from Liestøl, 1993 and Dowdeswell and Bamber, 1995) with an “*”.*
We now placed on Fig. 1 the label “Stonebreen” more to the center of the whole basin, which makes much clearer the distinction between the northern and southern basins without the need of any mark. Our work specifically concentrate on Stonebreen, therefore we think that marking all other previously identified as surge-type glaciers in Fig. 1 will only diverge the reader to not necessary information for the understanding of our paper. If a reader is interested to this kind of information, the appropriate references are provided.

L7-11: Please provide an indication of the relatively uncertainty between glacier delineations versus pixel size between sensors. Have all the images been georeferenced to a common image?
Landsat data are available orthorectified from the U.S. Geological Survey and were not co-registered to a common geometry but relative co-registration between the scenes used was checked as well as absolute georeferenced against mapped rock outcrops and non-glaciated coastlines. Only Landsat scenes that passed these visual checks were used further. All images are from the summer months with good contrast on clean ice. The relatively uncertainty of glacier delineations is on the order of one pixel, i.e. up to 30 m.

L15: Please provide an uncertainty value for the NPI DEM.
From a study on the nearby Digerfonna (just west of Edgeøyajokulen) we estimate the accuracy of the elevations of the NPI DEM to be on the order of few meters to around ±12m for difficult terrain (Kääb 2008).

L23: “Digerfonna Kääb (2008)” -> “Digerfonna Ice Cap, Kääb (2008)”
Done.

L1-9: Please provide a description of the window sizes used for the SAR offset matching algorithm.
Matching window sizes of 64x196, 30x120, 128x128 and 512x128 pixels were applied to the ALOS PALSAR, Radarsat-2 Wide, Radarsat-2 WUF and Sentinel-1 IWS data, respectively.

L12: "Landscape 8" -> "Landsat 8"
Done.

L13: "For good visual contrast such as given for our study site and data due to the crevassed and snow-free glacier" -> "For areas of good visual contrast, such as those in our study site due to crevassed and snow-free glacier surfaces, displacement accuracies. . ." also please provide a reference for these values.
Done.

L1-16: For both the SAR offset tracking and the optical feature tracking, please describe how mis-matches or blunders are removed from the dataset. Was this completed manually? Was the strength of the cross-correlation value used to flag poor matches? Please describe in more detail.
For both SAR and optical tracking mis-matches or blunders were filtered by applying a threshold on the correlation coefficient, by iteratively discarding matches based on the angle and size of displacement vectors in the surrounding area, and by using a high-pass filter on the resulting displacement fields.

L20: "on a Landsat image of 14/07/2014" this can be removed as it appears in the figure caption.
Done.

PAGE 7:
L2: "NPI DEM of 1990" -> "NPI DEM of 1970"
Done.

L3: "From 1990" -> Please check here and throughout the manuscript and figures. You note that the NPI DEM is derived from aerial photography in 1970 (Page 4, L16), however at other times in the manuscript (see section 4.2 you describe it as being from 1990). Please correct.
Done.

L2-4: This section is somewhat awkwardly phased and could be clarified and would benefit from further description. Please describe more fully what "height losses of up to 150 m over current sea level and up to 100 m over current ice" really means. Suggest changing "current" to the last year when DEM data is available. It is noted that height changes of 100-150 m are observed, however the Figure scaling only shows elevation changes +/- 50 m, please adjust the scale bar so that the description in texts describes what can fully be seen in the figure.
This sentence was reformulated. "From 1990 to 2010/2012 we observe a general pattern of height losses along the coast of Stonebreen. Over the southern lobe the ice surface losses were up to 150 m along the coast."
The Fig. 3a scale bar was selected to match that of Fig. 3b, to best infer the large pattern of ice surface losses along the coast, and to highlight the slightly increasing elevation changes at higher sections (see discussion in Section 5.5). We agree that adjusting the scale bar to larger values will permit better distinction between different rates of ice surface losses, but our choice is not to change the scale bar of this figure for the reasons mentioned above.

L13: "The velocity is lower towards south" -> "The velocity is lower towards the south"
Done.

L14: "The northern sector is decorrelated, i.e. flowing faster" -> Yes, this can cause decorrelcation, but what about change in the glacier surface that could cause decorrelation? Provide further evidence why you attribute it to faster flow speeds rather than changes in surface characteristics.
Please see the following sentence, where ALOS PALSAR results of the same year are discussed: "ALOS PALSAR data of the same period as ERS-2 SAR (Fig. 5a) quantifies the ice surface velocity in the northern to maximum 300 m/yr."

L17: "are indicating" -> "indicate"
Done.

L19: "in summer of 2014 (a) respectively 2015 (b)" -> awkwardly phrased, should be re-written.
Done.

L20: "with a migration of the front of increased speeds towards inland" -> "due to an inland migration of a front of elevated velocities"
Done.

L20: "1'500" -> "1,500" or just "1 500"
Done.

L24: "12-days" -> "12-day"
Done.

PAGE 8:
L5-6: "dynamically active sector is increasing again inland" -> does this mean that the dynamically active sector is again migrating inland?
Yes, this sentence was reformulated.

L13: "2'500" -> "2,500" or "2 500"
Done.

L14: "The different SAR and optical satellite sensors complement each other very well".
In principal I agree with this statement, however I would like to see the authors develop this idea further, especially because evaluating the potential of frequent standard acquisitions is stated as a secondary goal of this paper (Page 3, lines 6-8). To further illustrate this statement, I suggest creating a timeline figure that shows all the image acquisition broken down (colour coded) by sensor for the period from ∼2010-2016. For an example, see bottom panel of Figure 2 in Burgess et al., [2012] of how this can be accomplished. I recognize that this information is available in Table 2, however the visual timeline would show the ready more easily how much of the time during the study period that the site was under observation, and further highlight the point that frequent observations improve our understanding of the temporal evolution of glacier velocities. This newly created figure may have the potential to replace Table 2, or at least move that table to supplementary materials.
The potential of frequent standard acquisitions is now further developed in the conclusions of the paper (see below for further details).
Figure 9 is actually already a timeline figure that shows all the image acquisitions colour coded by sensor. In this figure we can indeed graphically easily see "how much of the time during the study period the site was under observation, and further highlight the point that frequent observations improve our understanding of the temporal evolution of glacier velocities."
We agree that Table 2 could be added as supplemental material.

L20: "increase in slope" -> "increase in surface slope"
Done.

L22: "increment" -> "increase"
Done.

PAGE 9:
L7-8: "The increased elevation loss towards the front lead to an increase" -> "The elevation loss at the glacier front between the NPI DEM and the IDEM led to an increase in surface slope of $\sim 2^{\circ}$ . . ."
Done.

L18-20: This sentence is somewhat awkward to me and should be rewritten to improve clarity.
This sentence was reformulated.

PAGE 10
L10-12: The method for extracting and comparing backscatter intensity needs to be more fully described, and this should be provided in the methods section. Have all the backscatter intensity values been corrected to sigma nought values to account for various incident angles to enable comparison from different acquisitions and incidence angles? Or can this be neglected because all of the images are interferometric pairs with the same viewing geometry? This is not clearly described in text and should be. In addition to only using the backscatter values to determine melt rates, is it possible to use nearby meteorological station data or NCEP reanalysis to strengthen your claims?
Agree, a few further details and a reference were added here to give more information about the method. We prefer however not to add a new chapter in Section 3 because this analysis is only marginal for our work.
We also agree that meteorological station data or NCEP reanalysis would help support our claims as well. However, we are not aware of nearby meteorological station data and NCEP reanalysis was not considered in our analysis. Here, we wanted to highlight the potential of the SAR backscattering intensity to spatially map in a quantitative way the surface melt-water.

PAGE 11
L13-17: This portion of the paragraph is somewhat unclear and could be tidied to improve clarity.
Done.

PAGE 12:
L1-5: These sentences can be modified to improve clarity.
Done.

L10: suggest changing "(surge-type?) instability" to just "instability"
Done.

L15-L19: Comparisons with unpublished data for Basin-2 should be presented at the end of the discussion section rather than being introduced within the conclusions.
We prefer to keep this comparison in the conclusions as a kind of outlook, because the discussion there is extending our findings over Stonebreen on a broader scale and is relating our specific work on a single glacier to the more general context of glacier destabilization over Svalbard.

L21: "at high temporal sampling", suggest quantifying this remark. How often will Svalbard be

covered with standard acquisitions in the future? Every 12 days going forward? Or does it change seasonally? Provide a bit more information here.
Done, we specified even up to every 6 days with Sentinel-1A and B.

PAGE 13:
L4: "The Reearch Council of Norway" -> "The Research Council of Norway"
Done.

PAGES 13-16:
Check all references, in some cases DOI numbers are missing.
Done.

Substantive Comments:
Methods/Results Sections
Please further discuss the comparison of Sentinel-1 backscatter values over the melt season. Currently, this topic only appears in the discussion section, but should also be described in the methods and results sections.
A few further details and a reference were added in the Discussion to give more information about this method. We prefer however not to add a new chapter in Section 3 because this analysis is only marginal for our work and does therefore not belong to the main methods.

Discussion Section
I would like to see the discussion section begin with a brief description of why the observed velocity pattern does/does not conform to traditional surge theory, which then narrows down to introduce the alternate processes provided by the authors that could explain the velocity variability. One potential mechanism that is not described by the authors, but may be relevant, is "pulsing" which has been observed in other Arctic regions (see Van Wychen et al., 2016). This mechanism involves geometry changes, glacier advance and glacier speed-up, and the authors may want to include this as another potential mechanism in their discussion.

In order to put our work on the frontal destabilization of Stonebreen more in the general context of glacier surges we first included a few more information about the mechanism of glacier surges over Svalbard in the Introduction.
"Surge-type glaciers undergo a cyclic behaviour, with periods of rapid acceleration and advance (active phase) followed by periods of slow flow where ice fluxes are less than balance fluxes (quiescent phase) (Clarke, 1987). In a typical Svalbard glacier surge cycle the surge starts with a years-long period of steady acceleration, followed by a months-long period of relatively rapid acceleration, a length of the active phase of typically 3-10 years, and a very gradual end of the fast flow phase with velocity decreasing over a years-long period (Murray et al., 2003). The long active (~7-15 years) and quiescent (~50-100 years) phases, combined with surge termination that occurs over a multi-year period and velocity changes between the two phase of one or two orders of magnitude, suggest that the Svalbard type surges are linked to changes in basal thermal conditions rather than subglacial water pressure (Murray et al., 2003)."

Then, we briefly discussed at the beginning of Section 5 why the observed velocity pattern over Stonebreen does not conform to traditional surge theory for glaciers over Svalbard.
"Over the southern lobe of Stonebreen we observe a slow steady retreat of the glacier from 1971 to 2011 followed since 2012 by a strong increase in ice surface velocity with prominent seasonal variations along with a decrease of volume and an advance in frontal extension. The acceleration phase of the southern lobe of Stonebreen was lasting at least 3 years, more than the months-long period of relatively rapid velocity increase of a typical Svalbard glacier surge cycle (Murray et al., 2003), and the acceleration was not constant but seasonally modulated. So far, no deceleration

phase is observed over the glacier.”

Finally, we expanded the conlusions to include also comparison to glacier surges or pulses in other regions as Patagonia (see Mouginot and Rignot, 2015) and the Canadian Arctic (see Van Wychen et al., 2016).
“Also other glaciers in different regions, such as Pío XI in Patagonia (Mouginot and Rignot, 2015), presents similar features as Stonebreen, such as shallow bed below sea level at the terminus, large thickness changes, strong seasonal and annual variations, and large melt water production. Over the Canadian Arctic Van Wychen et al. (2016) introduced the concept of pulse-type glaciers. Over this kind of glaciers the velocity variability initiates in and propagates upglacier from the lowermost sections of the glacier near the terminus and is largely restricted to regions where the bed lies below sea level. Even if also for Stonebreen the instability initiated near the terminus, the velocity variability is now migrating upglacier more than the 6km inland from the 2014 front where the glaciers is believed to be grounded.”

Given that the stated secondary goal of the paper is to evaluate the potential of frequent standard coverages of earth observation data to analyse glacier dynamics there needs to be a portion of the discussion section devoted to this topic. Currently, the discussion section does not provide any reason why the authors believe that frequent standard coverages are beneficial beyond a very brief statement. Although this may seem somewhat obvious, it needs to be discussed fully if the authors intend on it being a major outcome of the paper.
This is now discussed in the conclusions.

Conclusion Section
Again, given that the secondary goal of the paper is to show how beneficial it is to have frequent coverage of earth observation datasets for glacier monitoring, the conclusions should devote more than one sentence to this topic. Specifically, the authors should note that with the data they had available, that they were able to monitor the dynamic evolution of this glacier nearly continuously from ∼2011-2016, and that this likely would not have been possible in the recent past. The authors may also want to speculate as to how recently launched (Sentinel 1b) or future sensor (Radarsat Constellation Mission) will even further increase the amount of data available for this type of monitoring.
Done. The fact that with Landsat-8 and Sentinel-1 it is now possible to observe ice surface velocities of many Arctic glaciers at high temporal sampling is one of the major considerations we wanted to raise up with our paper. As suggested, we made more clear in the revised version of the conclusion the importance of frequent standard coverages of earth observation data for glacier velocity monitoring.

FIGURES:
Figure 1: needs to be modified and clearly indicate that the ice cap is named “Edgeøyjøkulen” and that “Stonebreen” is a glacier basin within the Edgeøyjøkulen Ice Cap. Suggest adding the glacier basin delineations from the GLIMS Randolph Glacier Inventory and provide an arrow to the Stonebreen Glacier Basin. Suggest also adding a notation, such as “” to the basins that have previously been identified as “surge type” in the literature. Increase the size of the north arrows as well as the font of the scale bars (particularly on (b), (c), (d)) to improve readability.*
The following changes were included in the revised version of this figure:
- the glacier's basin delineation from the RGI is included in Fig.1b;
- the label “Stonebreen” was placed more to the centre of the whole basin;
- the size of the north arrows and that of the font of the scale bars were increased;
- the specifications “southern lobe” and “northern lobe” are now included Fig.1b;
- the name of the ice cap (“Edgeøyjøkulen”) is now included Fig.1b.
On the other hand, because our work specifically concentrate on Stonebreen, we think that marking

all other previously identified surge-type glaciers in Fig. 1 will only diverge the reader to not necessary information for the understanding of our paper. If a reader is interested to this kind of information, the appropriate references are provided.

Figure 2: Please provide the background image as a panchromatic image rather than a multi-spectral image, right now the image appears washed out and for clarity would appear better as a grayscale background image. Suggest changing the colour scheme of the glacier outlines and use a graded colour scheme (blue to red with time) rather than a mixture of colour and gray outlines. Please add a scale bar to this figure as it will aid the reader to determine the scale of terminus position change along the calving front. Suggest adding an inset map to show the frontal advance of the southern lobe of Stonebreen between 2011 and 2015, at the current scale it is difficult to see.
The following changes were included in the new version of this figure:
- the background image is now a panchromatic one;
- the colour scheme of the glacier outlines is now following a blue-to-red graded colour scheme with time;
- a scale bar was added;
- an inset map was added to show the frontal retreat and advance of the southern lobe of Stonebreen with more details.

Figure 4: It would be more beneficial if these figures were projected to velocities rather than presented as interferomgrams. This would enable comparison of glacier velocities shown in Figures 5-8 and may be beneficial to readers that are not familiar with interpreting interferometric fringes.
See Section 3.3: "Phase unwrapping to obtain displacement values (Werner et al., 2002) was not attempted because undersampling of the SAR data in relationship to the rate of movement is easily causing phase unwrapping errors, similar to what is observed in the case of mining". For readers that are not familiar with interpreting interferometric fringes we are providing at the beginning of Section 4.3 very extensive explanations.

Figures 4-8: The authors should consider combining Figures 4-8 into a single figure with multiple panes and with a common glacier velocities scaled colour bar. By combining these figures together it would help the reader understand the dynamic evolution of the glacier more clearly. Also note, in figures 5-8, that the glacier velocity colour bar and the velocities provided on the map are fully saturated at the high end of the velocity bar, please consider increasing the colour bar scale to provide more distinction between velocity bands.
We think that how these figures are combined depends on the way the paper is read. If a printed version is considered, then we agree that having all the images in one page would be an advantage. But if a digital version of the pdf is considered on a computer screen, then we think that having only two large images side by side on the same position on every page that can be alternatively viewed with PgUp and PgDn is of great advantage for understanding how velocity changes are happening in time and space and how this is related to height changes (Fig. 3).
Colour saturation in these images was carefully selected in order to illustrate in the best way the spatial distribution of the instability. If the colour bar is increased then less distinction between slow and fast moving areas is provided. The colour bar of Fig. 5 is different in order to better highlight where the frontal instabilities started with lower velocities.

Figure 10: It may be beneficial to add a trend line for both data series which shows that RADAR backscatter values decrease as glacier velocities increase (albeit with some temporal lag) to indicate that melt may be modulating ice flow. Also, the figure caption needs to be more description, e.g. it needs to say that the blue marking indicate backscatter values and that red markings indicate ice surface velocities.
We also prepared an image with trend lines, both we found out that it was less clear than the one without trend lines. What the blue and red dots are is now explained in the caption.

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This reference is not included, because Figure 9 is already somehow a timeline figure that shows all the image acquisitions colour coded by sensor.

Van Wychen, W., Davis, J., Burgess, D.O., Copland, L., Gray, L., Sharp, M., and Mortimer, C. [2016], Characterizing interannual variability of glacier dynamics and dynamic discharge (1999-2015) for the ice masses of Ellesmere and Axel Heiberg Islands, Nunavut, Canada. Journal of Geophysical Research: Earth Surface, 121, doi:10.1002/2013JF003839.

This reference is now included and discussed.

Frontal destabilisation of Stonebreen, Edgeøya, Svalbard

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Abstract. In consideration of the strong atmospheric warming that has been observed since the 1990s in polar regions there is a need to quantify ~~ice~~ mass loss of Arctic ice caps and glaciers and their contribution to sea level rise. In polar regions a large part of glacier ablation is through calving of tidewater glaciers driven by ice velocities and their variations. The Svalbard region is characterized by glaciers with rapid dynamic fluctuations of different types, including irreversible adjustments of calving fronts to a changing mass balance and reversible, surge-type activities. For large areas, however, we do no~~'~~t have much past and current information on glacier~~'s~~ dynamic fluctuations. Recently, through frequent monitoring based on repeat optical and SAR satellite data, a number of zones of ~~speed~~velocity increases have been observed at formerly slow-flowing calving fronts on Svalbard. Here we present the dynamic evolution of the southern lobe of Stonebreen on Edgeøya. We observe a slowly steady retreat of the glacier front from 1971 until 2011, followed by ~~since 2012 by~~ a strong increase in ice surface velocity along with a decrease of volume and ~~an advance in~~ frontal extension since 2012. The considerable losses in ice thickness could have made the tide-water calving glacier, which is grounded below sea level some 6 km inland from the 2014 front, more sensitive to surface melt-water reaching its bed and/or warm ocean water increasing frontal ablation with subsequent strong multi-annual ice-flow acceleration.

1 Introduction

Mass loss from glaciers and ice sheets contributes about one third to current sea level rise (Church et al., 2013). In polar regions, a large part of glacier mass loss is through frontal ablation of tidewater glaciers (Rignot et al., 2008; Blaszczyk et al., 2009; Burgess et al., 2013; Khan et al., 2015; McNabb et al., 2015), which includes calving of icebergs and frontal melt. Related calving fluxes and their changes over time are mainly driven by lateral ice velocities and their variations. The increase of archived and newly acquired optical and Synthetic Aperture Radar (SAR) satellite data available for quantifying ice surface flow together with progress in methods in particular for handling large satellite data sets with increasing temporal resolution open up for new possibilities to monitor ice flow over large regions, and to detect and understand related changes.

For Svalbard, calving fluxes are assumed to be on a similar order of magnitude than the surface mass balanceIce mass fluctuation in Svalbard is similarly controlled by both dynamic and surface mass balance change, making glacier dynamics an important factor of glacier's mass turnover and change (Blaszczyk et al., 2009; Moholdt et al., 2010; Dunse et al., 2015). The total calving flux of Svalbard is dominated by a few large and fast-flowing glaciers (Dowdeswell et al., 2008), and variations in their speed can thus have large influence on the total mass balance of the archipelago's glaciers. So, far, two main types of fast-flowing glaciers have been described on Svalbard. A few glaciers, such as Kronebreen and Kongsbreen near Ny Ålesund, Western Spitsbergen, are continuously fast-flowing, with maximum speed of more than 2-3 m/day at the calving front. These glaciers show seasonal variations in speed related to meltwater input to the glacier base (Dunse et al., 2012; Schellenberger et al., 2015). Also, increases in overall speed are observed for these glaciers together with the retreat of calving fronts due to a combination of general glacier mass loss, overdeepenings inof the glacier bed, warm ocean water reaching the fronts and causing retreat and reduced butressing (Luckman et al., 2015), and changes in the back-stressing sea ice cover in front of the glaciers. On the time-scales of, at least, decades such calving front retreats are typically irreversible until a considerable mass gain enables the glacier to re-advance from one pin-point to the next.

A second, and very important type of fast-flowing glaciers on Svalbard are surging glaciers (Murray et al. 2003). Surge-type glaciers undergo a cyclic behaviour, with periods of rapid acceleration and advance (active phase) followed by periods of slow flow where ice fluxes are less than balance fluxes (quiescent phase) (Clarke, 1987). In a typical Svalbard glacier surge cycle the surge starts with a years-long period of steady acceleration, followed by a months-long period of relatively rapid acceleration, a length of the active phase of typically 3-10 years, and a very gradual end of the fast flow phase with velocity decreasing over a years-long period (Murray et al., 2003). The long active (~7-15 years) and quiescent (~50-100 years) phases, combined with surge termination that occurs over a multi-year period and velocity changes between the two phase of one or two orders of magnitude, suggest that the Svalbard type surges are linked to changes in basal thermal conditions rather than subglacial water pressure (Murray et al., 2003). TheySurging glaciers are able to temporarily discharge large ice masses into the ocean and thus vary the total glacier mass balance of Svalbardof the ice masses of the Svalbard Archipelago considerably over shorter time scales. Two recent prominent surges are the ones of Nathorstbreen in Southern Spitsbergen and Basin-3 on Austfonna. The Nathorstbreen glacier system started to surge in 2009 and an advance of about 15 km was observed (Sund et al. 2014). The northern branch of Basin-3 showed a stepwise acceleration over multiple years at least since 2008, which ended in a basin-wide surge starting in 2012 with velocities up to 20 m/day (McMillan et al., 2014, Dunse et al., 2015). The impact of climatic changes on surges on Svalbard is debated, but Dunse et al. (2015) suggest a hydro-thermodynamic feedback mechanism where increased meltwater production and input to the glacier bed is able to stepwise trigger a surge-type instability. Glacier mass losses due to surges are in principle reversible once the glacier stops its fast discharge and is thus able to replenish its mass through accumulation. Also, transitions between surge-type behaviour and more continuous fast-flow seems possible such as for Monacobreen (Schellenberger et al, ~~submitted~~2016).

Recently, through frequent monitoring based on repeat optical and SAR satellite data, a number of zones of speed increases have been observed at formerly slow-flowing calving fronts on Svalbard, and questions arise whether these are forms of irreversible adjustments of calving fronts to a changing mass balance, or parts of reversible surge-type activities. For instance, a frontal zone of Basin-3 of Austfonna that accelerated spatially separated from the main glacier stream was later incorporated in the surge once it reached its full extent, and thus it was viewed as part of the Basin-3 surge (Dunse et al., 2015). Here, we investigate a zone of recent acceleration of a formerly very slow flowing calving front of Stonebreen on Edgeøya, Eastern Svalbard (23.8 E, 77.8 N), in order to characterise its spatio-temporal dynamic pattern and the potential nature and significance of the instability. As a secondary goal, we also evaluate the potential of frequent standard acquisitions by new earth observation missions such as Sentinel-1 (radar) and Landsat 8 (optical) to detect and analyse such spatially limited and temporally variable glacier instabilities.

2 Study site

Edgeøya is located in the southeast of the Svalbard archipelago and is 5,073 km^2 in area, making it the third largest island in the Svalbard archipelago. ~~Its~~The eastern side of Edgeøya is covered by ~~an ice cap,~~the Edgeøyjøkulen ice cap, which had an extension of 1365 km~~2~~^{2} ~~in area~~ in 1985 (Dowdeswell and Bamber, 1995). The ice cap on Edgeøya, together with its neighbour ice cap on Barentsøya, is among the least well known in Svalbard (Dowdeswell and Bamber, 1995). To our best knowledge, there are no existing field studies of either the ice thickness or the mass balance of these glaciers and ice caps.

The tidewater ice cliffs of eastern Edgeøya are over 80 km long and produce small tabular icebergs (Dowdeswell and Bamber, 1995). With the exception of the surge-related advances, the tidewater ice masses of eastern Edgeoya have been in retreat over the Twentieth Century (Nuth et al., 2013, Arendt et al., 2015).

Several of the ice-cap outlet glaciers on Edgeøya are interpreted to be of surge-type, based on a combination of direct observations and analysis of vertical and oblique aerial photographs (Liestøl, 1993). Stonebreen (Fig. 1) is the largest glacier on the ice cap with an ~~extension~~area of 687 km^2 in 1971 (Nuth et al., 2013) and of 582 km^2 in 2006-2007 (Arendt et al., 2015). The northern lobe of Stonebreen appears to have surged between 1936 and 1971. However, the southern lobe investigated here does not appear to have surged during this period, indicating that different basins within this ice cap behave as dynamically separate units (Dowdeswell and Bamber, 1995).

Airborne radio-echo sounding at 60 MHz over the ice masses of Edgeøya has provided ice thickness and elevation data (Dowdeswell and Bamber, 1995). Ice is grounded below sea level up to about 20 km inland from the tidewater terminus of the northern lobe of Stonebreen. For the southern lobe of Stonebreen investigated here, ice seemed to be grounded below sea level some 8 km inland in 1986 (Dowdeswell and Bamber, 1995), corresponding to 6 km from the 2014 front. Ice thickness is from <100 m close to the margins to about 250 m in the interior of Edgeøyjøkulen. The ice masses on Edgeøya are believed to be at the pressure melting point with a basal hydrological system (Dowdeswell and Bamber, 1995).

3 Data and Methods

3.1 Coastal Outlines

Coastal outlines were manually digitized from Landsat imagery from 1994 to 2015 with additional information from the Randolph Glacier Inventory (RGI) 5.0 (Arendt et al., 2015) and vertical aerial photograph in 1971 (Nuth et al., 2013). Acquisition dates and sensors name of the satellite optical imagery used for the mapping of the coastal outlines are indicated in Table 1. The primary data set used for RGI 5.0 is SPOT5 orthoimages at 5m resolution from 2007-2008 (Arendt et al., 2015; Nuth et al., 2013). Landsat data are available orthorectified from the U.S. Geological Survey and were not co-registered to a common geometry but relative co-registration between the scenes used was checked as well as absolute georeferenced against mapped rock outcrops and non-glaciated coastlines. Only Landsat scenes that passed these visual checks were used further. All images are from the summer months with good contrast on clean ice. The relatively uncertainty of glacier delineations is on the order of one pixel, i.e. up to 30 m.

3.2 Glacier Elevation Change

Three Digital Elevation Models (DEM) were available for our analysis: the Norwegian Polar Institute DEM (NPI DEM), the TanDEM-X Intermediate DEM (IDEM), and an ASTER DEM (AST14DEM).

The NPI DEM (Norwegian Polar Institute, 2014) is based on 1:100'000 scale topographic maps derived from aerial photography in 1970. It is provided at 20 m posting in UTM projection for zone 33N and the WGS 1984 spatial reference system. From a study on the nearby Digerfonna ice cap (just west of Edgeøyajokulen) we estimate the accuracy of the elevations of the NPI DEM to be on the order of few meters to around ±12m for difficult terrain (Kääb 2008). The IDEM (DLR EOC, 2013) is based over Edgeøya on TanDEM-X acquisitions from 12/12/2010 to 26/03/2012. It is provided in 3 arcsec geographic coordinates, with a posting corresponding to approximately 90 m. The indicated absolute horizontal and vertical accuracies are < 10 m (DLR EOC, 2013). Independent tests performed with a TanDEM-X DEM of Mount Etna (Italy) indicated that the difference of the elevations provided by TanDEM-X with those measured with GPS over more than 100 benchmarks are 0.7 m with a standard deviation of 5.2 m (Wegmüller et al., 2014). For an ASTER satellite stereo scene of 15/07/2014 we acquired an AST14DEM product (LPDAAC, 2016). The product is provided with a posting of 30 m. Over the nearby Digerfonna Ice Cap Kääb (2008) found an accuracy of the AST14DEM of ±12 m RMS or better.

Glacier elevation change is computed by subtraction of the IDEM from the NPI DEM and of the AST14DEM from the IDEM after resampling of all DEMs to 100 m posting on the UTM 33 projection. Visual inspection suggested that lateral co-registration between the three DEMs was not necessary and would have little to no effect, among others because the slope of the lower part of the Stonebreen studied here is only about 1°-2° steep (Nuth and Kääb, 2011). Vertically, all DEM differences were checked over stable terrain and an offset of 40 m was corrected for the AST14DEM.

3.3 Ice Surface Velocity

We analysed a series of satellite SAR images acquired by the ERS-1, ERS-2, ALOS PALSAR, Radarsat-2, and Sentinel-1 missions from 1994 to 2016 and of optical Landsat 8 images from 2014 to 2016 (Table 2).

ERS-1 data of 1994 and ERS-2 data of 2011 are from the 3-days repeat campaigns and were processed to differential SAR interferograms with use of the IDEM (Bamler and Hartl, 1998; Rosen et al., 2001). The acquisition date of the IDEM matches that of the ERS-2 data and we don't expect any major topographic signal left on the differential interferogram. On the other hand, important ice surface elevation changes (> 100 m) occurred between the date of the IDEM (2010-2013) and that of the ERS-1 data (1994), but because the perpendicular baseline of the ERS-1 pair is only 15 m the phase artefacts are small (i.e. 0.32π or 57° for a height error of 100 m) (Strozzi et al., 2001). Therefore, on both ERS-1 and ERS-2 differential SAR interferograms the phase signals can be interpreted as ice surface displacement in the satellite line-of-sight direction with possible atmospheric disturbances. Phase unwrapping to obtain displacement values (Werner et al., 2002) was not attempted because undersampling of the SAR data in relationship to the rate of movement is easily causing phase unwrapping errors, similar to what is observed in the case of mining (Spreckels et al., 2001, Przyłucka and al., 2015) or rockglaciers (Barboux et al., 2015). Processing of the ERS-1 and ERS-2 3-days data with offset-tracking procedures (Strozzi et al, 2002; Paul et al., 2015) did not produce useful results, because a 1/20th of pixel precision in offsets estimation over a 3 days repeat period yields a displacement error of about 100 m/yr, which is larger than the velocity observed over Stonebreen in past years.

ALOS PALSAR Fine-Beam Single (FBS), Radarsat-2 Wide and Wide Ultra-Fine (WUF) and Sentinel-1 Interferometric Wide Swath (IWS) SAR images were processed with offset-tracking procedures (Strozzi et al, 2002; Paul et al., 2015) to three-dimensional ice surface displacement maps combining the slant-range and azimuth offsets by assuming that flow occurs parallel to the ice surface estimated from the DEM (e.g. Mohr et al., 1998). Matching window sizes of 64x196, 30x120, 128x128 and 512x128 pixels were applied to the ALOS PALSAR, Radarsat-2 Wide, Radarsat-2 WUF and Sentinel-1 IWS data, respectively. Mis-matches or blunders were filtered by applying a threshold on the correlation coefficient, by iteratively discarding matches based on the angle and size of displacement vectors in the surrounding area, and by using a high-pass filter on the resulting displacement fields (Paul et al., 2015). The error in the estimation of ice surface velocity with ALOS PALSAR data separated by a repeat-cycle of 46 days is on the order of 10 m/yr (Paul et al., 2015). For a repeat-cycle of 92 days a similar error is expected, although the spatial coverage with valid information is reduced. The expected displacement error of the Radarsat-2 Wide, Radarsat-2 WUF and Sentinel-1 IWS data was estimated by assuming a precision of 1/20th of a pixel in the offset estimation. We estimate for (i) Radarsat-2 Wide data with pixel sizes in ground-range and azimuth direction of about 20m x 5m and a time interval of 24 days a displacement error of ~15 m/yr, for (ii) Radarsat-2 WUF data with pixel sizes in ground-range and azimuth direction of about 3m x 3m and a time interval of 24 days a displacement error of ~5 m/yr, and (iii) for Sentinel-1 IWS data with pixel sizes in ground-range and azimuth direction of 8m x 20m and a time interval of 12 days a displacement error of ~30 m/yr.

Ice velocities from repeat Landsat 8 data were measured to fill temporal gaps in the SAR-derived velocity time series using standard normalized cross-correlation methods (Kääb and Vollmer, 2000; Debella-Gilo and Kääb, 2011; Heid and Kääb, 2012). In this study, matching window sizes of 15 pixels were applied based on ~~Landscape~~ Landsat 8 pan band data (15 m resolution). For ~~a~~areas of good visual contrast, such as ~~given~~those in ~~for~~ our study site ~~and data~~ due to ~~the~~ crevassed and snow-free glacier surfaces, displacement accuracies of 10-20% of a pixel (15 m) can be reached (Heid and Kääb, 2012), i.e. 1.5-3 m corresponding to 24-48 m/yr for a time interval of 16 days. For time intervals different than the optimal factor of 16 days nominal repeat cycle or integer multiples of it, displacement accuracies are potentially reduced due to differential orthorectification errors (Kääb et al., 2016). We minimized these effects by choosing scenes where Stonebreen is close to the satellite ground track, and carefully checked the scenes by flickering the repeat images and the resulting velocity vectors for offsets in cross-track direction. Further, flow direction is not perpendicular to the Landsat track direction which further reduces the effect of orthorectification offsets. In sum, differential orthorectication offsets should affect our Landsat-derived velocities only to a minor extent and not the conclusions drawn from them. Co-registration of the matching scenes was also checked for stable ground and did not reveal any statistically significant offsets. Mis-matches were removed using the same approach as for SAR results (Paul et al., 2015).

4 Results

4.1 Coastal Outlines

The coastal outlines from the vertical aerial photograph in 1971, the Landsat imagery in 1976, 1994, 2011 and 2015, and RGI 5.0 of the years 2006 and 2007 are shown in Fig. 2~~ on a Landsat image of 14/07/2014~~. From the aerial and satellite imagery we observe a prominent retreat of all glaciers along the eastern coast of Edgeøya. The maximal retreat of the front of Stonebreen from 1971 to 2011 was larger than 3 km. However, from 2011 to 2015 we observe an advance of almost 500 m of the front of Stonebreen at the centre of Fig. 2.

4.2 Glacier Elevation Change

Glacier elevation changes were computed between the NPI DEM of ~~1990~~1970 and the IDEM of 2010/2012 and the IDEM and the ASTER DEM of 2014 and are presented in Figs. 3a and 3b, respectively. From 1990 to 2010/2012 we observe a general pattern of height losses along the coast of Stonebreen. Over the southern lobe the ice surface ~~height~~ losses were~~of~~ up to 150 m along the coast~~ over current sea level and up to 100 m over current ice~~. Between 2010/2012 and 2014 we observe over an area of about 15 km^2 in the inland of Stonebreen ice surface losses of 50 to 70 m.

4.3 Ice Surface Velocity

ERS differential SAR interferograms and ALOS PALSAR, Radarsat-2, Landsat 8 and Sentinel-1 ice surface velocity maps are presented in Figs. 4 to 8. Slow-flowing ice becoming dynamically active is identified over the southern lobe of Stonebreen. In the ERS-1 differential SAR interferogram of 1994 (Fig. 4a) two small dynamically active sectors of about 4 km^2 each are identified. The line-of-sight velocities are on the order of 12 (~4 fringes of 2.8 cm each) to 20 cm (~6 fringes) in 3 days, i.e. 15 to 25 m/yr, or 40 to 60 m/yr on a horizontal plane taking into account the 23° incidence angle of the ERS-1 SAR sensor. In the ERS-2 differential SAR interferogram of 2011 (Fig. 4b) a single dynamically active sector of about 14 km^2 is visible. The velocity is lower towards the south, where it is approaching 14 cm (~5 fringes) in the line-of-sight direction or 45 m/yr on a horizontal plane. The northern sector is decorrelated, i.e. flowing faster.

ALOS PALSAR data of the same period as ERS-2 SAR (Fig. 5a) quantifies the ice surface velocity in the northern to maximum 300 m/yr. The size of the dynamically active sector determined with ALOS PALSAR is similar to that observed with ERS-2 SAR. Radarsat-2 results of late 2011, i.e. the following winter season (Fig. 5b), ~~are~~ indicate~~ing~~ a larger dynamically active sector with higher velocities up to more than 500 m/yr. ~~Fig. 6 presents two i~~Ice velocity maps at higher spatial resolution from Landsat 8 are presented in Fig. 6a for the ~~in~~ the summer of 2014 a~~m~~nd in Fig. 6b for the summer of ~~(a) respectively~~ 2015~~ (b)~~. The size of the dynamically active sector increased steadily ~~with a migration of the front of increased speeds towards inland~~due to an inland migration of a front of elevated velocities. Maximal velocities are over

1,500 m/yr in both years. The coverage with valid ice surface velocity data are restricted to crevassed fast-flowing glacier sections.

In order to retrieve recent winter ice velocity data we used data of the Sentinel-1 SAR sensor. In the winter of 2015 Sentinel-1 data (Fig. 7a) quantified the size of the dynamically active sector to about 50 km^2 with maximal velocities approaching 600 m/yr. After three 12-day campaigns performed in January and February 2015 with nearly identical results over Stonebreen, no further Sentinel-1 data are available until mid of August 2015, when Sentinel-1 acquisitions over Svalbard started on a regular 12-days basis (Table 2). The Sentinel-1 tracking results with winter images have a better spatial coverage with valid information, in particular over the interior of the ice cap, but the coverage with valid information over the dynamically active sector of Stonebreen is very good also for the summer data (Fig. 7b). Results are similar to those obtained with Landsat 8 data of the summer of 2015 (Fig. 6b), although at lower spatial resolution and with a less complete picture of glacier speed.

In the newest Sentinel-1 results of the winter of 2016 (Fig. 8a) we observed that the size of the dynamically active sector is increasing again inland due to a further migration of the front of elevated velocities. Almost coincident Radarsat-2 WUF data (Fig. 8b) with a ground resolution of about 3 m can be used for validation of the Sentinel-1 IWS data. The standard deviation of the difference of ice surface velocity over Stonebreen between Radarsat-2 WUF and Sentinel-1 IWS data are about 50 m/yr. On ice free regions the standard deviations of the Radarsat-2 WUF and Sentinel-1 IWS displacements are between 5 to 10 m/yr and 20 to 30 m/yr, respectively.

A time series of ice surface velocities close to the front of the southern lobe of Stonebreen (716080 E / 8646230 N) is presented in Fig. 9. Thanks to the frequent monitoring based on repeat optical and SAR satellite data it is possible to well follow the speed-up of Stonebreen from 2009 to 2015, with large seasonal fluctuations. The maximal velocity was reached in October 2015 with values approaching 2,500 m/yr, followed by a decrease down to 500 m/yr in April 2016. The different SAR and optical satellite sensors complement each other very well.

5 Discussion

Over the southern lobe of Stonebreen we observe a slowly steady retreat of the glacier from 1971 to 2011 followed since 2012 by a strong increase in ice surface velocity with prominent seasonal variations along with a decrease of volume and an advance in frontal extension. The acceleration phase of the southern lobe of Stonebreen was lasting at least 3 years, more than the months-long period of relatively rapid velocity increase of a typical Svalbard glacier surge cycle (Murray et al., 2003), and the acceleration was not constant but seasonally modulated. So far, no deceleration phase is observed over the glacier. The following processes or their combination could be involved in the instability observed since 2012 and are thus discussed in more detail:

→ increase in surface slope and related increment in driving stress;

→ decrease in ice thickness and related reduction of basal drag;

→ increased surface melt-water input to the glacier bed and related ~~increment~~increase in basal pressure;

→ increased frontal ablation due to warm ocean water.

Our interpretation of the observed instability is complicated by the lack of detailed bathymetry in the front of Stonebreen, because water depth is an important factor for the stability and behaviour of tidewater calving glaciers (e.g., Van der Veen, 1996; Vieli et al, 2001). To our best knowledge, only the Norwegian Sea Navigation Chart (2016) gives approximate indications of water depths in front of the southern lobe of Stonebreen. Approximate values are around 25 m (Fig. 1).

5.1 Increase in slope

Over the 6-7 km of the current instability (measured in ice flow direction), which roughly coincides with the glacier section that could be grounded below sea level, the surface slope amounted to only ~ 1° in the 1970s NPI DEM. ~~The increased elevation loss towards the front led to an increase in slope to ~ 2° in the 2010-2012 IDEM.~~ The elevation loss at the glacier front from the 1970s (NPI DEM) to 2010-2012 (IDEM) led to an increase in surface slope of ~ 2°. Assuming a glacier depth of 200 m (Dowdeswell and Bamber, 1995) and an infinite slab with standard parametrization (Cuffey and Paterson., 2010), this increase in slope would have increased ice deformation speeds at the surface from a few dm/yr to a few m/yr. Both these speeds are lower than the surface speeds observed, pointing to a significant contribution of basal sliding even before the instability. At the upper end of the current instability, where large elevation losses of up to 70 m are found between the 2010-2012 IDEM and the 2014 ASTER DEM (Fig. 3b), the surface slope increased from ~ 1.5° to ~ 3.5° , which could have caused an increase in ice deformation from ~ 1 m/yr to almost ~ 20 m/yr at the surface. Although hardly being a main reason behind the increase in flow speed, the increase in slope could be involved in a basal feedback mechanism.

5.2 Reduction in ice thickness

In 1970 (NPI DEM) the southern lobe of Stonebreen was around 80 m high above sea level. During 2010-2012 (IDEM) it was only 35 m high above sea level. At the location of the 2010-2012 front surface elevation in 1970 was around 110 m. This is a considerable reduction of ice thickness. However, the current glacier thickness should still be far over the floatation level that would only be reached for several hundreds of metres water depth, which is very unlikely. Though, the loss in ice thickness - from ~ 135 m in 1970 to ~ 60 m in 2010/2012 if we assume 25 m water depth at the 2010/2012 location of the front of the southern lobe of Stonebreen - will have caused a significant decrease in basal pressure and thus basal drag. In Fig. 9 we observe that the instability started around 2011, when most of the ice thickness loss should already have happened. This suggests that reduction of ice thickness is not a result of the increase in flow and discharge to the ocean, but rather an independent process or causea cause or part of a combination of causes. However, even if a connection between the thickness losses and the increase in ice flow is not unlikely, we can in theory not rule out from the data we have collected that the thickness changes are independent from the change in flow.

5.3 Increased surface melt-water input

The strong seasonal component of the increase in surface speed (Fig. 9), with repeated maxima around September of each year since 2012, suggests a link between surface-melt and multi-annual ice-flow acceleration instead or in combination with the above potential effects from increase in slope or decrease in ice thickness. The variation in speed in Fig. 9 has considerable similarity with the step-wise acceleration of Basin-3 on Austfonna (Dunse et al. 2012; Dunse et al., 2015), where surface speeds fell back only to a higher speed level after summer speed maxima. Dunse et al. (2015) identified an annual hydro-thermodynamic feedback that successively mobilizes stagnant ice regions, initially frozen to their bed, thereby facilitating fast basal motion over an expanding area. Also for Stonebreen the annual increase in speed starts in July with strong increase in production of surface melt water in the region, which is well visible from a strong reduction of the backscattering intensity on Sentinel-1 Extended Wide Swath (EWS) images (Fig. 10). The time-series of the SAR backscattering coefficient in Fig. 10 was computed using Sentinel-1 EWS images from various orbital configurations to increase the temporal sampling. Ground Range Detected (GRD) data were considered applying a radiometric calibration but not a correction for the different incidence angles. The capability of mapping wet snow and ice conditions by means of SAR data is well proven (e.g. Strozzi et al., 1999) and is due to vanishing background contribution because of increasing absorption and reflection of the incident radiation by liquid water. The speed maxima seem to be reached a bit later (around one month) on Stonebreen than on Basin-3, though the remote sensing measurements on Stonebreen are less resolved than the automatic GPS and 11-day repeat data from TerraSAR-X available for Basin-3. In addition, in contrast to Basin-3 winter velocities over Stonebreen are low, in particular in 2016.

5.4 Increased frontal ablation

Besides the impact of surface melt-water reaching the glacier bed, a second process inducing seasonal variations could be seasonal changes in frontal ablation. For Kronebreen in western Spitsbergen the influx of warm ocean water was recently suggested to have triggered a decoupling of the calving front from its former pin point, associated increases in surface speed, and retreat until a new pin point is reached (Luckman et al. 2015; Schellenberger et al., 2015). No data are available to us about changes in ocean temperatures in front of Stonebreen or the recent influx of warm water. However, the fact that the front of the section of Stonebreen investigated here is currently advancing by several hundreds of meters every year rather than retreating does not support the hypothesis that the increase in speed is due to adjustment of the glacier to a new pin point further inland. Though, the influx of warm ocean water could lead to seasonally increased frontal ablation and subsequent reduction of frontal backstress and rapid glacier acceleration (McMillan et al., 2014).

5.5 Frontal destabilisation of Stonebreen

In sum, we showed that the lower part of the southern lobe of Stonebreen has been subject to considerable losses in ice thickness. This could have made the tide-water calving glacier, which is grounded below sea level some 6 km inland from the 2014 front, more sensitive to either surface melt-water reaching its bed and/or warm ocean water increasing frontal ablation. Until 2014, such summer effects seem to have triggered a feedback mechanism where also winter speeds did not fall back to pre-instability speeds, for instance due to basal strain heating or destruction of the subglacial drainage network and related increased basal water pressure, so that summer speed maxima of a specific year can reach higher speed levels than in the previous year. However, in early 2015 and 2016 the winter speeds were decreasing again as now observed thanks to the frequent standard satellite coverages.

In contrast to the strong elevation losses between 1970 and 2014 in the lower part of Stonebreen (Fig. 3), the upper part of the glacier seems to have been quite stable in elevation over this period. This is in agreement with elevation changes found on Digerfonna on Edgeøya (Kääb, 2008). We have to leave open if these stable elevations at higher altitudes are a climatic signal from stable or even increased accumulation or from a dynamic imbalance of the glacier. However, the combination of strong elevation losses at the lower part (of up to almost 2 m/yr as 40-yr average (and up to ~20-30 m/yr between 2010-2012 and 2014) at the lower part with stable (,or perhaps even slightly increasing) elevations at higher sections, shows that the glacier was not in a dynamic equilibrium before getting unstable.-

Due to the lack of bathymetric data of sufficient quality, only a rough estimation of calving flux and sea-level contribution by the Stonebreen instability is possible. Assuming a water depth of about 25 m, an average front height above sea level of about 45 m (IDEM), a length of the calving front of around 6 km, an annual average speed of 1'200 m/yr, and pure sliding gives a flux of ~0.5 km^3/yr through a flux gate close to the 2014 calving front. This total sea level contributionvalue can be roughly partitioned into the advance of the calving front (on average ~ 350 m/yr for 2014-2015 corresponding to ~ 0.15 km^3/yr) and the actual frontal ablation (~ 0.35 km^3/yr or ~ 0.31 Gt/yr). Again, these numbers are rough initial estimates that directly depend on the little known water depth in front of Stonebreen. For instance as some kind of upper bound, an average water depth of 50 m instead of the 25 m assumed would give a total sea level contribution of ~ 0.68 km^3/yr, and an average water depth of 15 m as some kind of lower bound would give ~ 0.43 km^3/yr. All tThese numbers show that the investigated instability currently plays an important role in the overall mass balance of Edgeøyjøkullen which was analysed by Nuth et al. (2010). uUsing the 1970 NPI DEM and ICESat altimetry data over 2003-2007 period,, Nuth et al. (2010) found a mean elevation loss of 0.79 ± 0.15 m/yr (0.58 ± 0.11 m/yr water equivalent) for the entire Edgeøyjøkulen, which Stonebreen is part of. This corresponds to an average mass loss of about 0.8 Gt/yr.

6 Conclusions

Though the process currently observed for Stonebreen does not seem a classical surge where a mass surplus in the accumulation area leads to increased speeds and travels down the glacier, the investigated instability could well have a similar effect when the section of increased speed extends upwards the glacier and is able to drain accumulated ice from the upper parts of the ice cap. Independent of its future development, however, the underlying cause of the (surge-type?) instability seems to be an adjustment of the glacier front, which is grounded below sea level over some 6 km, to significant thickness losses during the recent decades. Influx of surface melt-water to the glacier base or of warm ocean water to the front could have triggered the instability and seasonally modulated its variation in surface speed over time. As similar decadal losses in ice thickness of slow-flowing calving fronts are also found elsewhere on Svalbard (e.g. over the northern lobe of Stonebreen or on the southwestern coast of Austfonna), processes like the one investigated here could happen also at these other locations or seem already to have started for the southeastern tip of Austfonna (sometimes called Basin-2) as seen in unpublished velocity maps based on Sentinel-1 data. The shape of the velocity field of Basin-2 resembles the one of the Stonebreen instability, but like on Basin-3 the speeds seem not to fall back on a winter level as low as for Stonebreen. However, a longer time-series might be needed for Basin-2 to draw more detailed conclusions. Also other glaciers in different regions, such as Pío XI in Patagonia (Mouginot and Rignot, 2015), presents similar features as Stonebreen, such as shallow bed below sea level at the terminus, large thickness changes, strong seasonal and annual variations, and large melt water production. Over the Canadian Arctic Van Wychen et al. (2016) introduced the concept of pulse-type glaciers. Over this kind of glaciers the velocity variability initiates in and propagates upglacier from the lowermost sections of the glacier near the terminus and is largely restricted to regions where the bed lies below sea level. Even if also for Stonebreen the instability initiated near the terminus, the velocity variability is now migrating upglacier more than the 6km inland from the 2014 front where the glaciers is believed to be grounded..

Through frequent monitoring based on repeat optical and SAR satellite data (e.g. Sentinel-1, Sentinel-2, Landsat 8, Radarsat-2 and ALOS PALSAR-2) the future evolution of these glaciers on Svalbard and elsewhere can be now recorded at high temporal sampling. . A comprehensive temporal record of surface ice velocities is beneficial to glaciological studies, allowing more in deep understanding of glacier flow mechanisms. With the recent launch of the Sentinel-1b satellite, regular SAR acquisitions are now available for many Arctic glaciers every 6 days. Radarsat-2 and ALOS PALSAR-2 can complement the Sentinel-1 data with SAR images at higher spatial resolution and lower wavelength, respectively, which might be more favourable in many cases. Also satellite optical images are currently available with a high temporal frequency (Landsat-8 data every 16 days and Sentinel-2 every 10 days), complementing radar data in the case of summer, cloud-free conditions. Future radar sensors, such as the planned Radarsat Constellation Mission, will even increase the temporal coverage up to 4 days.

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Ice surface velocity data from ALOS PALSAR and Sentinel-1 images are available at the databases of the Glacier_CCI (https://glaciers-cci.enveo.at/crdp2/index.html) and FP7 SEN3APP (http://sen3app.fmi.fi) projects.

Competing interests

A.K. is a member of the editorial board of the journal.

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Table 1. Sensors (MSS: Multispectral Scanner System, TM: Thematic Mapper, ETM+: Enhanced Thematic Mapper Plus, OLI: Operational Land Imager) and acquisition dates of the Landsat imagery used for the mapping of the glacier outlines.

Sensor	Date
Landsat 2 MSS	16/07/1976
Landsat 5 TM	26/08/1994
Landsat 7 ETM+	28/07/2011
Landsat 8 OLI	02/09/2013
Landsat 8 OLI	07/07/2014
Landsat 8 OLI	06/07/2015

Table 2. Sensors, acquisition dates and time intervals of the satellite image pairs considered for ice surface velocity estimation.

Satellite Sensor	Acquisition Date 1	Acquisition Date 2	Time Interval
ERS-1 SAR	02/01/1994	05/01/1994	3 days
ERS-2 SAR	22/03/2011	25/03/2011	3 days
ALOS PALSAR Fine Beam Single	14/11/2010	14/02/2011	92 days
	04/01/2011	19/02/2011	46 days
Radarsat-2 Wide	09/02/2009	05/03/2009	24 days
	05/03/2009	29/03/2009	24 days
	29/03/2009	22/04/2009	24 days
	04/06/2010	28/06/2010	24 days
	06/05/2011	23/06/2011	48 days
	23/06/2011	17/07/2011	24 days
	17/07/2011	10/08/2011	24 days
	10/08/2011	03/09/2011	24 days
	03/09/2011	27/09/2011	24 days
	27/09/2011	21/10/2011	24 days
	21/10/2011	08/12/2011	48 days
	13/03/2012	06/04/2012	24 days
	06/04/2012	30/04/2012	24 days
	30/04/2012	24/05/2012	24 days
	24/05/2012	17/06/2012	24 days
	17/06/2012	04/08/2012	48 days
	04/08/2012	28/08/2012	24 days
	28/08/2012	21/09/2012	24 days
	21/09/2012	15/10/2012	24 days
	15/10/2012	08/11/2012	24 days
	08/11/2012	02/12/2012	24 days
	12/02/2013	08/03/2013	24 days
	08/03/2013	25/04/2013	48 days
	25/04/2013	19/05/2013	24 days
	12/06/2013	30/07/2013	24 days
	30/07/2013	23/08/2013	24 days
	23/08/2013	16/09/2013	24 days
	16/09/2013	10/10/2013	24 days
	10/10/2013	03/11/2013	24 days
	27/11/2013	21/12/2013	24 days
	21/12/2013	07/02/2014	48 days
Landsat 8	1~~5~~4/07/2014	06~~7~~/08/2014	23 days
	0~~7~~6/08/2014	24~~5~~/08/2014	18 days
	24~~5~~/08/2014	31~~01~~/08~~9~~/2014	7 days
	06~~7~~/07/2015	02~~3~~/08/2015	27 days
	02~~3~~/08/2015	18~~9~~/08/2015	16 days
	18~~9~~/08/2015	17~~8~~/09/2015	30 days
	26/06/2016	28/07/2016	32 days
Radarsat-2 Wide Ultra Fine	04/02/2016	28/02/2016	24 days
	28/02/2016	23/03/2016	24 days
Sentinel-1 Interferometric Wide Swath	21/01/2015	02/02/2015	12 days
	02/02/2015	14/02/2015	12 days
	13/08/2015	25/08/2015	12 days
	25/08/2015	06/09/2015	12 days

	06/09/2015	18/09/2015	12 days
	18/09/2015	30/09/2015	12 days
	30/09/2015	12/10/2015	12 days
	12/10/2015	24/10/2015	12 days
	24/10/2015	05/11/2015	12 days
	05/11/2015	17/11/2015	12 days
	17/11/2015	29/11/2015	12 days
	23/12/2015	04/01/2016	12 days
	28/01/2016	09/02/2016	12 days
	09/02/2016	21/02/2016	12 days
	21/02/2016	04/03/2016	12 days
	04/03/2016	16/03/2016	12 days
	16/03/2016	28/03/2016	12 days
	28/03/2016	09/04/2016	12 days
	09/04/2016	21/04/2016	12 days
	21/04/2016	03/05/2016	12 days
	03/05/2016	15/05/2016	12 days
	15/05/2016	27/05/2016	12 days
	27/05/2016	08/06/2016	12 days
	08/06/2016	02/07/2016	24 days
	02/07/2016	14/07/2016	12 days
	14/07/2016	26/07/2016	12 days
	26/07/2016	07/08/2016	12 days
	07/08/2016	19/08/2016	12 days
	19/08/2016	31/08/2016	12 days

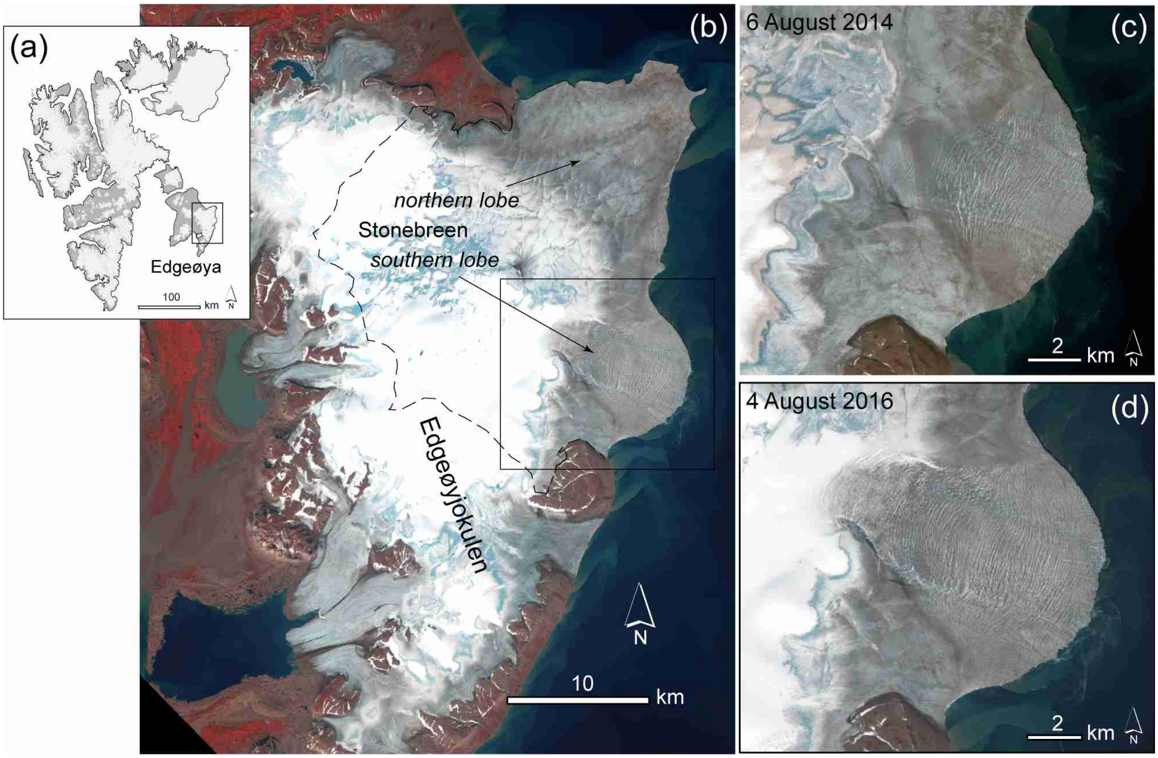


Figure 1. Location of Edgeøya on Svalbard (a) and of Stonebreen on Edgeøya on a Landsat 8 image 04/08/2016 (b). (c) and (d) show the front of the southern lobe Stonebreen on two Landsat images of 06/08/2014 and 04/08/2016.

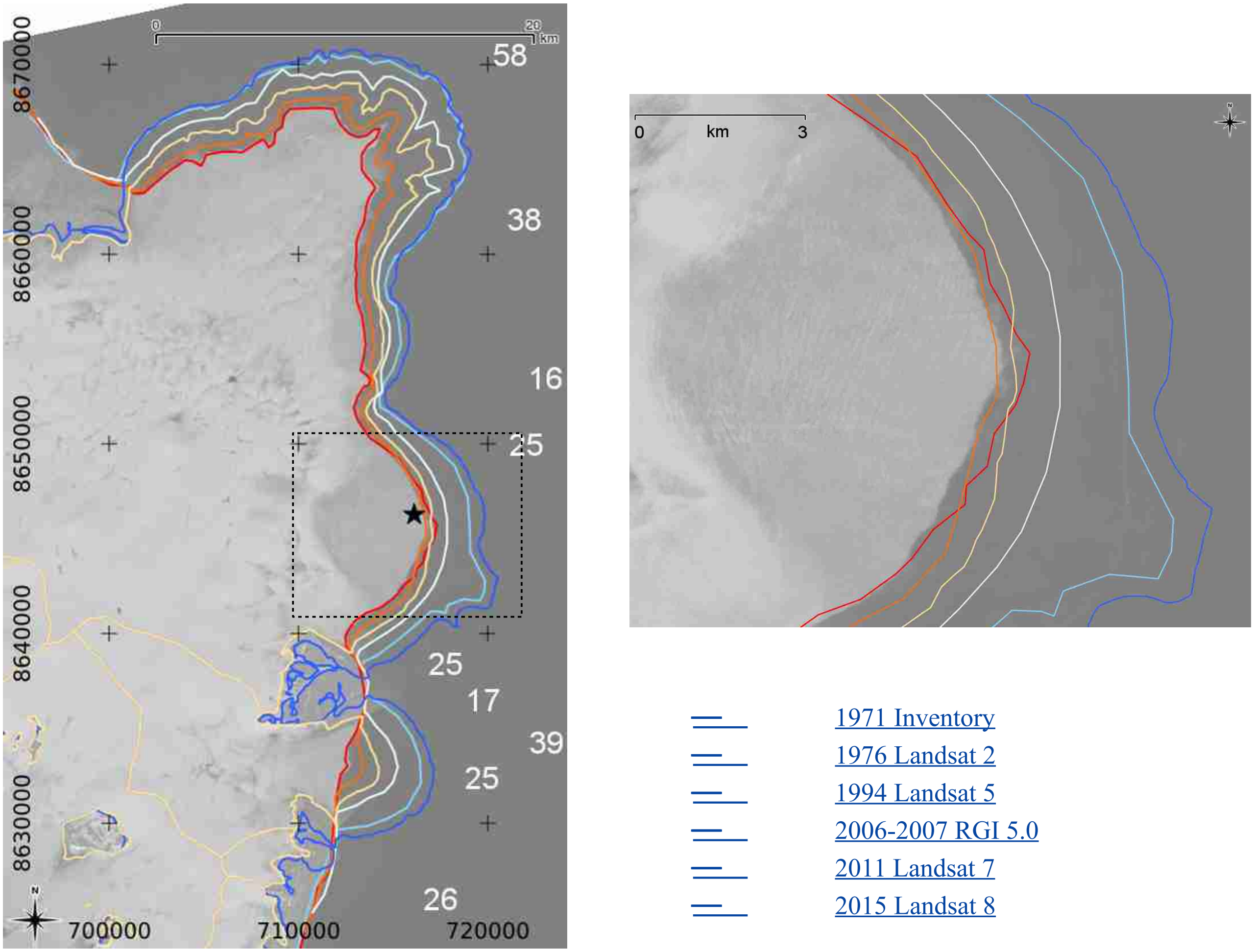


Figure 2. Coastal outlines from vertical aerial photographs in 1971 (Nuth et al., 2013), Landsat imagery from 1976 to 2015 (this study), and the Randolph Glacier Inventory Version 5.0 (RGI, 2015) in 2006-2007 on a Landsat image of 14/07/2014. Easting and northing coordinates in meters are in the WGS 1984 UTM zone 33N. The star indicates the position of the profile on Stonebreen of Fig. 9. The light ~~blue~~grey numbers indicate water depths from the Norwegian See Navigation Chart (2016). The inset shows a close up to the front of the southern lobe Stonebreen.

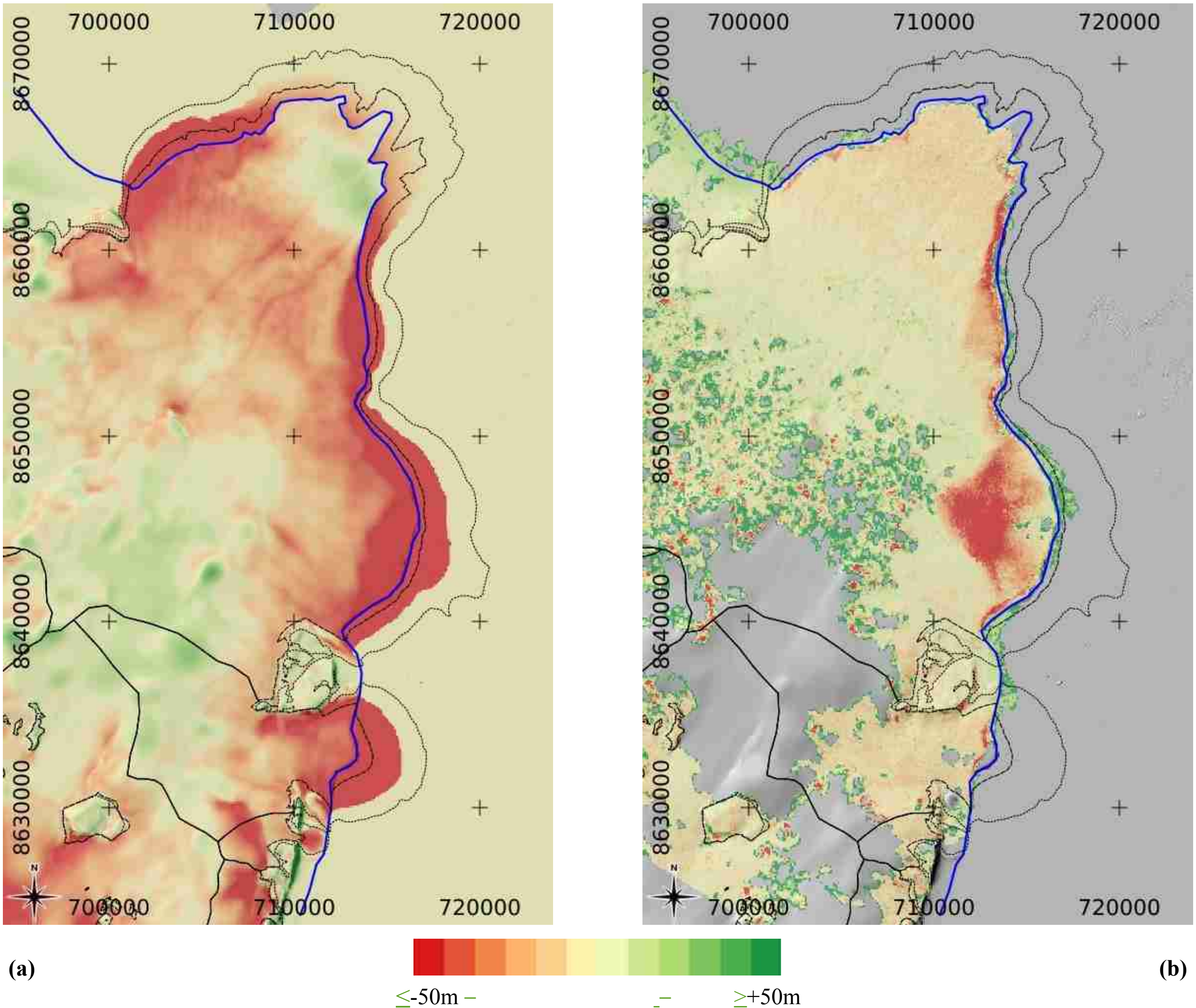


Figure 3. Glacier elevation change between (a) IDEM and NPI DEM (time lapse 2010/2012 - ~~1990~~1970) and (b) ASTER DEM and IDEM (time laps 2014 - 2010/2012). Image background is a shaded relief of IDEM. The coastal line from the Landsat imagery of 2011 (blue line) is shown along with glaciers inventories of 1971 (dotted line) and 2006-2007 (dashed line).

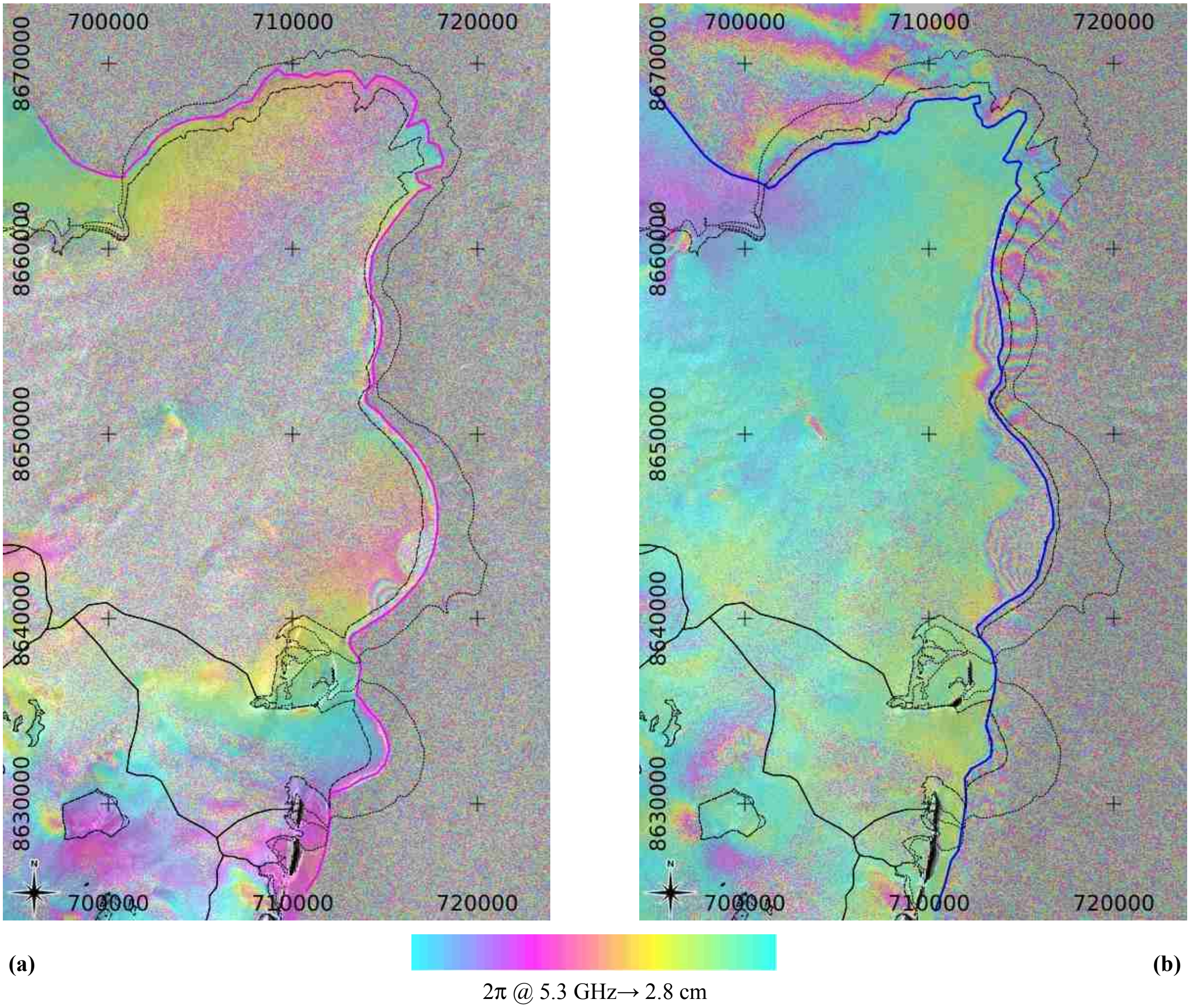
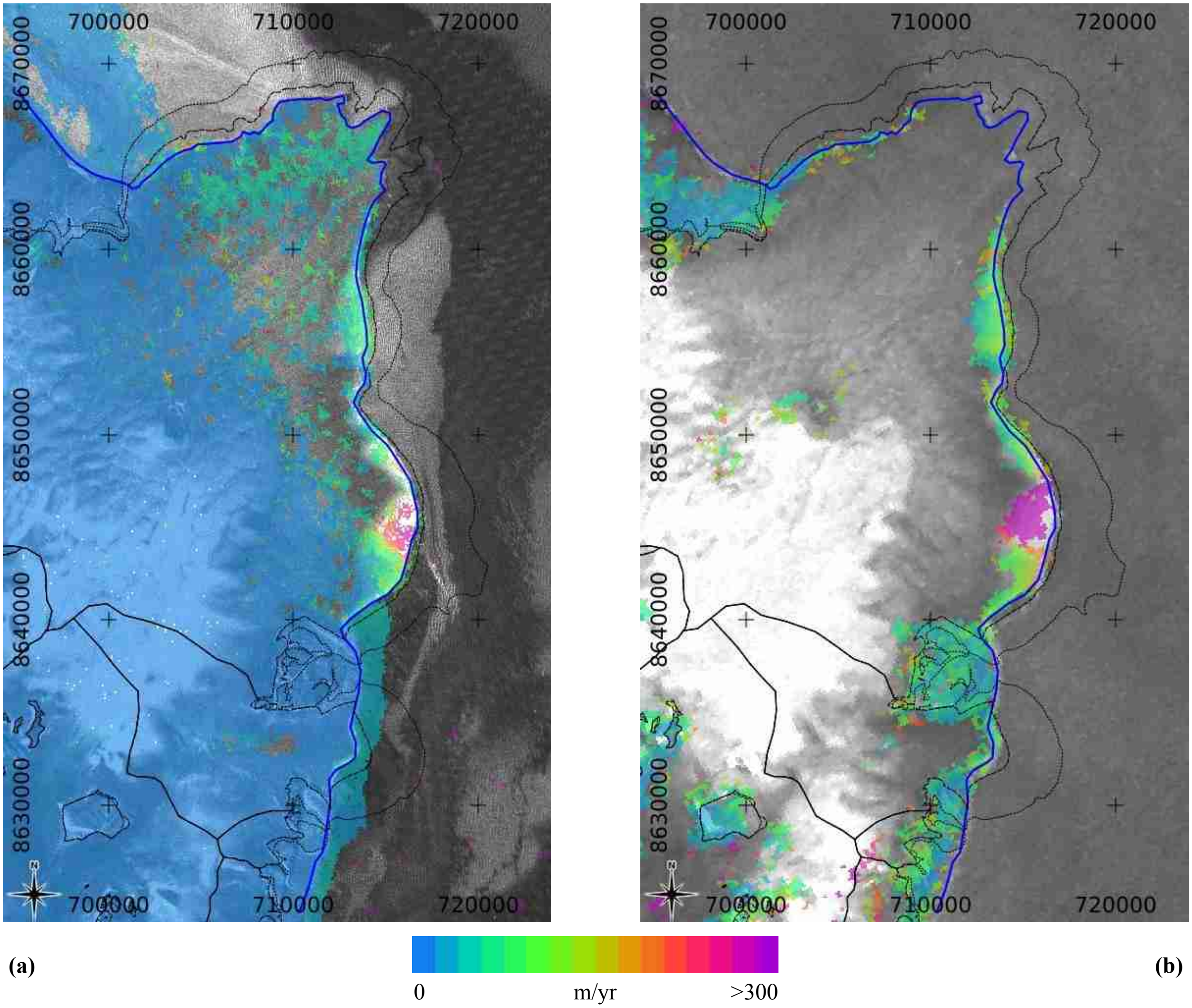


Figure 4. Differential SAR interferomgrams from (a) ERS-1 data of 02/01/1994 and 05/02/1994 and (b) ERS-2 data of 22/03/2011 and 25/03/2011. Image background is a backscattering intensity image of the master scene used for interferometry. The coastal line on the year of the SAR images is shown along with glaciers inventories of 1971 (dotted line) and 2006-2007 (RGI 5.0, dashed line).



(a) (b)

Figure 5. Ice surface velocity maps from (a) ALOS PALSAR data of the winter 2010/2011 and (b) Radarsat-2 Wide data of 21/10/2011 and 08/12/2011. Image background is a backscattering intensity image of the master scene used for offset-tracking. The coastal line in the summer of 2011 (continuous blue line) is shown along with glaciers inventories of 1971 (dotted line) and 2006-2007 (RGI 5.0, dashed line).

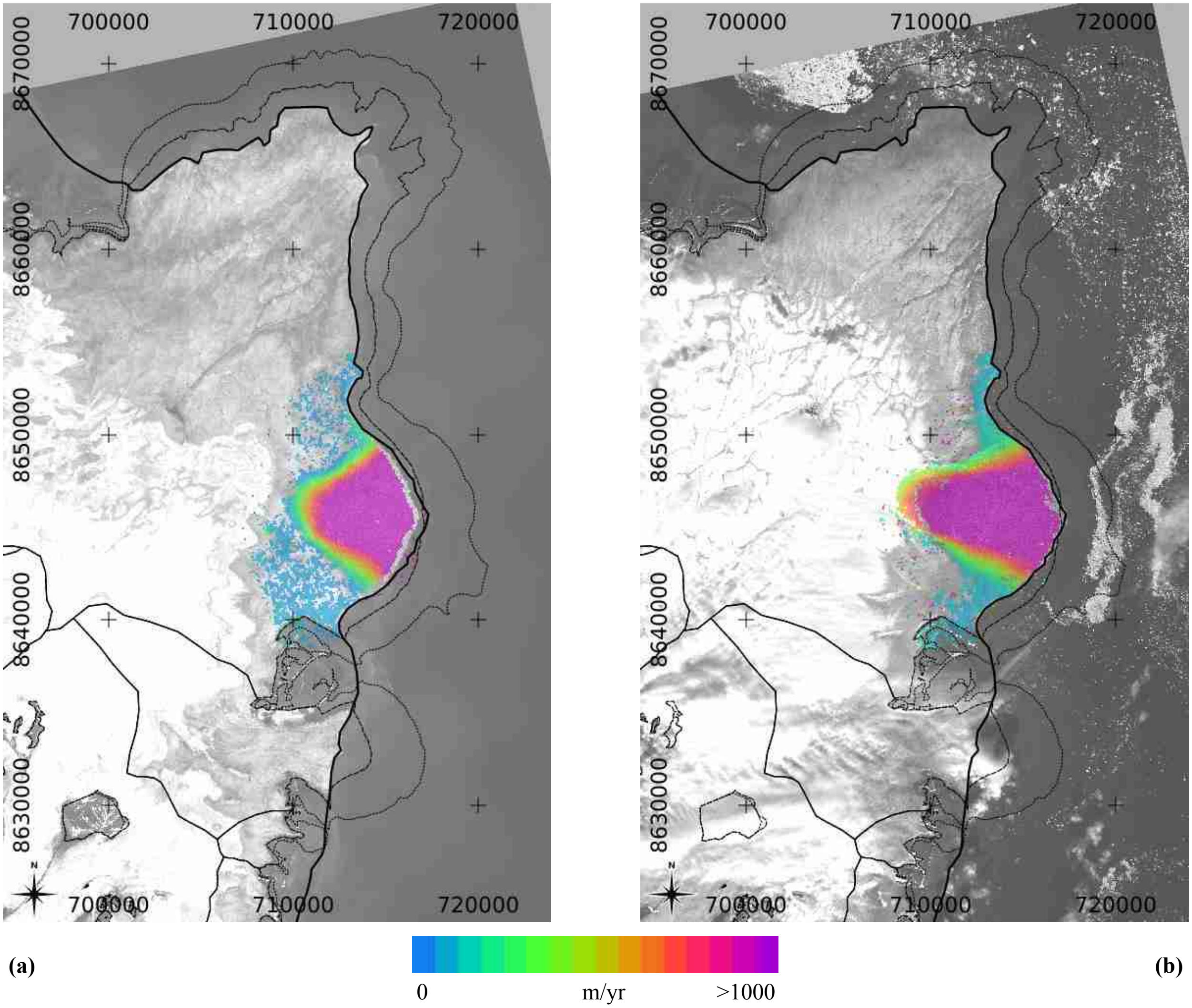


Figure 6. Ice surface velocity maps from Landsat 8 data of (a) 07/08/2014 and 25/08/2014 and (b) 19/08/2015 and 18/09/2015. Image background is from the respective first scene. The coastal line in 2015 (continuous line) is shown along with glaciers inventories of 1971 (dotted line) and 2006-2007 (RGI 5.0, dashed line).

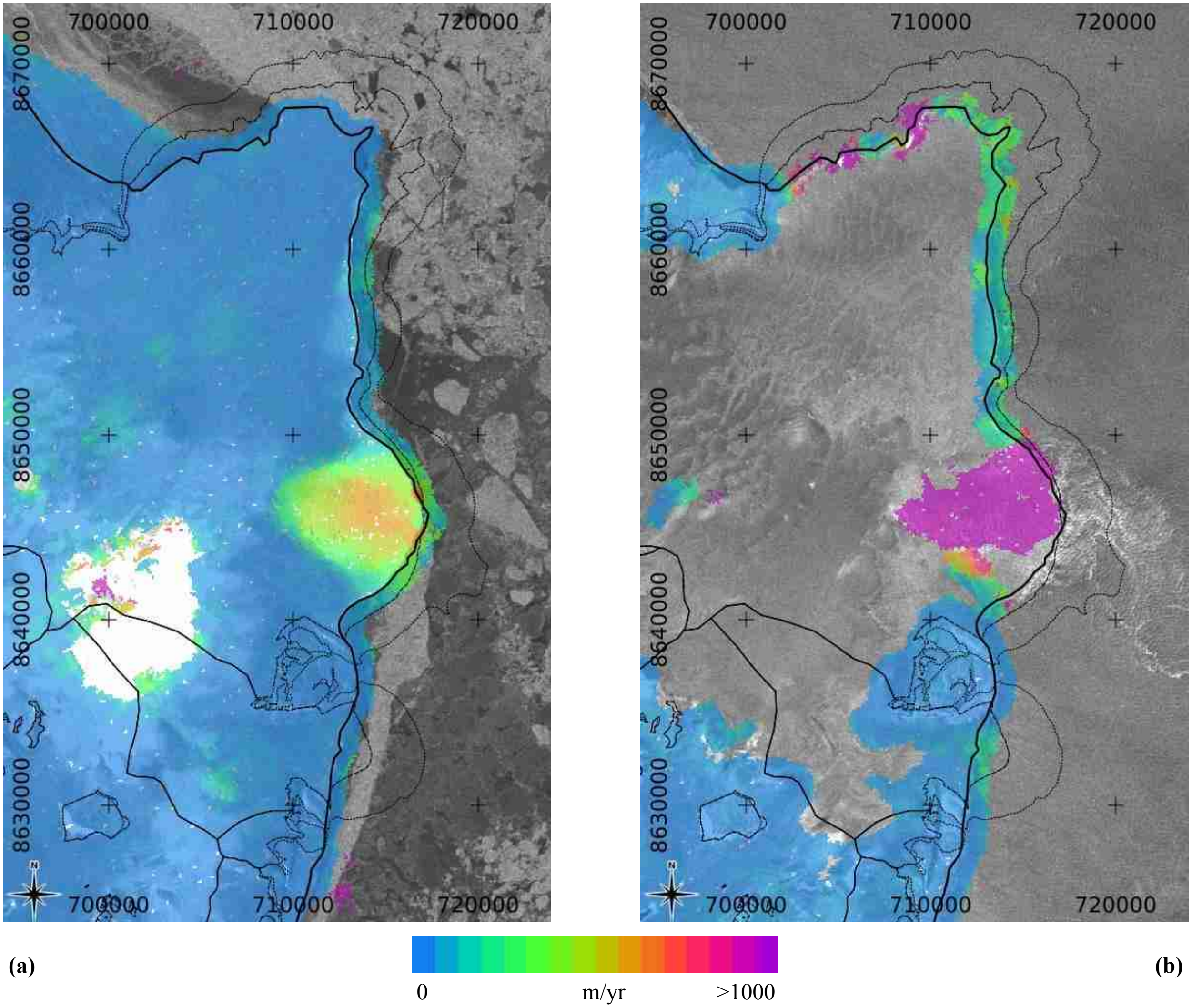


Figure 7. Ice surface velocity maps from (a) Sentinel-1 data of 21/01/2015 and 02/02/2015 and (b) Sentinel-1 data of 30/09/2015 and 12/10/2015. Image background is a backscattering intensity image of the respective first scene used for offset-tracking. The coastal line in 2015 (continuous line) is shown along with glaciers inventories of 1971 (dotted line) and 2006-2007 (RGI 5.0, dashed line).

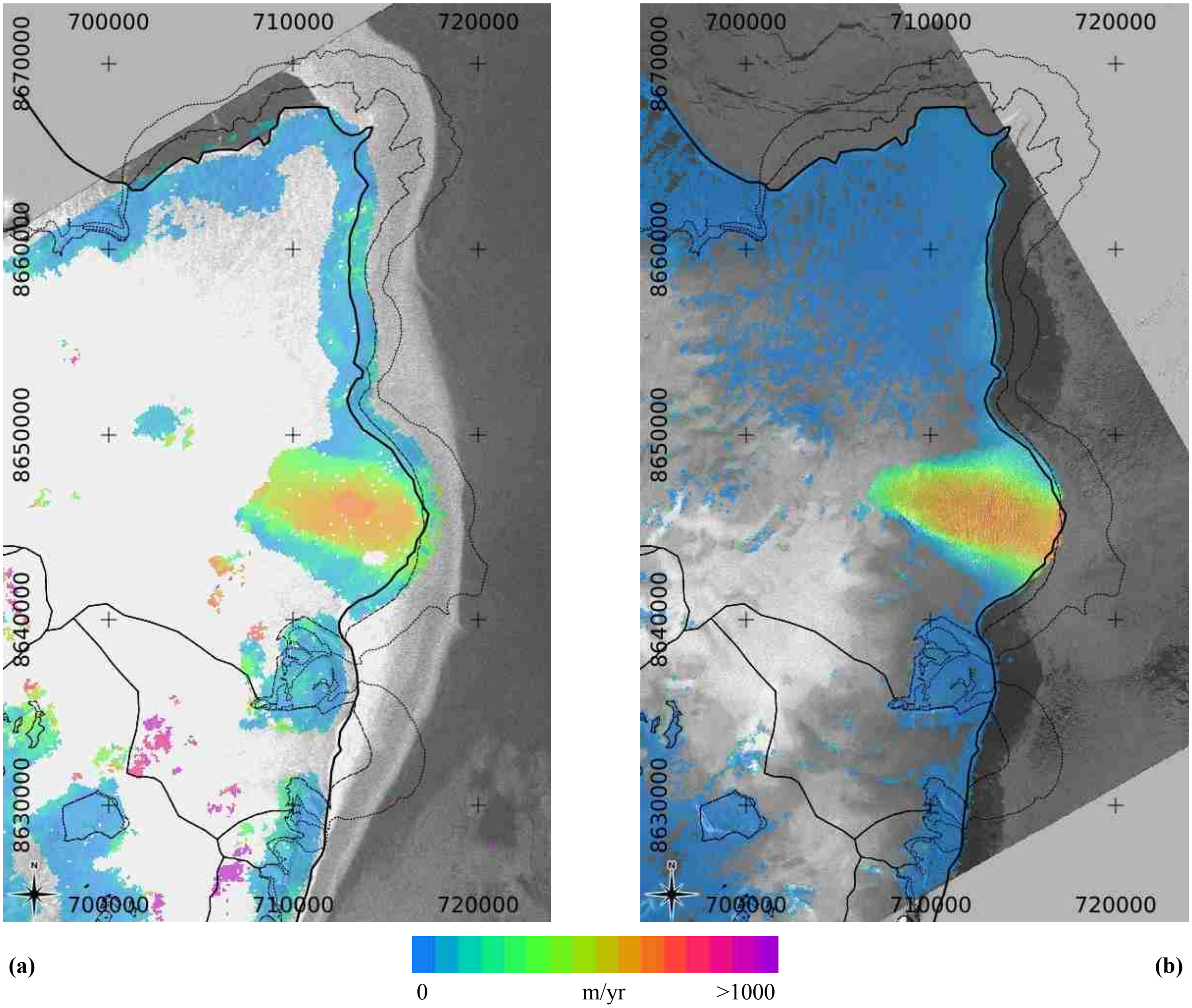


Figure 8. Ice surface velocity maps from (a) Sentinel-1 data of 04/03/2016 and 16/03/2016 and (b) Radarsat-2 UWS data of 28/02/2016 and 23/03/2016. Image background is a backscattering intensity image of the master scene used for offset-tracking. The coastal line in 2015 (continuous line) is shown along with glaciers inventories of 1971 (dotted line) and 2006-2007 (RGI 5.0, dashed line).

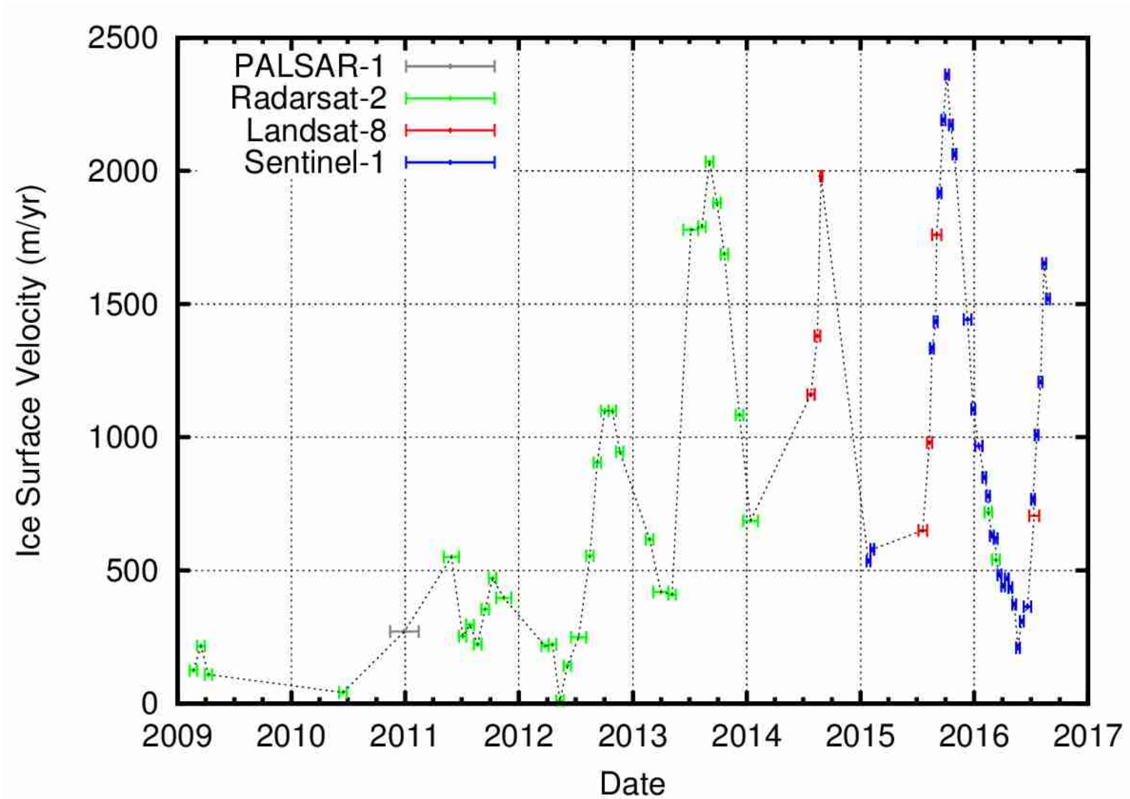


Figure 9. Time-series of ice surface velocities close to the front of the southern lobe of Stonebreen (716080 E / 8646230 N). For position see Fig. 2.

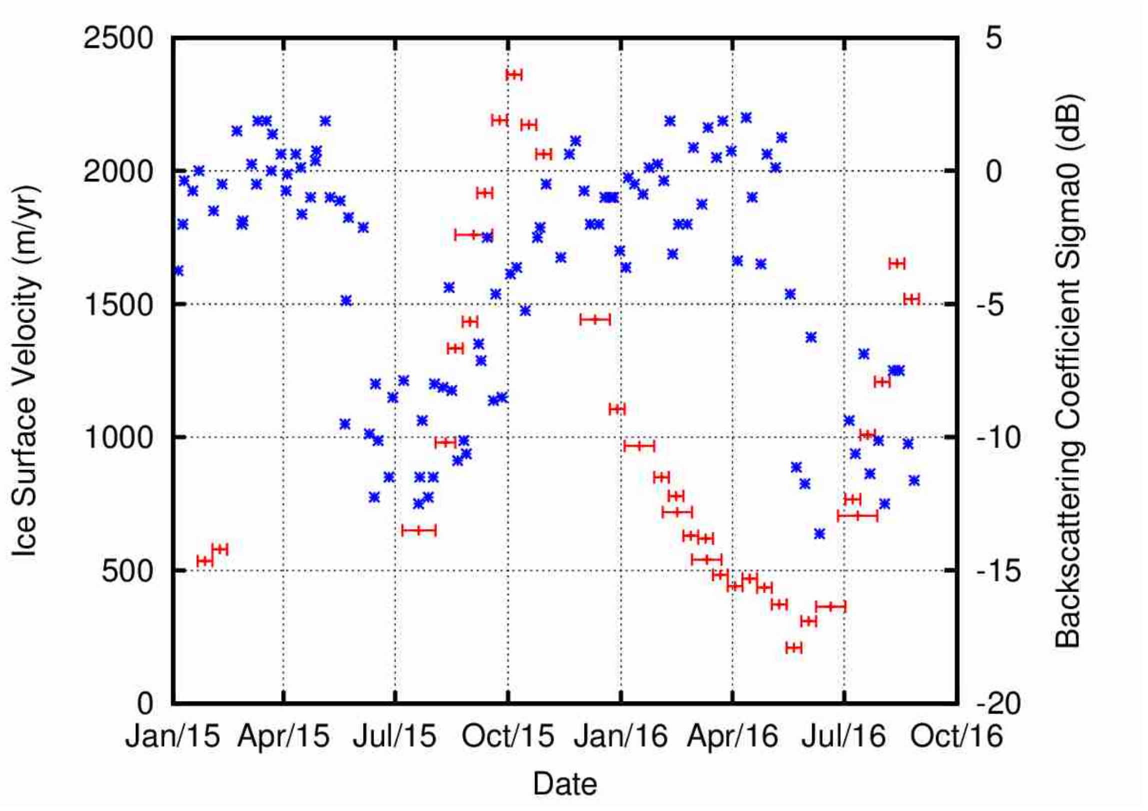


Figure 10. Time-series of backscattering coefficient σº from Sentinel-1 EWS data (blue stars) along with the time-series of ice surface velocities from Sentinel-1 IWS data (red crosses) close to the front of the southern lobe of Stonebreen (716080 E / 8646230 N). For position see Fig. 2.