SVALI

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Interim report of dynamic changes of land ice in the Arctic and North-Atlantic region

Stability and Variations of Arctic Land Ice

2014

What is SVALI

SVALI is a Nordic Centre of Excellence bringing together researchers from 17 Nordic institutes. It has been formed to study basic glaciological processes using remote sensing, airborne and in-situ measurements and carry out advanced Earth Systems Modelling with focus on land ice in the Arctic and North Atlantic area. The NCoE SVALI constitutes a platform for joint process studies, analyses, sharing of methods, researcher training, outreach activities and for reporting of scientific results regarding the impact of climate change on terrestrial ice.

SVALI is a part of the Top-level Research Initiative, which is a major Nordic collaborative venture for studies of climate, energy and the environment. The SVALI NCoE is together with NCoE's DEFROST and CRAICC within the TRI sub-programme "Interaction between Climate Change and the Cryosphere" (ICCC), which aims to improve our understanding of stability, variations and dynamics of the cryosphere.

Funding for SVALI

Funding for SVALI is provided by the Nordic Top Level Research Initiative which was initiated by the Nordic prime ministers in 2008 and is supported by Nordic institutions in particular those financing research and innovation. SVALI comprises participants from 17 Nordic institutions and is headed by the University of Oslo.

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Introduction

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This is the second Interim report of the current rates of changes of the land ice in the Arctic and North-Atlantic Region from the Nordic Centre of Excellence 'Stability and Variations of Arctic Land Ice' (SVALI). SVALI is one of three Nordic Centres of Excellence within the Nordic Top Research Initiative sub-programme 'Interaction between Climate Change and the Cryosphere'. The report is written by the partners in Theme 1 "Observing the present – baseline and changes".

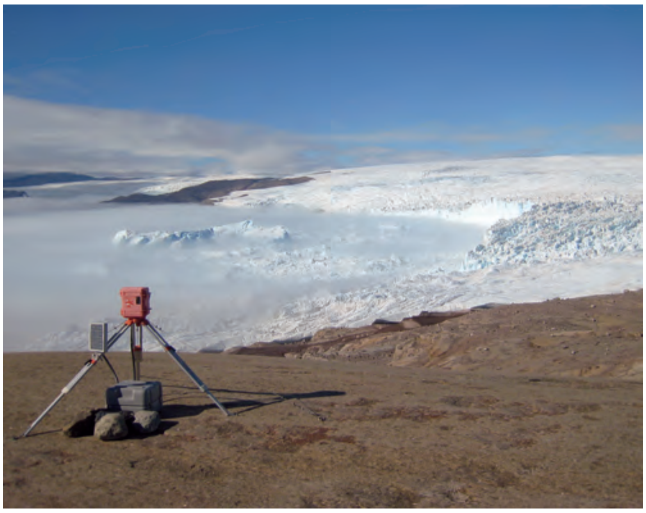
This second interim report addresses two key questions posed by SVALI:

- **Why is the ice-volume reduction more rapid than previously expected?**
- **Will the mass loss continue to accelerate?**

In doing so, we here focus on the part of those questions that has its roots in dynamic changes, that is, changes in the flow of the ice. Dynamic changes of land ice in the Arctic and North-Atlantic Region over the last decade has moved glaciological science to centre stage in the debate over the impact of global climate change, primarily due to the sudden synchronous acceleration of outlet glaciers that doubled the contribution to sea level rise from the Greenland Ice Sheet between 2000 and 2005 (Rignot and Kanagaratnam, 2006). This contribution continues to increase, rising from an average of 262±21 Gt/yr for 2007-2011 (Andersen et al., 2015) to 345±22 Gt/yr for the following period 2011-2014 (Helm et al., 2014). In Svalbard, comprehensive investigations on outlet glaciers provide valuable insight on the periodic surges that cause dramatic changes of glacier geometry, velocity and mass loss. Geothermal and volcanic activity is high in Iceland and a number of active volcanoes and geothermal areas are glacier covered. This causes frequent jökulhlaups – sudden meltwater floods originating from underneath the ice – which can have substantial effects on the glacier dynamics. In mainland Norway, Iceland and Greenland, the authorities operating hydro-electric power plants have an interest in understanding the changes occurring in order to prepare for the future, as catchment hydrology is often dominated by glacial meltwater.

This report provides a brief overview of the dynamic changes of the land ice the Arctic and North-Atlantic Region based on excerpts from recent scientific publications along with a view of current research and monitoring activities of SVALI members. Focus in this second interim report will be on velocity measurements from satellites and in situ instruments. Advances in the capability to derive velocity maps from both radar and optical satellite data has revolutionized our knowledge of large-scale glacier and ice sheet dynamics over the last two decades, whereas GPS and more recently, time lapse photogrammetry, has provided similar breakthroughs from the measurements carried out directly on the surface of the glaciers. SVALI members have played key roles in this development, employing and developing novel techniques, and currently engage in ambitious monitoring programmes and scientific projects aimed at increasing our understanding of ice-dynamics. Yet, understanding the governing physical processes and the response of land ice to climate change remains a challenge. The models used for predicting the future contribution of land ice to sea-level rise need further development to capture the complex interaction with the atmosphere and ocean. This model development is primarily driven by insights from observations and indeed it is the increasing abundance of available observations that has forced us to review our understanding of ice-dynamics.

Climate change is rapidly transforming the Arctic environment with an immediate impact on the rest of the world. If we wish to understand and predict how climate change will affect our societies in the future, we need to understand the physical processes at work – and those processes can only be captured through a sustained observational effort.



Greenland

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The Greenland Ice Sheet is contributing significantly to current global sea level rise and has been losing mass at an accelerating rate over the last decade (Shepherd et al., 2012; Andersen et al., 2015; Enderlin et al., 2014; Moon et al., 2012) with rates of loss recently reported as high as 345±22 Gt/yr (Helm et al., 2014). Between one third and half of this mass loss is due to iceberg discharge and melt at the ice-ocean interface of the outlet glaciers from the ice sheet while the remaining mass loss is due to surface melting (Enderlin et al., 2014; Shepherd et al., 2012). To predict the future contribution to sea level rise from the Greenland Ice Sheet, we need to understand the physical processes governing ice mass loss of the outlet glaciers and subsequently apply this knowledge to improve the ice sheet models.

In this report we outline activities by SVALI partners to characterize dynamic changes of the Greenland Ice Sheet. This includes pioneering continuous in situ GPS measurements of outlet glaciers (Ahlstrøm et al., 2013), quantification of the total ice sheet mass loss using satellite and airborne remote sensing (Andersen et al., 2015), ice sheet wide velocity mapping efforts from satellite synthetic aperture radar data by SVALI-associated monitoring and research activities and the utilization of a new velocity-mapping tool, ImGRAFT (Messerli and Grinsted, 2014), to derive recent velocities of major outlet glaciers from the Greenland ice sheet. The development of ImGRAFT was originally undertaken to evaluate velocities of Engabreen in Norway as reported elsewhere in this report and is thus a perfect example of Nordic added value.

The contributions thus utilize techniques which are to a large extent developed, shared and applied among Nordic research groups due to the SVALI network.

Seasonal velocities of outlet glaciers of the Greenland ice sheet using GPS instruments

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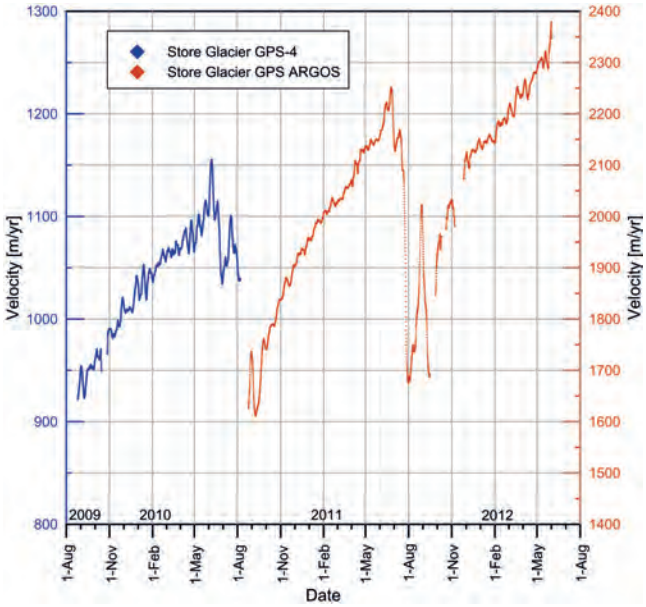

Figure 2. GPS velocities averaged over 7 days from Store Glacier (see Figure 1 for instrument position). Note the different scales for the two GPS velocity records.

The use of GPS has made it possible to measure the velocity of outlet glaciers directly by frequent transmission of instrument positions. Naturally, this kind of observation is prone to instrument loss as the fast-flowing outlet glaciers constitute an extremely hostile environment. Yet the Geological Survey of Denmark and Greenland has initiated and maintained a campaign since 2009 to track velocity variations of selected ice sheet outlet glaciers. The tracking continues as part of the Programme for Monitoring of the Greenland Ice Sheet (PROMICE), but results presented below are for the period 2009-2012 which was the initial deployment in the EU project ice2sea as reported in Ahlstrøm et al. (2013).

Here we present a total of 17 continuous velocity records from eight major marine-terminating outlet glaciers from the Greenland ice sheet derived from single-frequency stand-

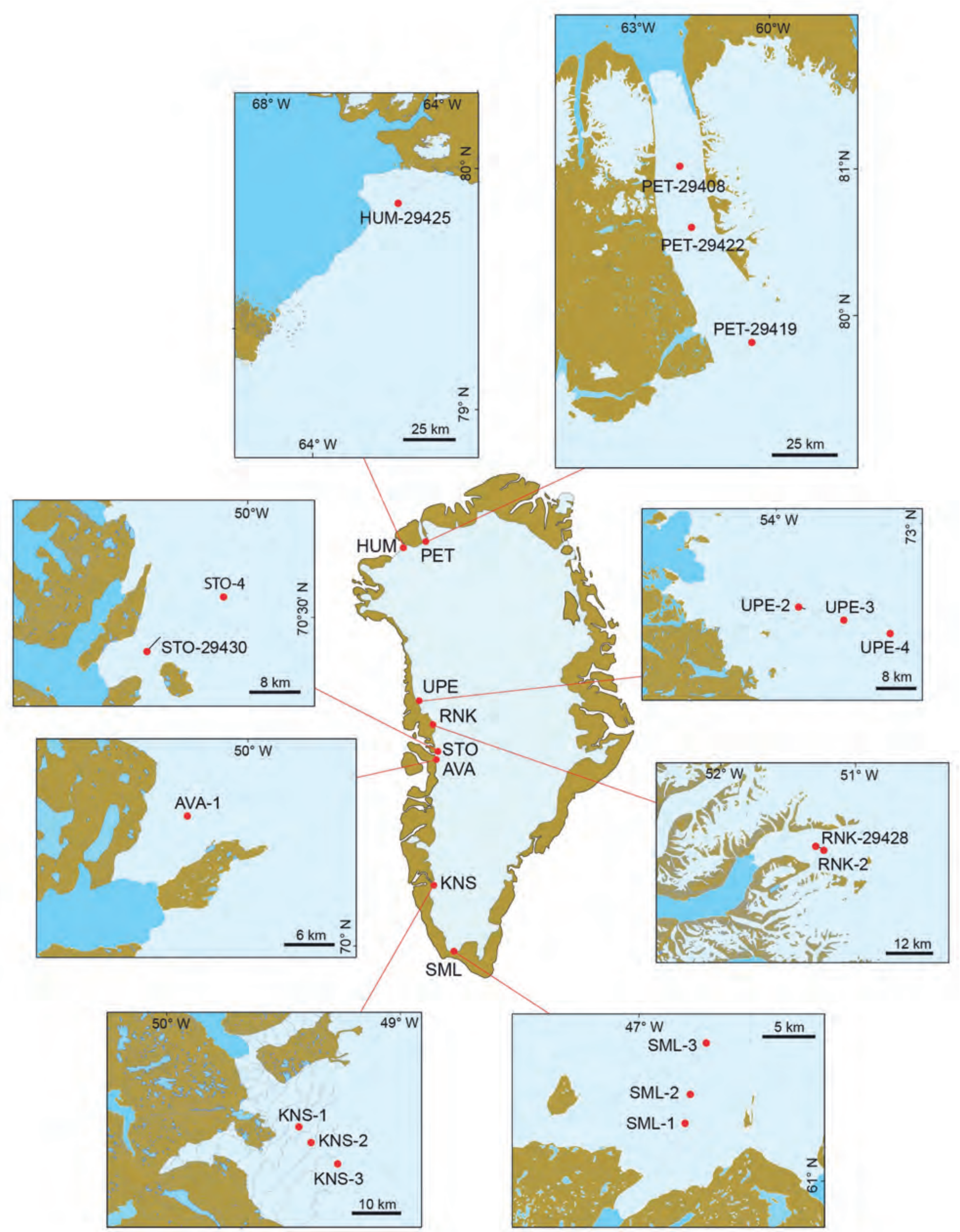

Figure 1. Map of instrument locations in Greenland, with inserts showing retrieval positions of GPS instruments on individual glaciers.

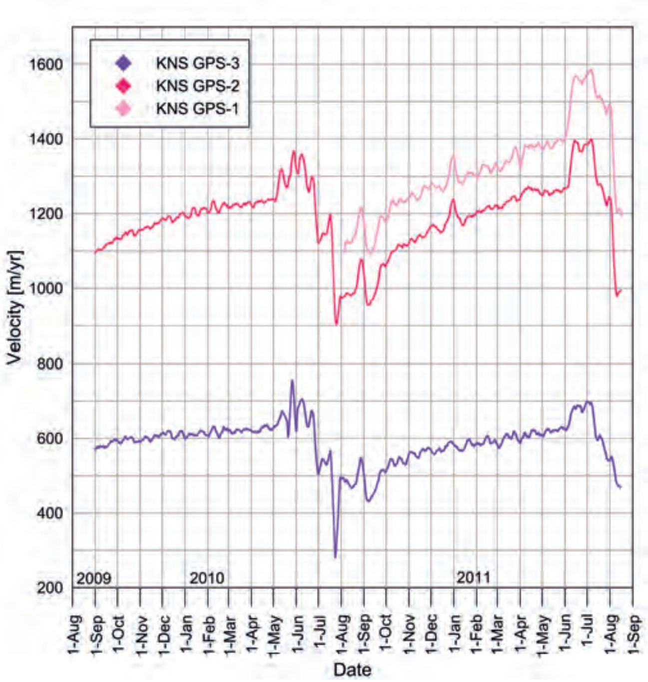

Figure 3. GPS velocities averaged over 7 days from Kangiata Nunata Sermia (see Figure 1 for instrument position). Note how the velocity gradually builds up from fall to early summer only to collapse again by late summer.

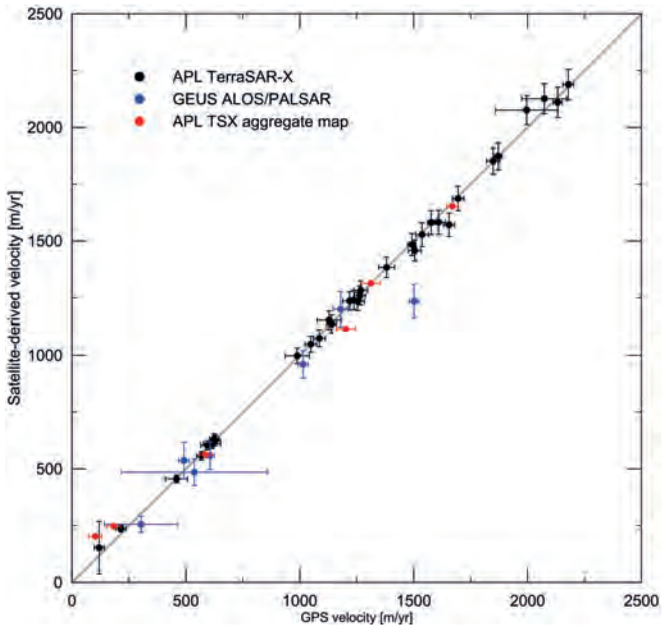

Figure 4. Comparison of satellite-derived velocities with GPS velocities. Horizontal error bars denote the standard deviation of the 7-day averaged GPS velocities in the period of the acquisition window. The vertical error bars denote the formal error from the processing added to a 3% maximum error due to slope-dependent effects.

alone Global Positioning System (GPS) receivers placed on the glacier surface, covering varying parts of the period summer 2009 to summer 2012. We present data from a range of different types of marine-terminating outlet glaciers along the entire western flank of the Greenland ice sheet from the southern tip to the northern coast (see Figure 1).

The continuous in situ GPS data presented here were acquired on a range of types of marine-terminating outlet glaciers in Greenland. Common to all the observed glacier velocity records is a pronounced seasonal variation, with an early melt season maximum. For some glaciers, this maximum is followed by a minimum in late summer, for others by a return to a background velocity. Generally, the onset of the acceleration comes later for northern glaciers. The GPS records spanning several years show that each individual glacier tends to reproduce its own pattern of seasonal velocity variation.

The GPS-derived velocities are compared to velocities derived from radar satellite imagery over six of the glaciers to illustrate the potential of the GPS data for validation purposes. Three different velocity map products are evaluated, based on ALOS/PALSAR data, TerraSAR-X/Tandem-X data and an aggregate winter TerraSAR-X data set (see Figure 4). The velocity maps derived from TerraSAR-X/Tandem-X data have a mean difference of 1.5% compared to the mean GPS velocity over the corresponding period, while velocity maps derived from ALOS/PALSAR data have a mean difference of 9.7%. The velocity maps derived from the aggregate winter TerraSAR-X data set have a mean difference of 9.5% to the corresponding GPS velocities. The data are available from the GEUS repository at http://dx.doi.org/10.5280/GEUS000001.

The GPS velocities compare well with velocity maps derived from different satellite data and by different processing chains, supporting the validity of the velocity mapping technique, even over fast-flowing outlet glaciers. The comparison improves with higher resolution and shorter time span of the satellite-derived velocities, suggesting that the in situ GPS data presented are indeed useful for ground-truthing the satellite products, despite being single-frequency stand-alone instruments.

The seasonal variability in the velocities documented in the GPS data also calls for caution when employing the satellite-derived velocity maps to infer discharge from the ice sheet, as the latter will only rarely capture the full range of variability. As previously discussed by Moon et al. (2012) the velocity of an outlet glacier cannot be considered as representing a larger region, as differences between neighboring glaciers can be large. It is therefore not straightforward to combine the temporal qualities of the GPS velocity records from a few glaciers with the regional spatial coverage of the satellite-derived velocity maps. Yet the GPS velocity records might be taken as an indication of how well a given velocity map represents the period for which it is used to calculate ice discharge.

To sum up, we have presented 17 separate records of velocity derived from GPS acquired on eight marine-terminating outlet glaciers from the Greenland ice sheet, over varying parts of 2009-2012. These records are useful as ground-truthing for ongoing velocity mapping efforts, but also for determining how well the velocity maps represent the periods outside the image acquisition windows. Finally, the GPS velocity records makes it possible to validate and calibrate current modeling efforts investigating the coupling between the ice sheet and the ocean/climate and thus serve to improve our understanding of the dynamic mass loss from the Greenland ice sheet.

Mass loss of the Greenland Ice Sheet from remote sensing

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Here, we present basin-scale estimates of Greenland ice sheet mass balance in the years 2007 and 2011. To assess the SMB and D components of mass balance in each basin, we draw on (i) airborne ice thickness measurements carried out by the PROMICE program (www.promice.dk), (ii) InSAR-derived ice surface velocity fields generated by the NASA MEaSUREs program, and (iii) SMB fields generated by the regional climate model MAR. Similar to Rignot and Kanagaratnam (2006) and Rignot et al. (2008), we estimate the solid ice flux across a flux perimeter extending around

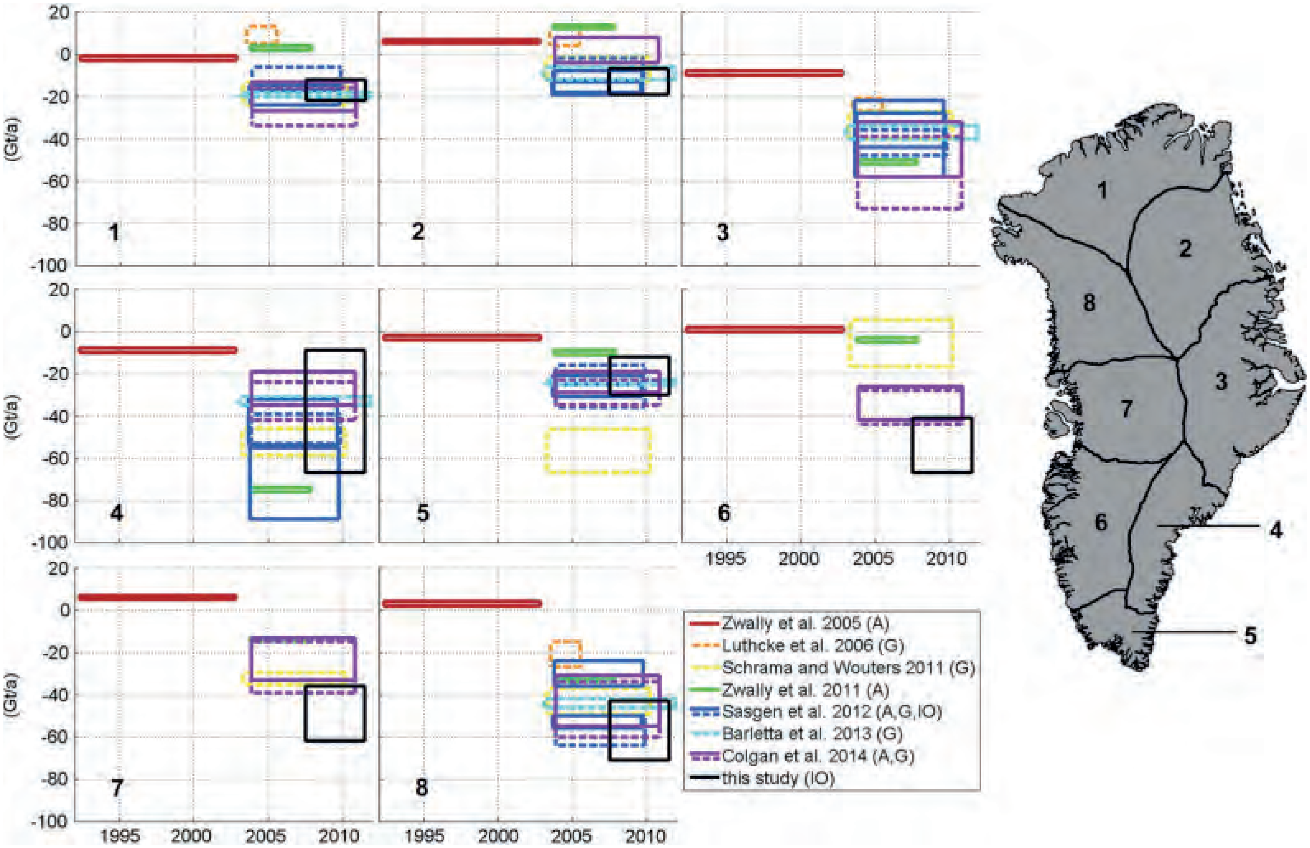

Figure 5. Mass balance estimates for Greenland's eight major drainage basins (inset) derived through altimetry (A), gravimetry (G) and input–output (IO) approaches (Zwally et al., 2005, Zwally et al., 2011, Luthcke et al., 2006, Schrama and Wouters, 2011, Sasgen et al., 2012, Barletta et al., 2013 and Colgan et al., 2014). The horizontal extent of each box denotes observation period, while the vertical extent denotes reported uncertainty. Solid lines denote estimates for the ice sheet proper, while dashed lines denote estimates that include peripheral glaciers.

the entire ice sheet. We correct this flux for downstream effects, between the flux gate and the grounding line, in order to derive the grounding line ice discharge. We then solve for mass balance by comparing this peripheral ice discharge to spatially integrated SMB. We compute both components of mass balance in eighteen major ice sheet drainage basins delineated by Zwally et al. (2012).

We estimate ice fluxes across a flux gate perimeter following the ~1700 m a.s.l. contour of the Greenland ice sheet for the years 2007 and 2011. We integrate a 1961–1990 reference period SMB field within the flux gate perimeter and estimate the interior mass balance to be 41±61 Gt/yr, i.e. zero within uncertainty. This result is concordant with previous studies (e.g. Thomas et al., 2000 and Krabill et al., 2000) that find that the interior of the Greenland ice sheet to be in neutral or slightly positive mass balance. Using reference period SMB values, and corrections for the dynamic volume change downstream of the flux gate, we infer the ice discharge at the grounding line, D. The total D value (mean 2007–2011 value of 515±57 Gt/yr) is consistent with values found in other studies. We then derive the mean 2007–2011 total mass balance for the whole ice sheet on basin level. Here we find that the ice sheet total (−262±21 Gt/yr) agrees well with other studies, but the reconciliation of the spatial distribution to other works is less obvious (see Figure 5).

Ice-sheet wide velocity mapping of the Greenland Ice Sheet

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Associated with the SVALI community two initiatives collaborate on the mapping of Greenland ice sheet velocities: The Programme for Monitoring of the Greenland Ice Sheet (PROMICE) (Ahlstrøm et al., 2008) and the ESA Climate Change Initiative project CCI Ice sheets (Hollmann et al. 2013). The aim is to provide ice sheet velocities at regular intervals in order to assess the changes in ice flow dynamics and quantify the impact of the changes on mass loss of the Greenland Ice Sheet.

Mapping of the entire ice sheet margin has presently been done for the winters 1995/96 and 2009/10 based on data from respectively ERS-2 and ALOS/PALSAR satellite data. Figure 6 shows selection of the ERS-2 1995/96 winter margin from NE Greenland. Time series of glaciers, presently the marine-terminating glaciers Jacobshavn Isbræ and Upernavik Isstrøm in West Greenland, have also been produced.

When comparing the velocity maps from 1995/96 and 2009/10 the overall picture is of increasing ice velocities and retreat of the outlet glaciers in accordance with other studies (Joughin et al., 2010; Moon et al., 2014). However, the dynamics of the Greenland ice sheet are complex and slowdown is also observed in a smaller number of cases. In Figure 7 the velocity changes of Academy Glacier and Hagen Glacier NE Greenland between the winters 1995/996 and 2009/2010 can

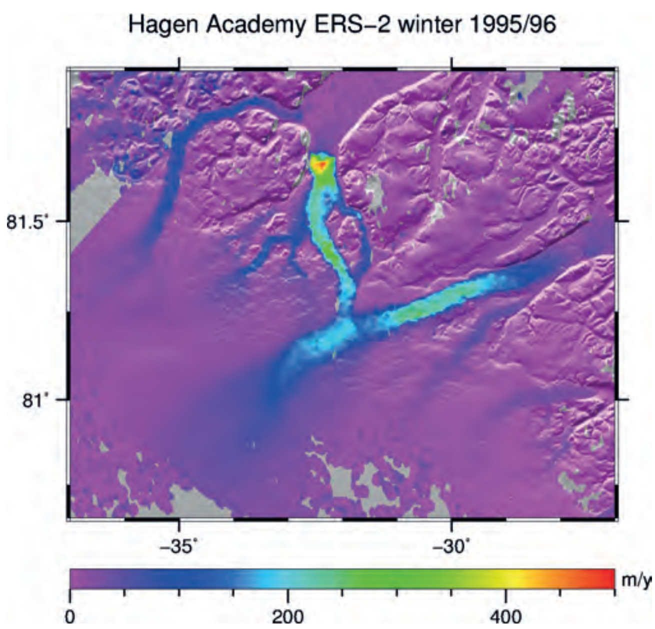

Figure 6. Ice velocities of Academy and Hagen Glacier NE Greenland from ERS-2 winter 1995/96.

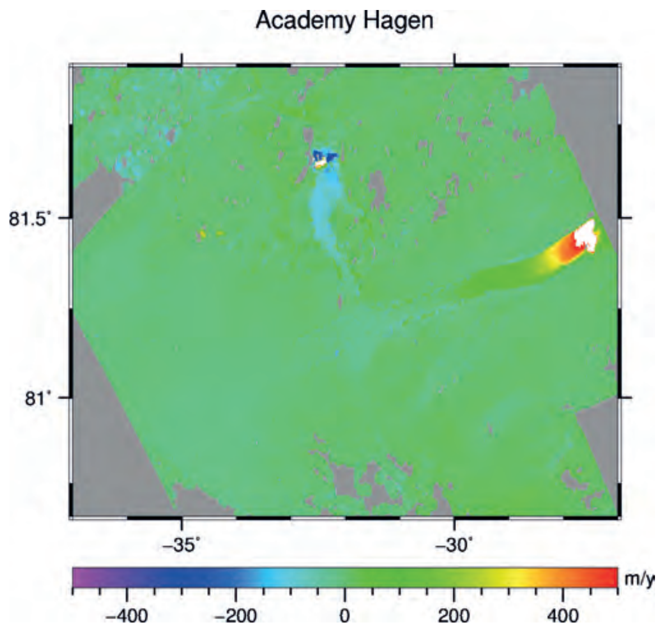

Figure 7. Ice velocity change of Academy and Hagen glacier NE Greenland between the winters 1995/96 and 2009/10 derived from ERS-2 and ALOS PALSAR data.

be seen, showing a speed up of Hagen Glacier and a slowdown of Academy Glacier.

Combining the ice velocity maps with ice thickness observations across a flux perimeter around the ice sheet, while correcting for changes in surface mass balance between the perimeter and the ice sheet margin, allows quantification of the dynamic mass loss from glacier discharge (Rignot and Kanagaratnam, 2006). Recent results reveal a 2007-2011 mean dynamic mass loss of 514± 55 Gt/yr leading to a 2007-2011 mean total mass balance of −261 ± 32 Gt/yr for the Greenland ice sheet (Andersen et al., 2015).

Greenland ice sheet outlet glacier velocity and flux in 2014 from optical remote sensing

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Here we provide up to date 2014 velocity and flux estimates for five major Greenland marine-terminating outlet glaciers as reported in Messerli et al. (2014). At the same time, we test ImGRAFT (Messerli and Grinsted, 2014) comprehensively on satellite data to assess the effectiveness of the toolbox to produce velocity fields using satellite imagery.

The results match well with existing radar velocity fields that cover large areas of the Greenland Ice sheet and provide the first major results using ImGRAFT. We use the latest Landsat 8 Band-8 Panchromatic band, with a 15 m pixel resolution as the images to feature track and produce the velocity fields. Additionally we used ice thickness data from CReSIS (https://data.cresis.ku.edu/data/grids/) to estimate the ice flux (Table 1) through defined flux gates visible in Figure 8.

We use the Landsat scenes in combination with the newly developed ImGRAFT feature tracking toolbox to track features between image pairs. We use data from the August 2013 to September 2014. The temporal resolution of the data sets depends on the data availability, which is mostly limited by the presence of cloud in the scene and amount of daylight. The velocity fields are stacked and averaged, where there are

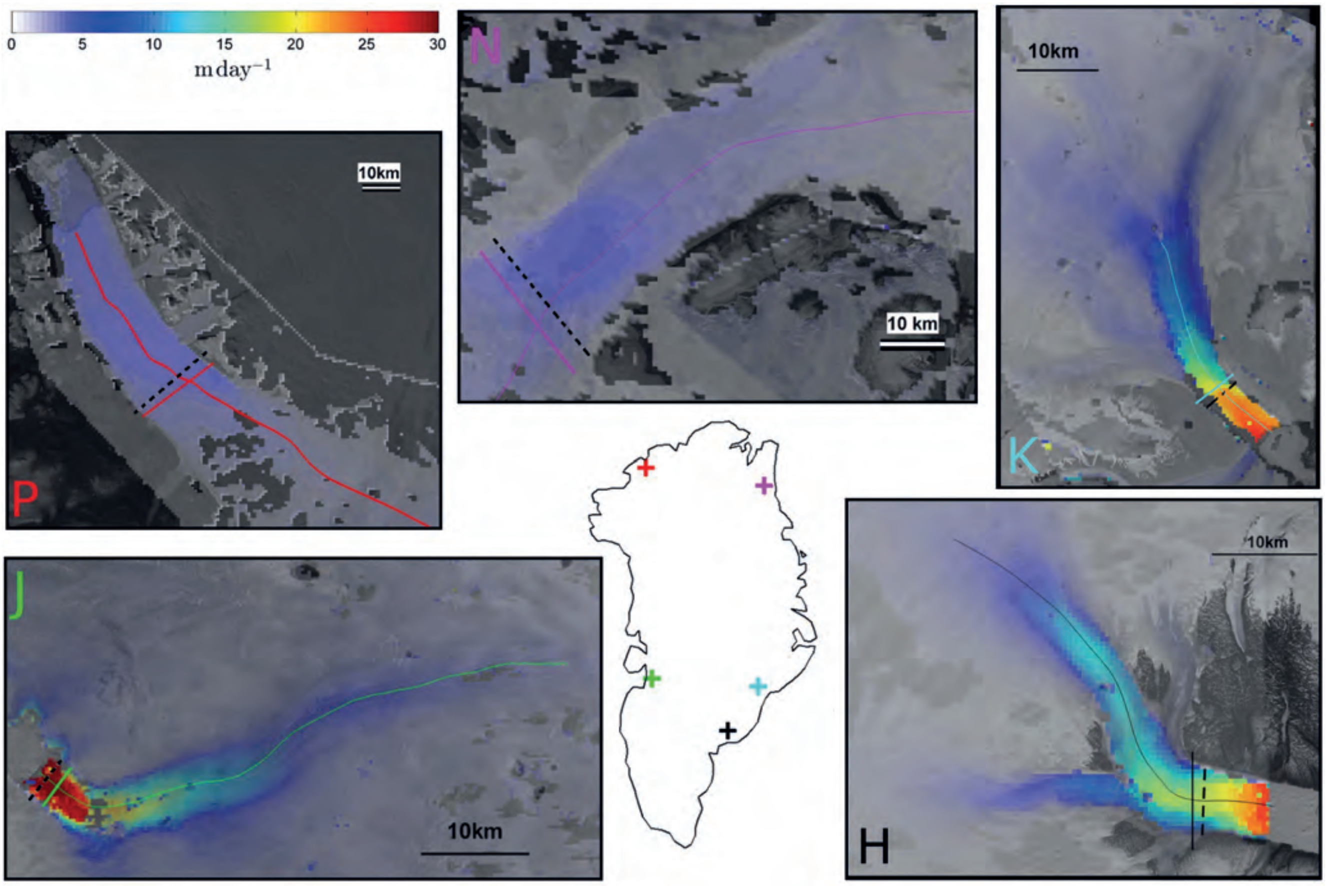

Figure 8. Individual velocity fields for each of the glaciers in the study: J=Jakobshavn, P=Petermann, N=Nioghalvfjerdsbræ, K=Kangerdlugssuaq H=Helheim. Each plot shows the location of the flow profile (Figure 9) and the location of the flux gates used to estimate the flux shown in the table 1 below. The estimated grounding line for each glacier is marked with a black dashed line. Each velocity map is on the same colour scale.

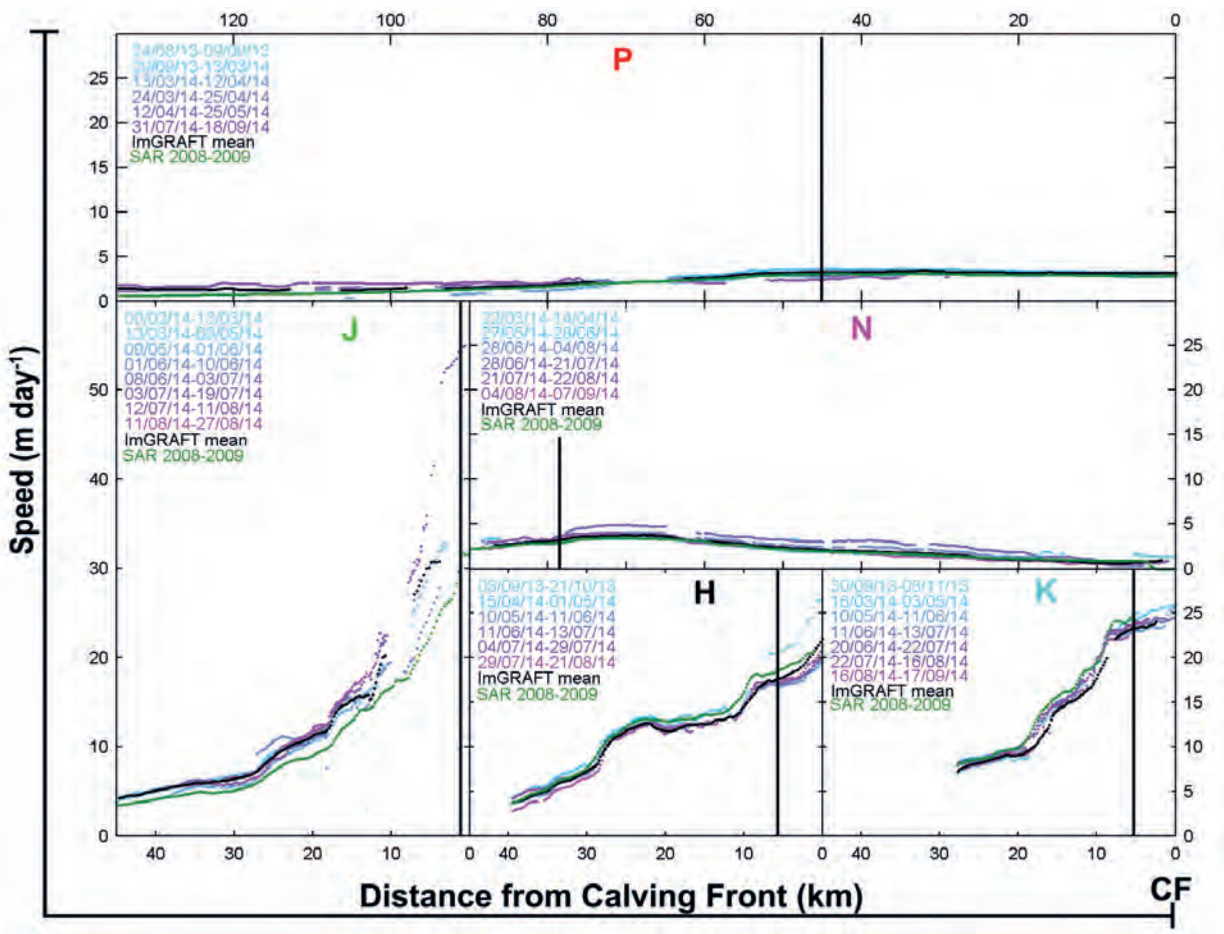

Figure 9. Speed along the flow profiles illustrated in figure 8 for each glacier. Note that Petermann, Nioghalvfjerdsbræ, Helheim and Kangerdlugssuaq all on the same Y-axis however Jakobshavn Isbræ on a much larger Y-axis due to the high speeds measured in July. The approximate location of the estimated grounding line for each glacier is marked with the black vertical bar.

Glacier Name	Flux km^3yr^{-1}	Bias km^3yr^{-1}	No. of days covered by observations	Drainage Area (%)
Petermann	7.3	+0.28	303	4.2
Nioghalvfjerdsbræ	10.0	-1.36	126	3.8
Kangerdlugssuaq	17.42	-0.07	217	2.9
Helheim	26.78	+0.56	176	3.0
Jakobshavn Isbræ	29.8	+6	199	5.1

Table 1. Flux estimates for each of the glaciers in the study. A seasonal flux bias is noted in column three, where a positive bias suggests an overestimation of the flux and a negative bias suggests an underestimation of the bias. The drainage area estimates are taken from Bevan et al. (2012).

overlapping time-periods the velocity fields are weighted according to the number of overlapping image-pairs.

The velocity estimates shown in Figure 9 match well with the recent years estimates form radar velocity mapping. An important finding is that Jakobshavn Isbræ has continued its speed-up reaching summer speeds of over 50 m/day accompanied by rapid retreat. This is attributed to the retreat of Jakobshavn Isbræ into a deep (1300 m) bed trough that has allowed for such rapid retreat and sustained high velocities.To the best of our knowledge this is the fastest observed speed recorded at Jakobshavn Isbræ exceeding the previous maximum recorded by Joughin et al. (2014) in summer 2012.

One interesting feature to note is that the two East coast glaciers Helheim and Kangerdlugssuaq showed very contrasting responses to a speed up event that took place in 2006. It took Helheim a much shorter time to returned to pre-speedup fluxes compared to Kangerdlugssuaq, which according to our flux estimate has only now, a decade later return to pre-speedup flux. The results confirm the ability of ImGRAFT to reproduce consistent velocity fields using optical Landsat data.

Iceland

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Regular field observations on the motion of Icelandic glaciers started in the early 1990's when GPS made positioning of objects, with ~1 m horizontal precision, viable. Since then the position of each stake, in the networks of ablation stakes deployed every spring on Langjökull, Hofsjökull and Vatnajökull ice caps (Figure 10), has been measured both in spring and autumn reveling the average surface velocity during the ablation season. In the past decade have GPS stations (both with ~1 m precision and <10 cm precision) recording its position continuously been operated at several locations (Figure 10). Many of these field campaigns are still ongoing whereas others have been successfully concluded (e.g. Magnússon et al., 2011).

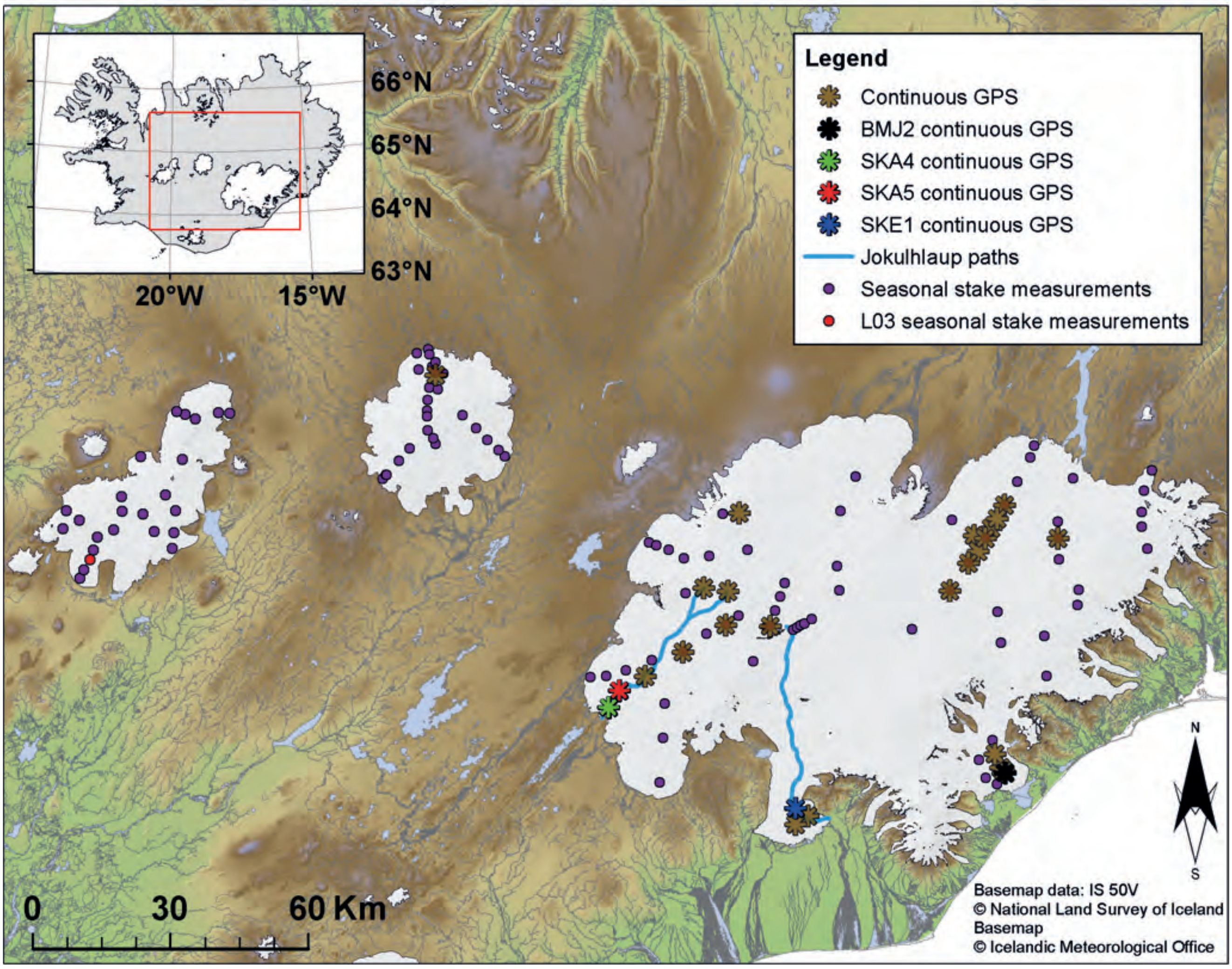


Figure 10. The locations of seasonal stake measurements (dots) and GPS stations (asterisk) operated on Langjökull (west), Hofsjökull (middle) and Vatnajökull ice cap (east) by the Institute of Earth Sciences, University of Iceland and by the Icelandic Meteorological Office. The path of Jökulhlaups from Grímsvötn and Skaftár cauldrons are shown with blue lines.

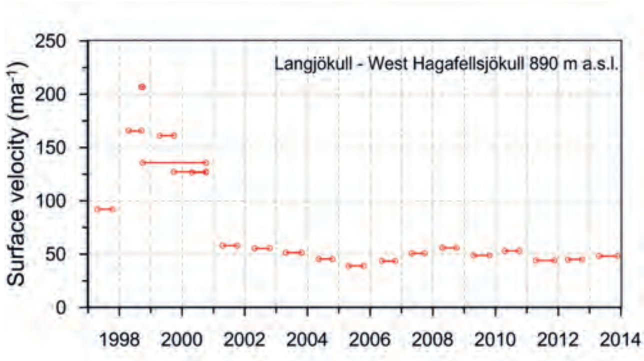


Figure 11. The surface velocity at stake location L03 on Langjökull ice cap (see Figure 10 for location) derived from biannual measurements of stake positions. New stake is deployed every spring and measured again in the autumn. Stake locations are generally not retrievable the following year. The speed up in 1998–2000 is associated with the propagation of a surge wave (Björnsson et al., 2002).

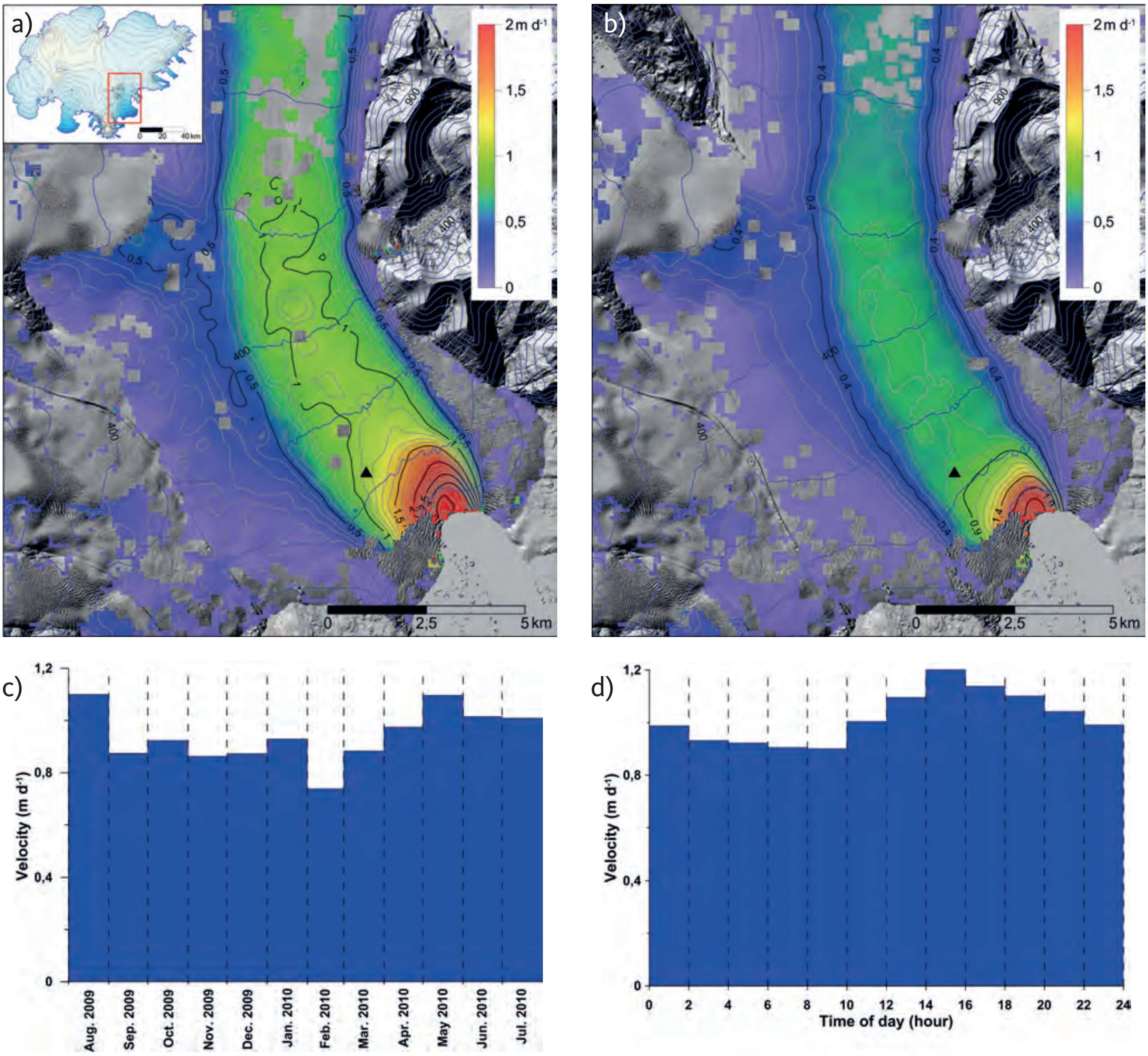


Figure 12. a) The horizontal velocity of the Breiðamerkurjökull calving glacier in southern Vatnajökull (see inlet image for location) 2–13 August 2009 derived from TerraSAR-X images by applying amplitude offset tracking. Shaded relief background image and elevation contours are from a LiDAR DEM obtained in August 2011 (Jóhannesson et al., 2013). b) The horizontal velocity of the Breiðamerkurjökull 5–16 February 2010 derived from TerraSAR-X. c) The average monthly velocity at station BMJ2 on Breiðamerkurjökull (see black triangle on a and b as well as Figure 10 for location). d) The average velocity at given time of day for 2 hour intervals at BMJ2 in June 2010 reflecting the diurnal velocity fluctuation.

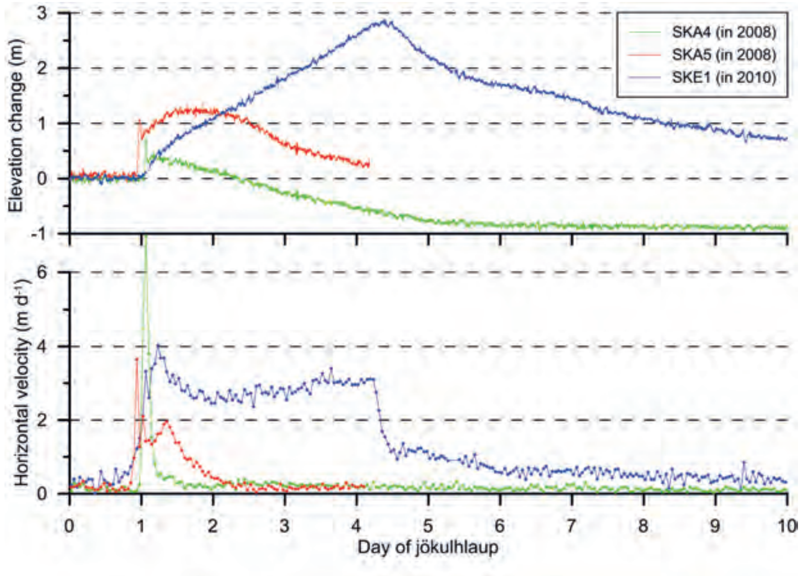


Figure 13. The elevation change (above) and horizontal velocity (below) during jökulhlaups measured at GPS stations SKA4 and SKA5 on Skáftárjökull in the autumn of 2008 and on at station SKE1 on Skeiðarárjökull in the autumn of 2011 (from Einarsson et al., in prep.). See Figure 10 for location of GPS stations.

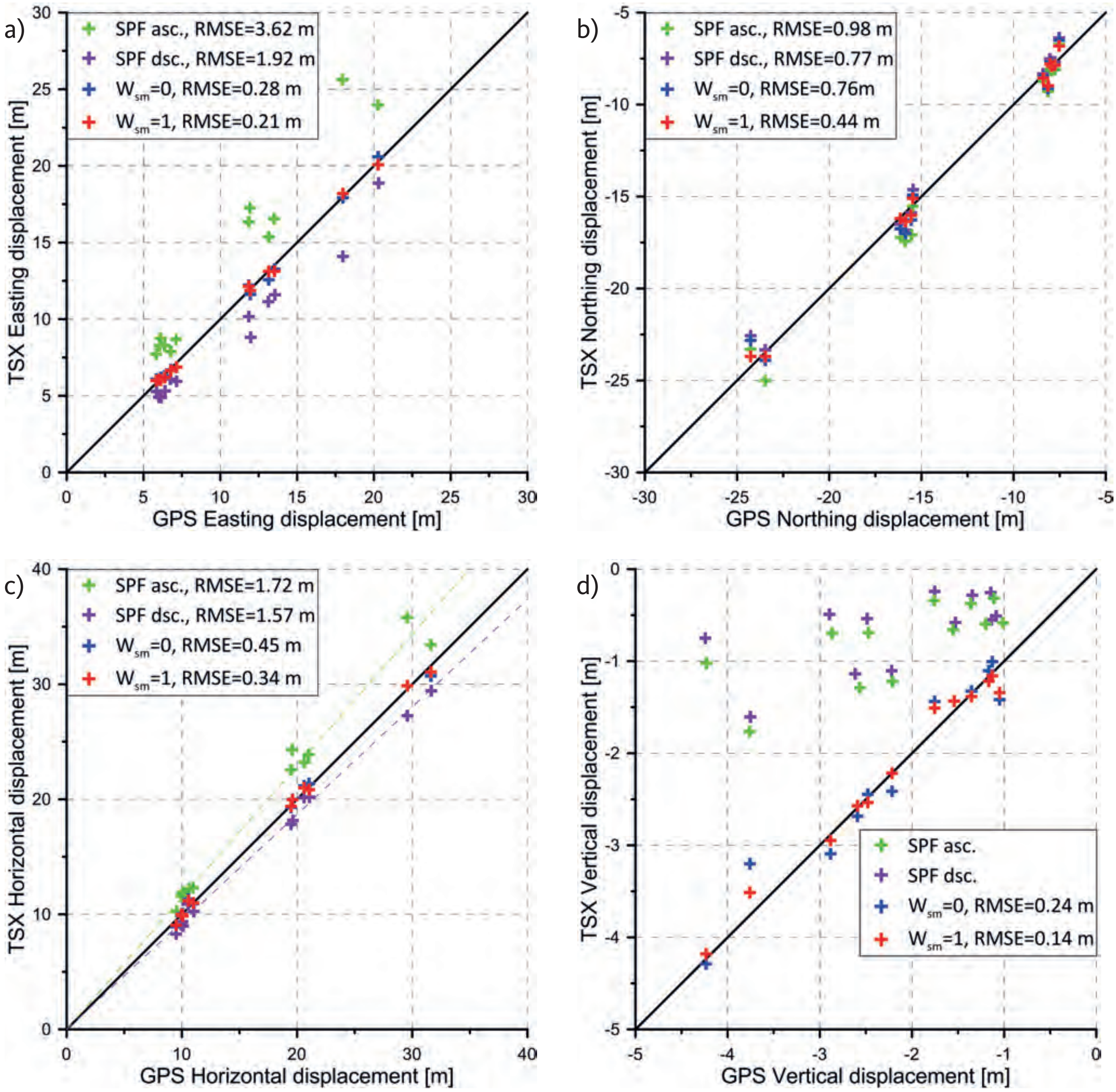
Remote sensing has provided data for deducing velocity fields of Icelandic glaciers since the 1990's. The first substantial source of such data came from the ERS1 and ERS2 radar satellites of ESA, utilizing the Interferometric Synthetic Aperture Radar (InSAR) approach to measure the glacier motion in the radar line of sight. Due to rapid changes in surface conditions of Icelandic glaciers the InSAR approach is only applicable for relatively short repeat time. The InSAR approach is therefore only applicable for the ERS1 Ice Phase data in 1992–1994 (with 3 day repeat time) and the ERS1/2 Tandem data in 1995–2000 (with 1 day repeat time). Both these data sets have been widely used for studying the dynamics of Icelandic glaciers (e.g. Guðmundsson et al., 2002 and Palmer et al., 2009). These data sets have though by no means been fully exploited yet as recent studies depending on them reveal (e.g. Oostveen, 2014).

Since 2000 almost no InSAR data, applicable for measuring glacier motion, have been acquired over Icelandic glaciers. This may be changing now with the recent option of acquiring 1 day tandem data with the Italian Cosmo Skymed satellites. Due to the lack of InSAR data, dynamic studies utilizing data acquired after 2000 have generally utilized feature tracking of both optical (Berthier, 2005) and radar satellite imagery (Nagler et al., 2012). This has changed the study focus from snap shot velocity observation over one or few days to long term average glacier motion over weeks to year.

The vast amount of velocity observations obtained from Icelandic glaciers manifests the high variability in the dynamics of Icelandic glaciers on various time scales. The fact that numerous outlet glaciers flowing from the ice caps are surge type, results in variability in the glacier motion of time scales of years to decades (Figure 11). Increased availability of water at the glacier bed during the ablation period results in seasonal variation in glacier motion (Figure 12a-c).

Diurnal fluctuations in glacier motion are also commonly observed related to diurnal fluctuations in the melt rate during the ablation period (Figure 12d). Speed-up events related to intense rainfall and/or changes in surface melt rate are frequent as well, even during the winter (Magnússon et al., 2011). Jökulhlaups drain regularly under some of the outlet glaciers and cause a significant acceleration in the glacier motion (e.g. Magnússon et al., 2007). Surveying the motion on glaciers affected by jökulhlaups can serve the purpose of a warning system to detect jökulhlaup approaching the glacier margin. Jökulhlaups do also provide opportunities to study how the subglacial hydrology system and consequently the glacier dynamics respond to extreme events when the subglacial drainage system may be completely over saturated with flood water (Figure 13).

Due to lack velocity observation before the 1990's and the high temporal variability in the dynamics of Icelandic glaciers it is difficult to extract any long term trends of motion rates in the past decades associated with changes in climate conditions. In fact some data even suggest that the motion rate of some glaciers has been rather stable in the past years (Figure 11). Icelandic glaciers do however serve the purpose of an accessible natural laboratory for studying how processes in glacier hydrology can influence glacier dynamics. The accessibility also makes Icelandic glaciers ideal for obtaining in situ data to validate remote sensing instruments and methods for deducing velocity fields (Figure 14).



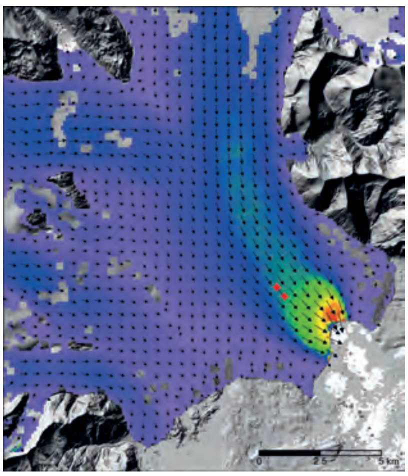


Figure 14. a-d) Comparison of displacements measured by two GPS stations (red diamonds on e) and 3-dimensional displacement fields deduced from TerraSAR-X (TSX) images obtained with 11 day interval between 11 August and 13 September 2010 over Breiðamerkurjökull. The TSX velocities are derived using amplitude offset tracking and by; i) applying the conventional surface parallel flow (SPF) assumption, ii) combining amplitude offset tracking results from ascending (asc.) and descending (dsc.) orbits, with almost identical timespan (only 12 hour mismatch), and without any smoothing (smoothing coefficient Wsm=0), iii) combining amplitude offset tracking results from ascending and descending orbits and applying smoothing on the displacement field (smoothing coefficient Wsm=1). The root mean square error (RMSE) is shown for all displacement components (assuming that GPS reveals true displacement) for each method. The vertical component of the SPF approach since this approach is not expected to give realistic vertical displacement values. The SPF assumption results in 14 % overestimate or 7 % underestimate in the horizontal motion (broken lines in c) depending on whether data from ascending or descending orbits is used. e) The horizontal surface velocity 11 August – 13 September 2010 derived TSX data with method iii (from Magnússon et al., in prep.).

Norway

Application of the Image GeoRectification And Feature Tracking toolbox (ImGRAFT) to Engabreen, Norway

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The use of time-lapse camera systems is becoming an increasingly popular method for data acquisition. The camera setup is often cost-effective and simple, allowing for a large amount of data to be accumulated over a variety of environments for relatively minimal effort. The acquired data can, with the correct post-processing, result in a wide range of useful quantitative and qualitative information in remote and dangerous areas. The post-processing requires a significant amount of steps to transform images into meaningful and comparable data, such as velocity data. To the best of our knowledge at present a complete, openly available package that encompasses georeferencing, georectification and feature tracking of terrestrial, oblique images is still absent. This study presents a complete, yet adaptable, open-source package developed in MATLAB that addresses and combines each of these post-processing steps into one complete suite in the

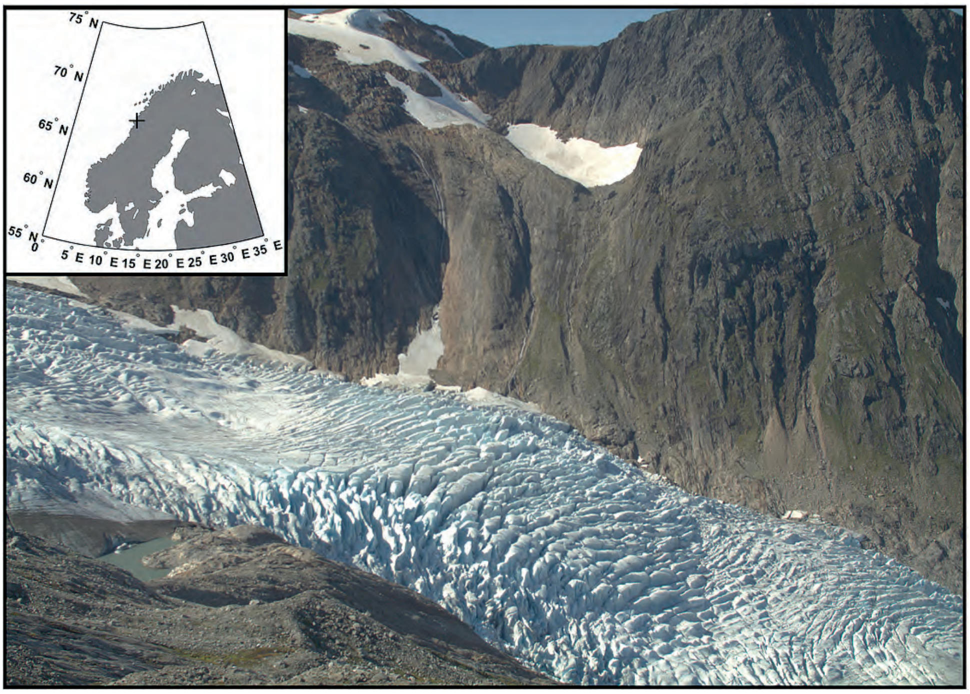

Figure 15. A sample image taken by the time-lapse camera located at Engabreen, northern Norway (inset). Note the distinct crevasse features in the main icefall.

Table 2. Image pair IDs and parameters used in the error calculation, including the median velocity for Subset 1 (Figure 16) for each image pair.

Image Pair ID	Date *image A*	Date *image B*	Time	Interval	Median velocity (m day $^{-1}$)
1151a	17 Jul 2013	22 Jul 2013	11:04	5 days	0.54
1252b	17 Jul 2013	22 Jul 2013	14:04	5 days	0.49
1167a	17 Jul 2013	24 Jul 2013	11:04	7 days	0.53
1268b	17 Jul 2013	24 Jul 2013	14:04	7 days	0.51
1175a	17 Jul 2013	25 Jul 2013	11:04	8 days	0.54
1276b	17 Jul 2013	25 Jul 2013	14:04	8 days	0.52
1183a	17 Jul 2013	26 Jul 2013	11:04	9 days	0.53
1284b	17 Jul 2013	26 Jul 2013	14:04	9 days	0.53
1191a	17 Jul 2013	27 Jul 2013	11:04	10 days	0.54
1292b	17 Jul 2013	27 Jul 2013	14:04	10 days	0.52
					Mean: 0.53
					Range: 0.05

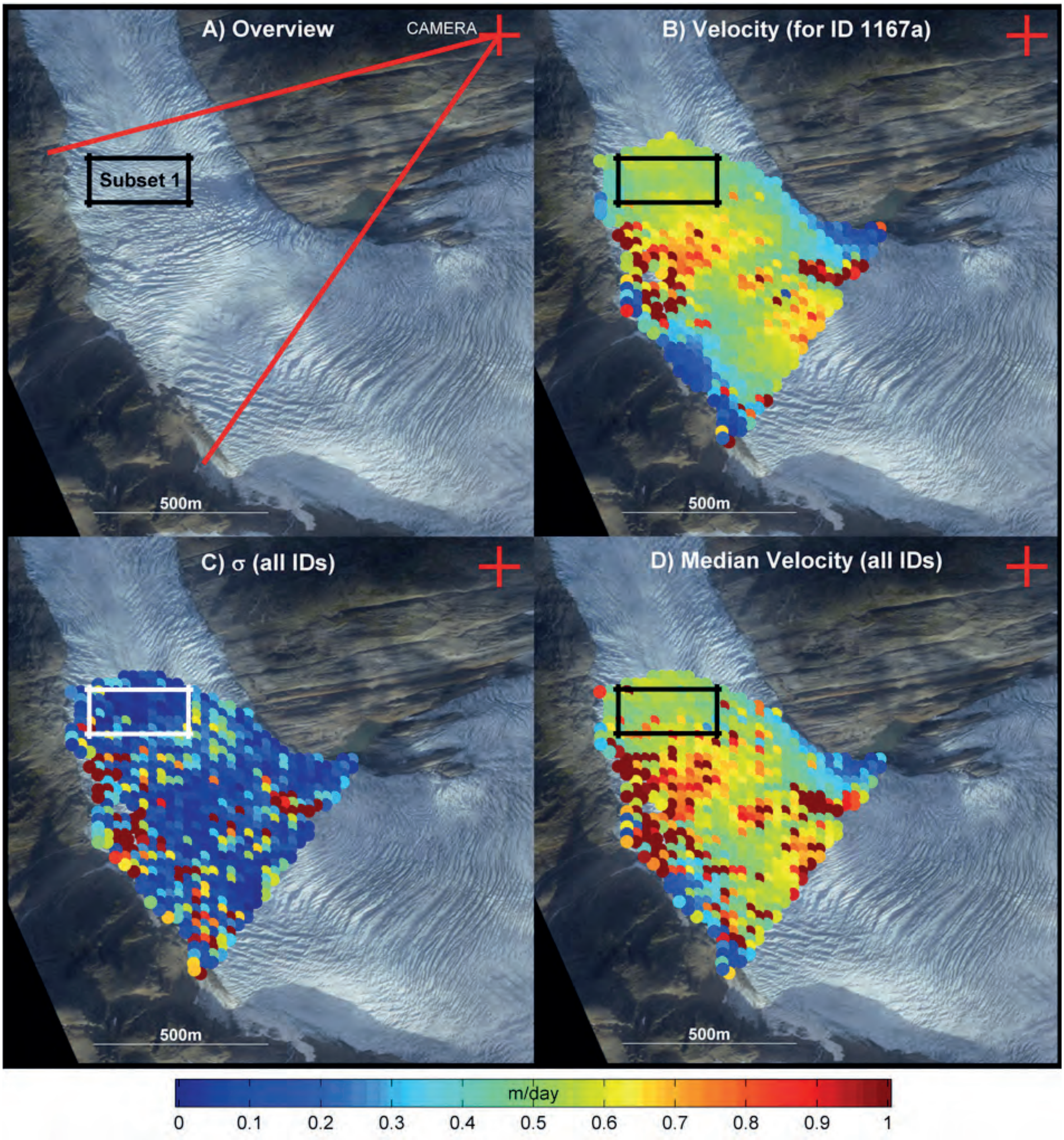

Figure 16. (a) provides an overview of the time-lapse location on the valley side and the red lines indicate the viewshed. Subset 1 is the test area used to derive the median displacements presented in Table 2. (b) is an example of the raw velocity field produced as output from the ImGRAFT toolbox. (c) is an example standard deviation plot of velocity fields produced from all the image pairs in Table 2. (d) is a median velocity plot for all the image pairs presented in Table 2. Note that we use the median over the mean as it is robust to outliers.

form of an "Image GeoRectification and Feature Tracking" (ImGRAFT: http://imgraft.glaciology.net) toolbox. The toolbox can also independently produce other useful outputs, such as viewsheds, georectified and orthorectified images. ImGRAFT is primarily focused on terrestrial oblique images, for which there are currently limited post-processing options available.

In this study we illustrate ImGRAFT for glaciological applications on a small outlet glacier Engabreen, Norway (Figure 15). For details on the technical setup, the processing chain and the error estimation we refer to Messerli and Grinsted (2014) which is the source of this contribution.

Engabreen is a small Arctic valley glacier and outlet of the large Svartisen Ice Cap. Engabreen has a large icefall located at approximately 850 m a.s.l. An icefall is a steep area of the glacier where there is high ice flow and as a result extensional flow leading to extensive development of large crevasses and unstable ice blocks known as séracs. In previous years attempts have been made to instrument the icefall however due to the nature of the moderate flow (> 300 m/yr) and the extensive crevassing the longevity of any instrument in this region is generally short-lived.

ImGRAFT produces consistent velocity fields over the mid icefall section of Engabreen. They match the expected flow pattern of a small alpine glacier and that of two SAR velocity fields (Unpublished data, Schellenberger, 2014) over the same area. As well as comparing to the SAR maps we also improve the existing surface velocity estimates from Engabreen (Jackson et al., 2005). We significantly improve the temporal coverage due to the high number of images acquired each day. We achieve a dense velocity field at Engabreen albeit over a smaller area than Jackson et al. (2005). The Jackson et al. (2005) study uses a similar photogrammetric approach using IMCORR software, whereby they feature track two aerial images from 2002. They found that the central part of the glacier was moving slower than the margins. Our results and preliminary SAR data indicate that this feature is likely an artefact of the processing due to the long time interval between image acquisitions (> than 20 days). This long interval between images results in features deforming beyond recognition and are thus no longer feasibly trackable. Crevasses tend to generate false matches when the displacement is comparable to the typical crevasse separation distance. The high flow can be separated into two distinct areas; firstly the edge of the upper ice fall flowing into an overdeepening and secondly the ice flowing out of the overdeepening into the lower ice fall as demonstrated by the yellow/orange areas in Figure 16b.

Our aim is to allow for further algorithm development and improvement through our own efforts and those within the user community. We try to automate as many of the processes as possible but further automation is conceivable. ImGRAFT has the scope to process images taken on lower quality cameras with lower quality lenses as the toolbox incorporates a full distortion model to correct this. This significantly increases the diversity of the toolbox as it accommodates a wide range of image sources and possibilities for feature tracking. ImGRAFT was also tested on Landsat satellite images with very good results, in this instance only the "Template Match" part of the toolbox is required as the satellite images are already fully georeferenced (Messerli et al., 2014). ImGRAFT produces consistent velocity fields that require minimal post processing and filtering. A set of standard filters may be applied to the data to remove false matches within the feature tracking algorithm. We propose an empirical approach for error assessment that incorporates the accumulated errors throughout the processing chain. With this approach we do not account for any inaccuracies within the DEM, as these are likely to be negligible in our case as a result of the simultaneous acquisition of the DEM and one of the oblique images on 25 August 2013. ImGRAFT provides a flexible, adaptable tool to process large volumes of image data to obtain quantitative data in the form of displacement. Whilst we developed ImGRAFT with a focus on glaciological applications, there is nothing to suggest this will not work for other deformation applications.

Svalbard

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Svalbard has a glaciated area of c. 35 000 km2 and plays a significant role, not just because of its contribution to sea level rise, but also as a field laboratory for Arctic and North-Atlantic glaciology in general due to its relative accessibility. To exemplify, year-round deployment of GPS trackers in the field were first tested here (Den Ouden et al., 2010) and we continue to learn about the complex interaction between surging glaciers and climatic forcing (Dunse et al., 2014). Several partner institutions of the SVALI network are active in Svalbard and the following sections will present results from selected parts of their work dealing with observed ice-dynamic changes. Methods include both repeated ground observation campaigns and satellite remote sensing. Areas of interest here includes Nordenskiöldbreen, conveniently located near the main town Longyearbyen, Kronebreen and Kongsbreen which represents some of the fastest flowing glaciers on Svalbard and finally Vestfonna and Austfonna, the two large ice caps occupying Nordaustlandet in the north-eastern part of Svalbard.

Trend in surface speed and frontal ablation of Kronebreen and Kongsbreen, NW-Svalbard

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Kronebreen and Kongsbreen are among the fastest flowing glaciers on Svalbard, and therefore important contributors to

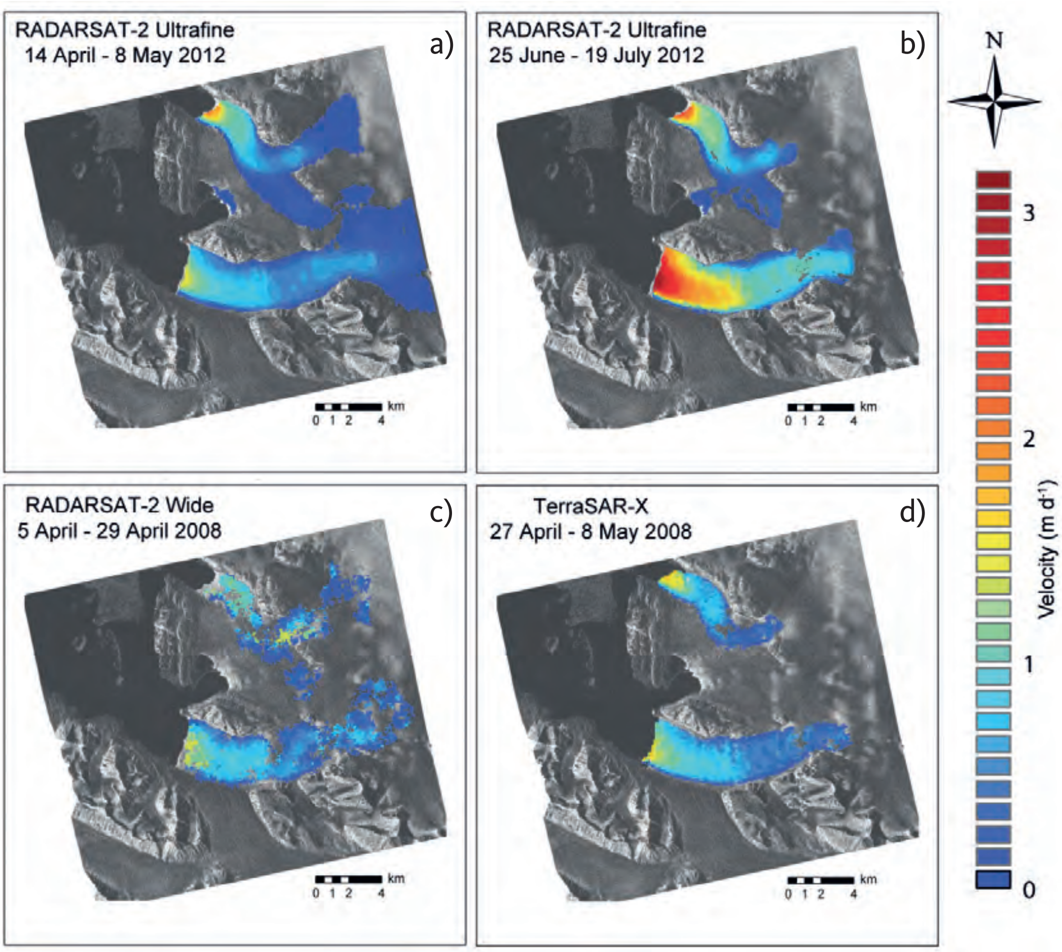


Figure 17. Selected speed fields of Kronebreen and Kongsbreen from SAR feature tracking. (a) RS-2 UF 14 April 2012-08 May 2012 (b) RS-2 UF 25 June 2012-19 July 2012 (c) RS-2 W 05 April 2012-29 April 2012 (d) TSX 27 April 2008 – 08 May 2008. Speeds close to zero were masked out.

glacier mass loss from the archipelago through frontal ablation. A time series of area-wide surface velocity fields from April 2012 to December 2013 was measured based on offset tracking on repeat high-resolution Radarsat-2 Ultrafine data (Figure 17). Surface speeds reached up to 3.2 m d-1 near the calving front of Kronebreen in summer 2013 and 2.7 m d-1 at Kongsbreen in late autumn 2012. Additional velocity fields from Radarsat-1, Radarsat-2 and TerraSAR-X data since December 2007 together with continuous GPS measurements on Kronebreen since September 2008 revealed complex patterns in seasonal and interannual speed evolution (Figure 18). Part of the ice-flow variations seem closely linked to the amount and timing of surface melt water production and rainfall, both of which are known to have a strong influence on the basal water pressure and lubrication. In addition, terminus retreat and the associated reduction in backstress appear to have influenced the speed close to the calving front, especially at Kongsbreen in 2012 and 2013. Since 2007, Kongsbreen retreated up to 1800 m, corresponding to a total area loss of 2.5 km2. In 2011 the retreat of Kronebreen of up to 850 m, responsible for a total area loss of 2.8 km^2, was triggered after a phase of stable terminus position since ~1990. The retreat is an important component of the mass balance of both glaciers, in which frontal ablation is the largest component. Total frontal ablation between April 2012 and December 2013 was estimated to 0.21 - 0.25 Gt a-1 for Kronebreen and 0.14 - 0.16 Gt a-1 for Kongsbreen.

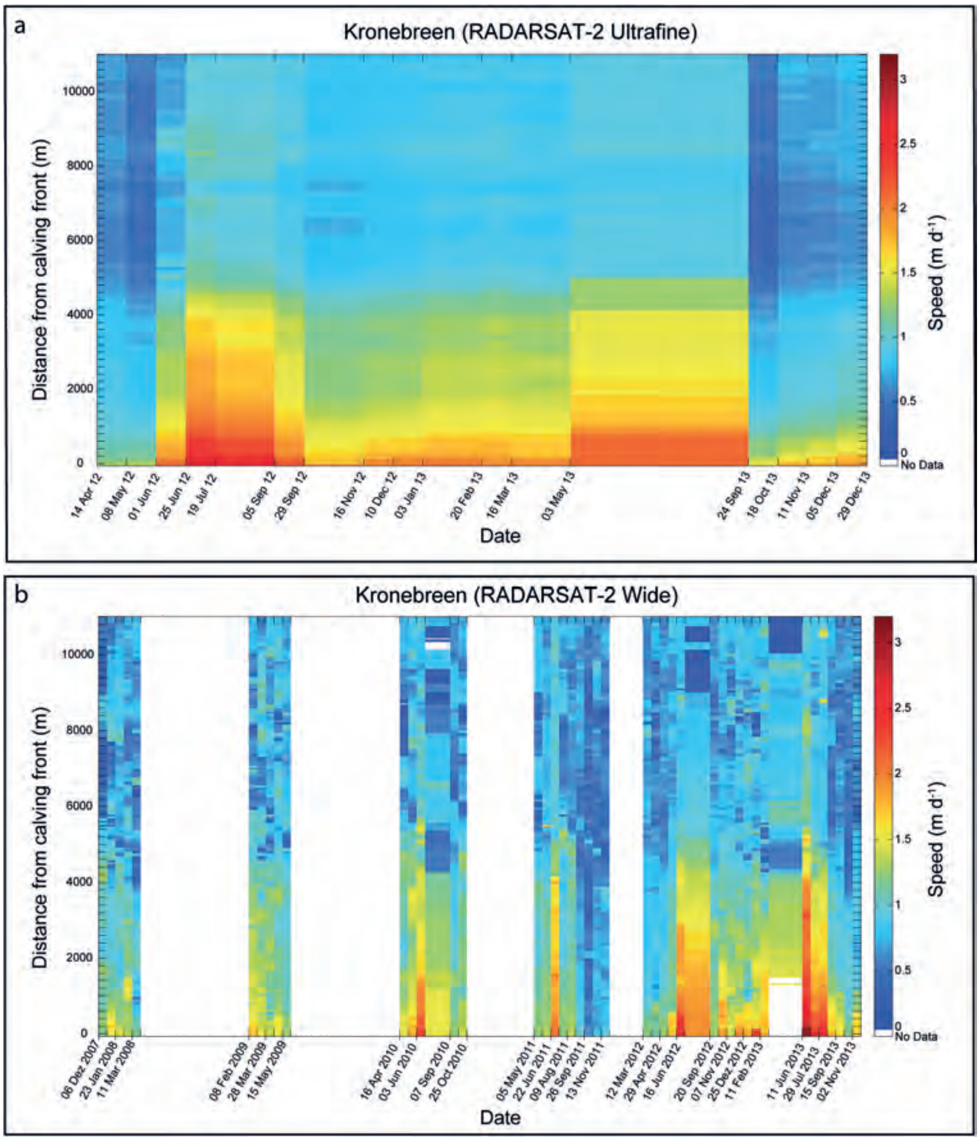


Figure 18. Time series of glacier speed along a center line of Kronebreen between (a) 14 April 2012 and 29 December 2013 based on RS-2 UF data and (b) 06 December 2007 and 26 November 2013 based on RS-1 W data (2007-2008) and RS-2 W data (2009-2013), respectively.

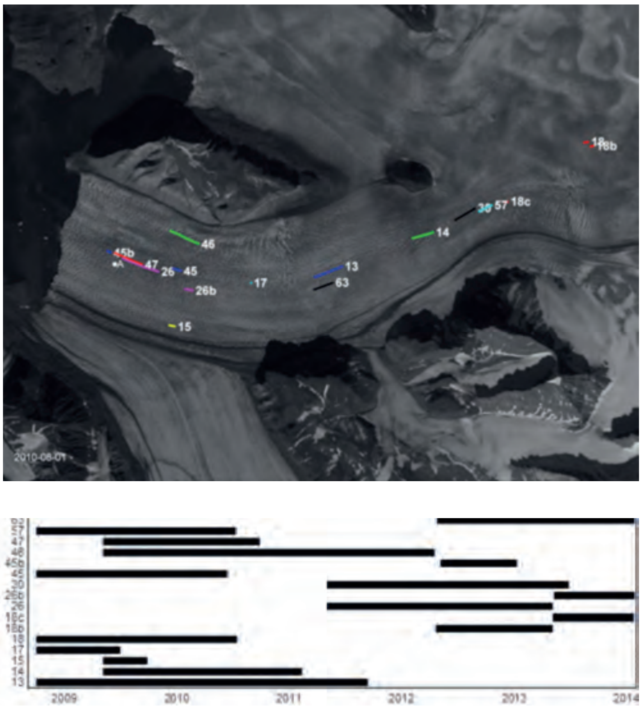


Figure 19. Upper panel: Tracks of all IMAU GPS stations on Kronebreen, 2009-2014
Lower panel: Dates active for IMAU GPS stations shown above.

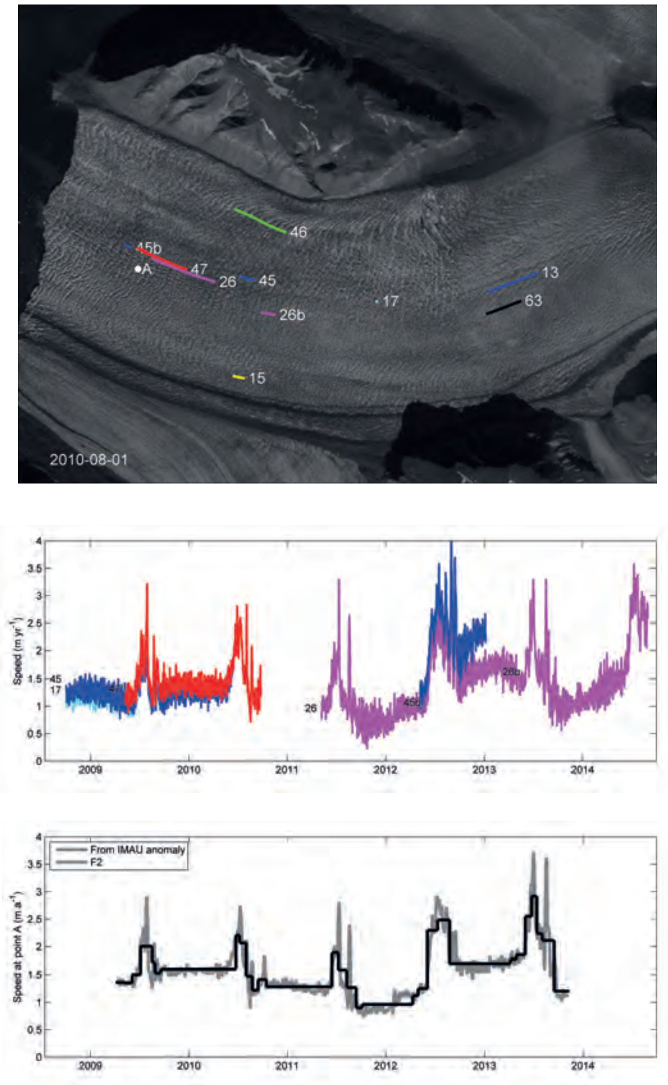
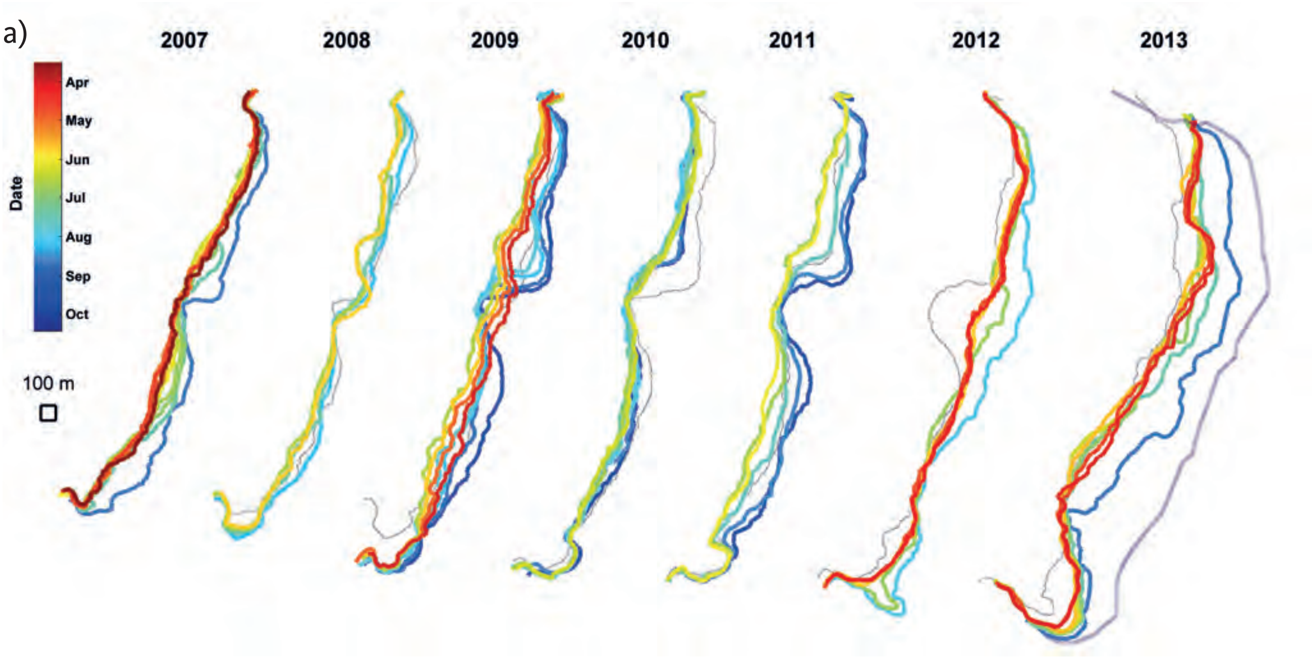


Figure 20. a) Tracks of 5 IMAU GPS stations in lower part of Kronebreen, 2009-2013. b) Total speed (m a-1) for these GPS stations, derived from the positions after smoothing with a moving slope filter, which performs a linear fit within a moving time window of 57 points, equivalent to 7 days. c) Spatial gradients lead to changing speed along a track, even in the absence of temporal variability. Provided that the spatial pattern scales in a relatively constant way through time, we can derive a high resolution temporal signal at an arbitrary location (point A, see map), by combining the IMAU-GPS speeds with the high spatial resolution F2-derived velocity maps.



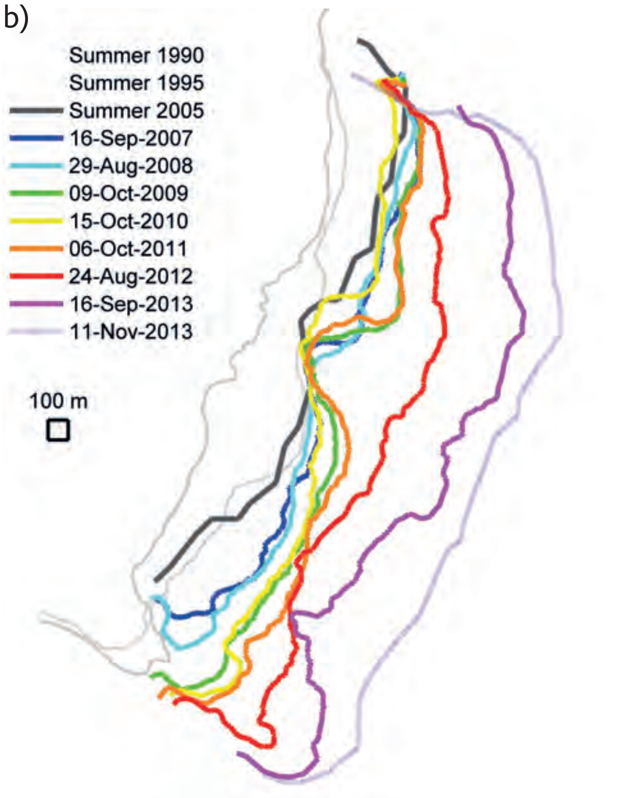


Figure 21. a) F2-derived front positions of Kronebreen for the years 2007-2013. Colors indicate date of front positions, dashed lines in 2008-2013 indicate the last front position measured in the previous year. Heavy dashed line indicates front position Nov. 2013 derived from Radarsat-2 Ultrafine scene. b) Historical front positions from maps (1990, 1995, 2005), final F2-derived front positions measured in each year (2007-2013), and 2013 R2 front position.

Stand-alone single-frequency GPS ice velocity observations on Nordenskiöldbreen

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Precise measurements of ice-flow velocities are necessary for a proper understanding of the dynamics of glaciers and their response to climate change. We use standalone single-frequency GPS receivers for this purpose. They are designed to operate unattended for 1–3 years, allowing uninterrupted measurements for long periods with hourly temporal resolution. We present the system and illustrate its functioning using data from 9 GPS receivers deployed on Nordenskiöldbreen, Svalbard, for the period 2006–2009 (Figure 22). The accuracy of the receivers is 1.62 m based on the standard deviation in the average location of a stationary reference station (NBRef). Both the location of NBRef and the

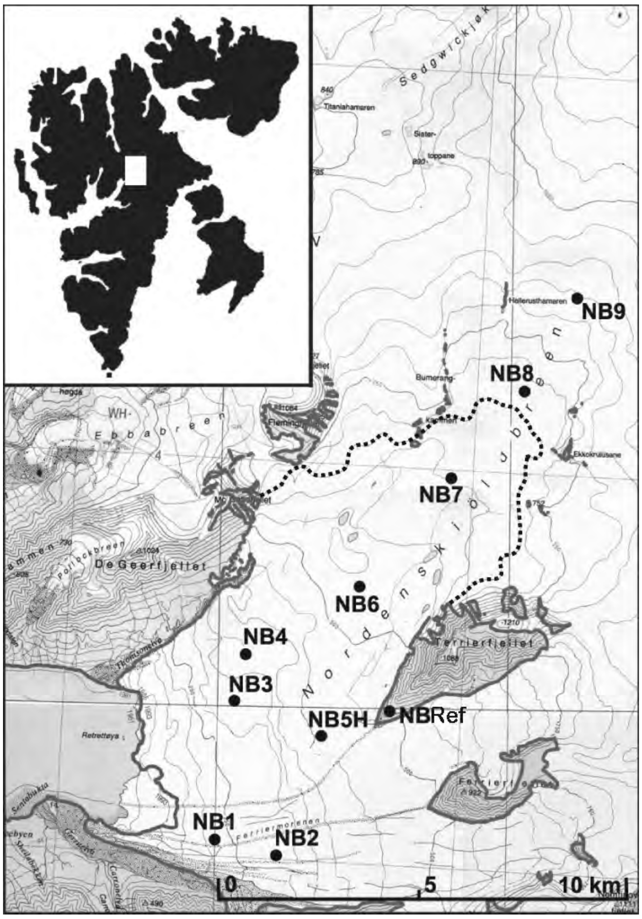

Figure 22. Map of Nordenskiöldbreen, Svalbard, with the locations of the GPS stations (NB1-NB9) and sonic ranger (NB5H) on the glacier, and the reference station on Terrierfjellet (NBRef). The approximate equilibrium line is indicated with a dashed line (Hagen et al., 2003).

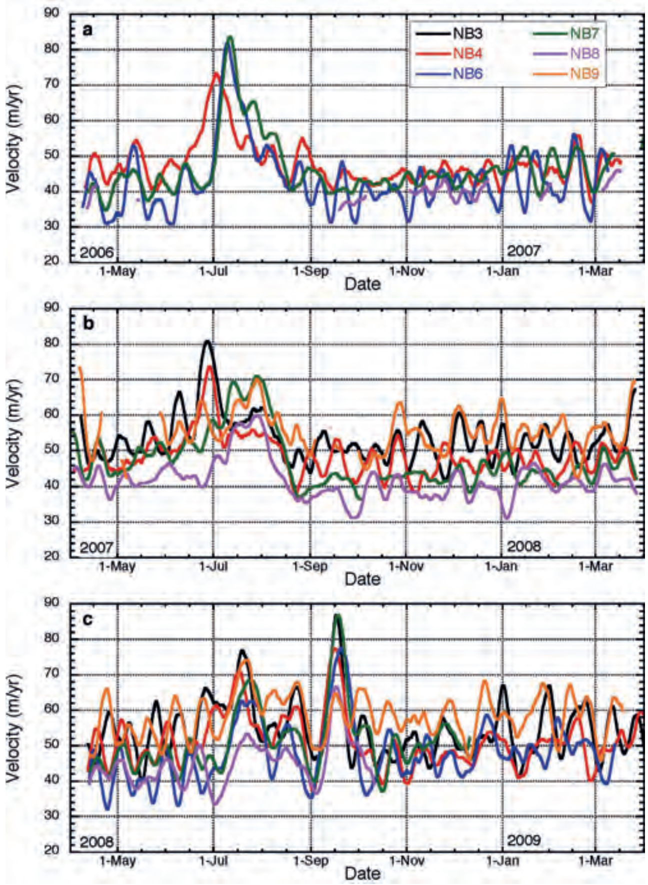

Figure 23. Time series of velocity measurement of the stations on the central flow-line for the period 2006-2007 (a), 2007-2008 (b) and 2008-2009 (c). A running average of 240 h is applied.

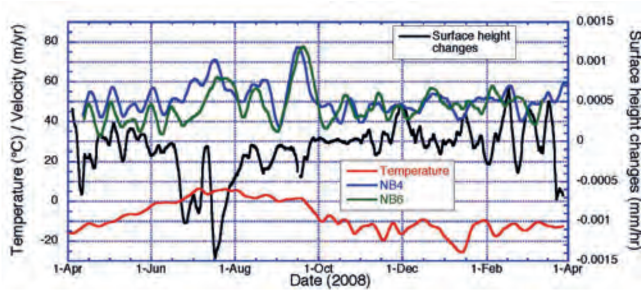

Figure 24. Time series of temperature, surface height changes and velocity of two stations, NB4 and NB6, for 2008. Surface height changes are derived from sonic height ranger data at NB5H. Negative surface height changes illustrate melt rates. All variables are calculated with a running average of 240 h.

observed flow velocities agree within one standard deviation with DGPS measurements. Periodicity (6, 8, 12, 24 h) in the NBRef data is largely explained by the atmospheric, mainly ionospheric, influence on the GPS signal. A (weighed) running-average on the observed locations significantly reduces the standard deviation and removes high frequency periodicities, but also reduces the temporal resolution. Results (seen in Figure 23) show annual average velocities varying between 40 and 55 m/yr at stations on the central flow-line. On weekly to monthly time-scales we observe a peak in the flow velocities (from 60 to 90 m/yr) at the beginning of July related to increased melt-rates (see Figure 24). No significant lag is observed between the timing of the maximum speed between different stations. This is likely due to the limited temporal resolution after averaging in combination with the relatively small distance (max. ±13 km) between the stations.

Spatial distribution and change in the surface ice-velocity field of Vestfonna ice cap

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[3] Faculty of Earth Science, University of Silesia, Katowice, Poland
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Earlier work has presented satellite-derived velocity fields over Vestfonna (Bevan et al. 2007; Strozzi et al. 2008). These observations have been contradictory, with large differences in the derived ice speeds. No ground truthed measurements have previously been available. During 2007 we launched a geodetic campaign on the Svalbard ice cap Vestfonna in order to estimate the velocity field of the ice cap (see Figure 25). We present here the velocity measurements derived from our campaigns 2007–2010 and compare the geodetic measurements against InSAR velocity fields from satellite platforms from 1995/96 and 2008. The geodetic measurements were done both as static surveying of stakes and as continuously recording GPS stations.

The satellite derived velocity fields are presented in Figure 26, where InSAR uxy is parallel to the glacier surface. There is

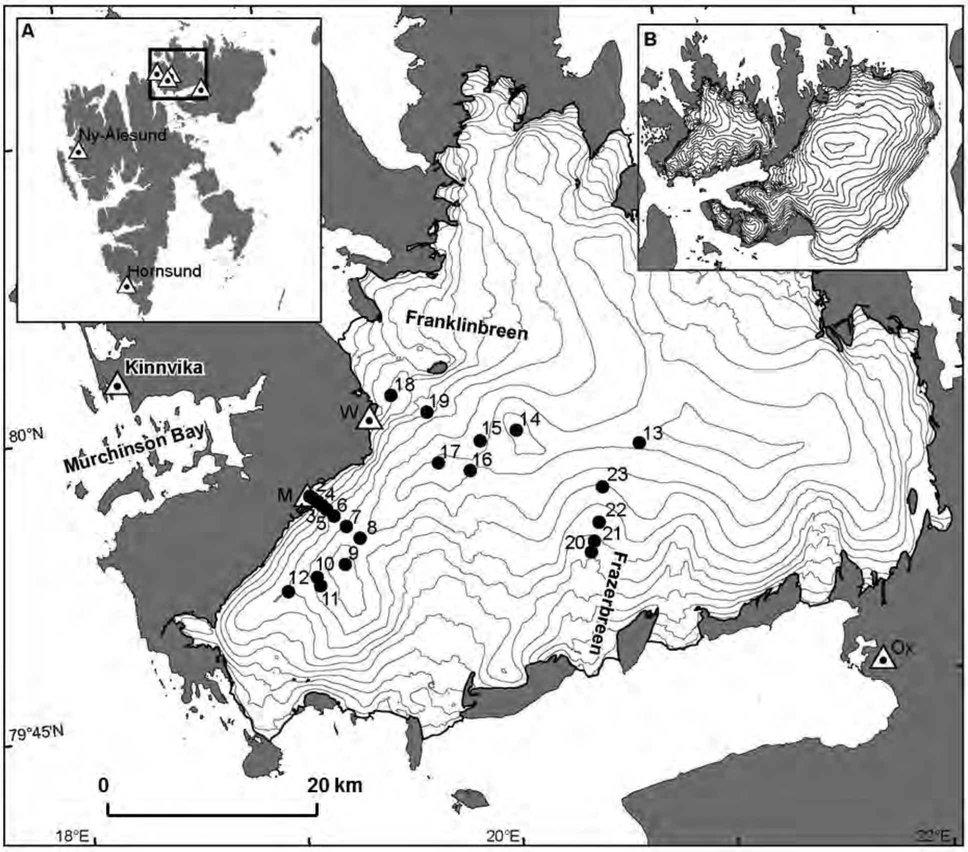

Figure 25. Svalbard, Nordaustlandet and the ice cap Vestfonna. Elevation and coast line contours are from the Norwegian Polar Institute DEM. The elevation contour spacing is 500 m. The black dots mark the position markers used for our DGPS surveys. The triangular symbols are the fixed points / base stations. The letter at each fixedpoint / base station refers to the first letter of its name. The Matti- and Weasel lobes are the bulging features with fronts ending at the base stations marked with M and W respectively. Donckerfjellet is the terrain SW of Franklinbreen, where the Weasel base station is marked. Inset a) show the base stations and inset b) show the topography of all the ice caps on Nordaustlandet. The contours are from the NPI DEM.

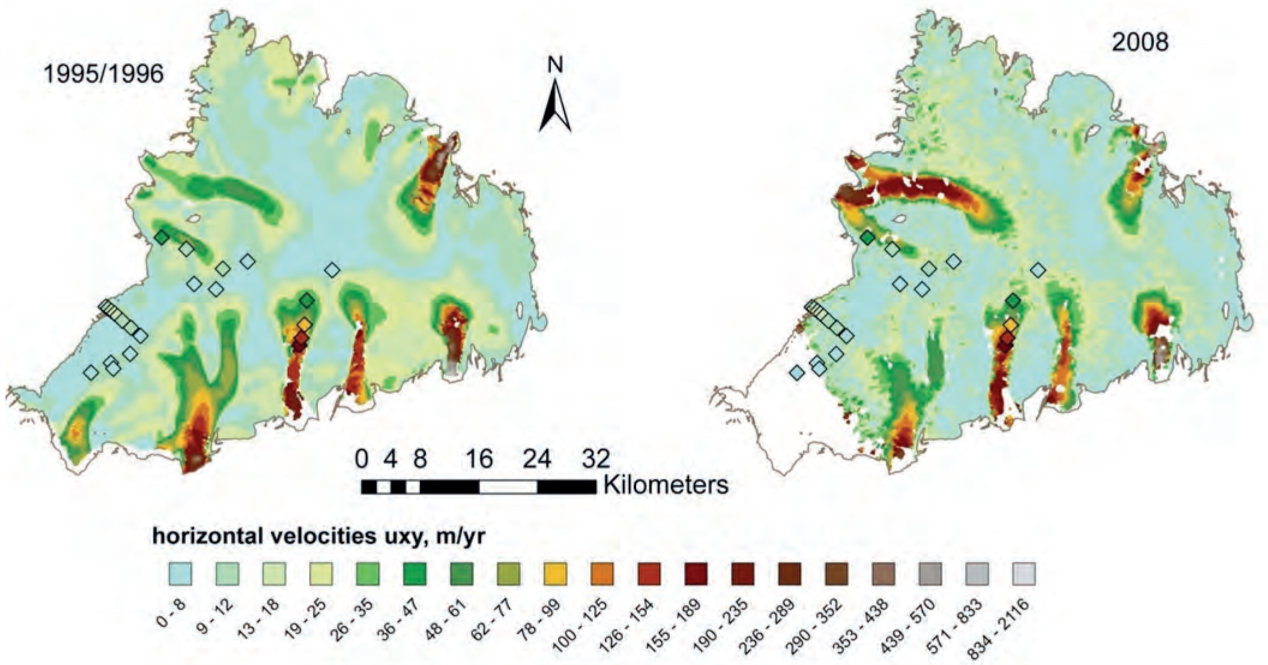

Figure 26. Vestfonna interferometry speeds during the winters 1995/96 and 2008. The diamonds mark the geodetic measurements at the DGPS stations. Note the fill color of the diamonds show InSAR speeds, which brings different colors when ice speed from the two methods fall into different classes. The ID of the geodetic (DGPS) positions is found in Figure 25. The classes are not equally spaced. The southwest area of Vestfonna marked white has no data.

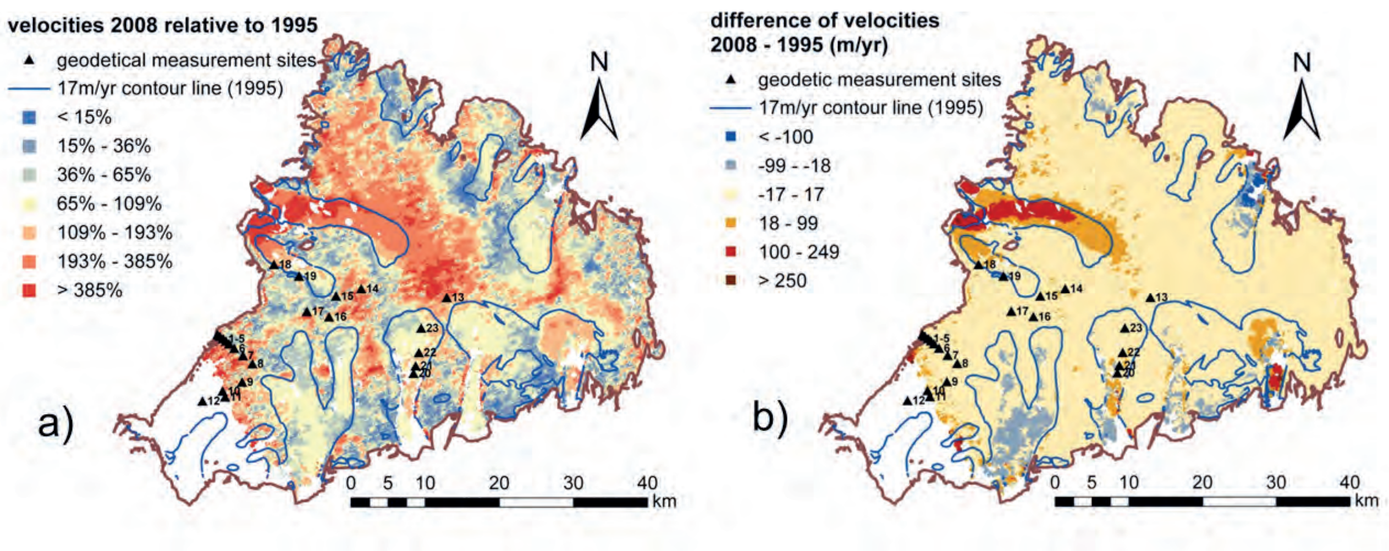

Figure 27. a) The ratio and b) the difference of InSAR ice speed between the two scenes (2008 – 1995/96). The 17 m/yr contour line marks the maximum uncertainty combining the two scenes. The triangles mark the geodetic (DGPS) stations.

a clear general pattern of slow ice flow on the main area of the ice cap, with pronounced high velocity lanes within the outlet glaciers. Both of the InSAR derived ice velocity scenes show the same general pattern. Figure 27 shows the ratio and the difference in uxy of the two InSAR scenes of 1995–96 and 2008.

Figure 27a shows a relatively large extent of differing uxy between the two periods. Most of this uncertainty is over the slow flowing area of the ice cap, where the uncertainty of the method is about as large as the derived signal. The maximum uncertainty of the two maps in Figure 27 is 17 m/yr, and is in the

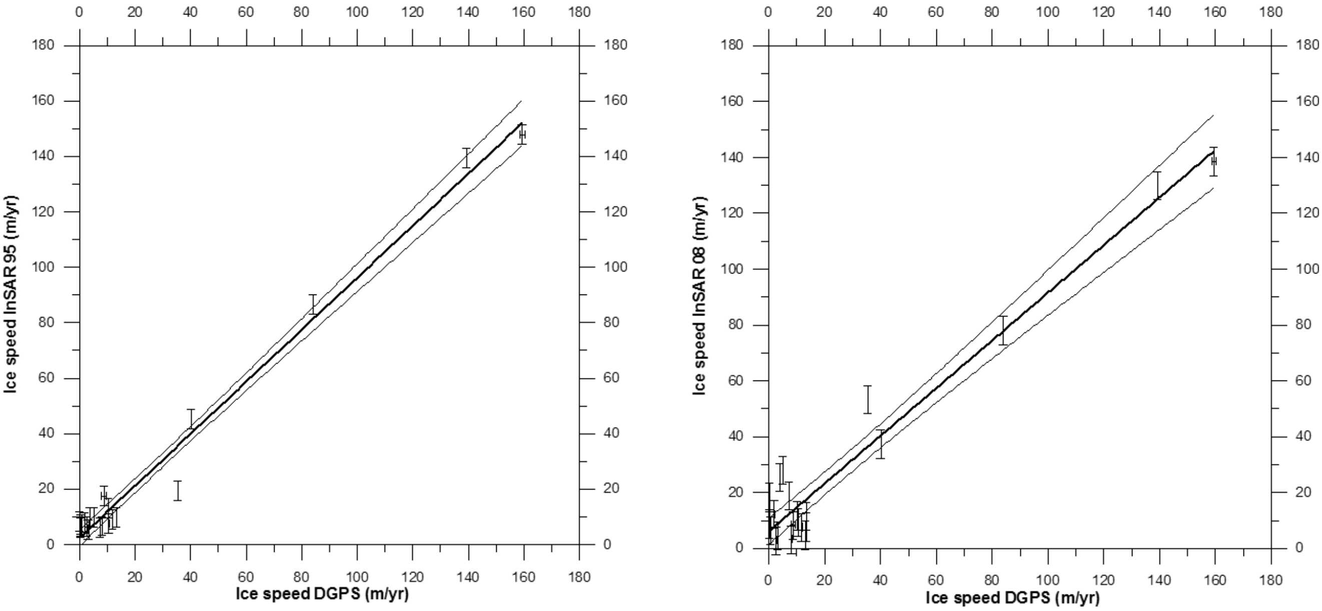

Figure 28. Comparison of InSAR and geodetical (DGPS) ice speeds. a) shows InSAR 1995/96 and b) InSAR (2008). Note that the InSAR uncertainty is more than a magnitude larger than DGPS uncertainty in most cases. The linear regressions (inner lines) are r2 = 0.96 (a) and r2 = 0.89 (b). The outer lines show the 95 % confidence intervals.

range of the ice speed outside the outlet glaciers. It is striking that the misfit drastically decreases to a few percent in most of the basins of the fast flowing outlet glaciers. Figure 27b showing the absolute difference in uxy between the scenes gives a clearer picture of the change in ice speeds on the outlets.

We find the spatial distribution of ice speeds from the InSAR is in good agreement within the uncertainty limits with our geodetic measurements. We observe no clear indication of seasonal ice speed differences, but we find a speed-up of the outlet glacier Franklinbreen between the InSAR campaigns, and speculate the outlet is having a surge phase.

We conclude that our derived InSAR velocity fields compare well with the ground-truthing we have from geodetic measurements of ice speeds within the uncertainty limits. We also find that ice speeds are comparable, within the uncertainty and resolution, between our methods within our different periods of cover. The exception to this is Franklinbreen, where a pronounced speed-up during the last decade is detected. We generally observe no clear indication of seasonal ice speed differences, except for the speed-up of the outlet glacier Franklinbreen between the InSAR campaigns, and speculate the outlet is having a surge phase. We further suggest that the balance and/or elevation change of Vestfonna may be more controlled by the outlet glaciers dynamics than Austfonna due to Vestonna's larger outlet glacier/ice cap area ratio.

Changes of glacial front positions of Vestfonna

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Glaciers in Svalbard have shown considerable mass loss in recent years with a reported acceleration in the western and southern parts of the archipelago. However, for the ice cap Vestfonna, in northeastern Svalbard, climatic mass balance modelling has suggested almost balanced conditions over a period of nine years (2000–2009). A slightly positive geodetic mass balance (1990–2005) has been reported from a comparison of laser altimetry to older DEMs. A heterogeneous situation has been depicted for the various catchments, and hence changes in glacier extent can reveal additional information of glacier status, in particular when dealing with surge-type glaciers. We analysed a 34-year data record of multi-spectral satellite imagery in order to study changes in glacier frontal positions of the ice cap Vestfonna. A consistent pattern of almost steady retreat of the southern and northeastern outlet glaciers of the ice cap is observed (Figure 29)

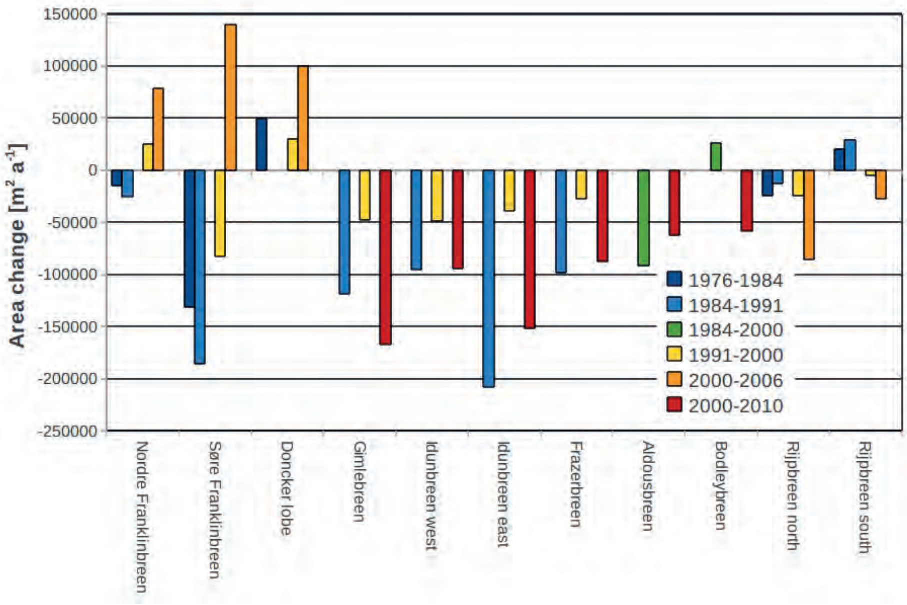

Figure 29. Rate of change at the glacier front for the different time periods according to satellite image availability.

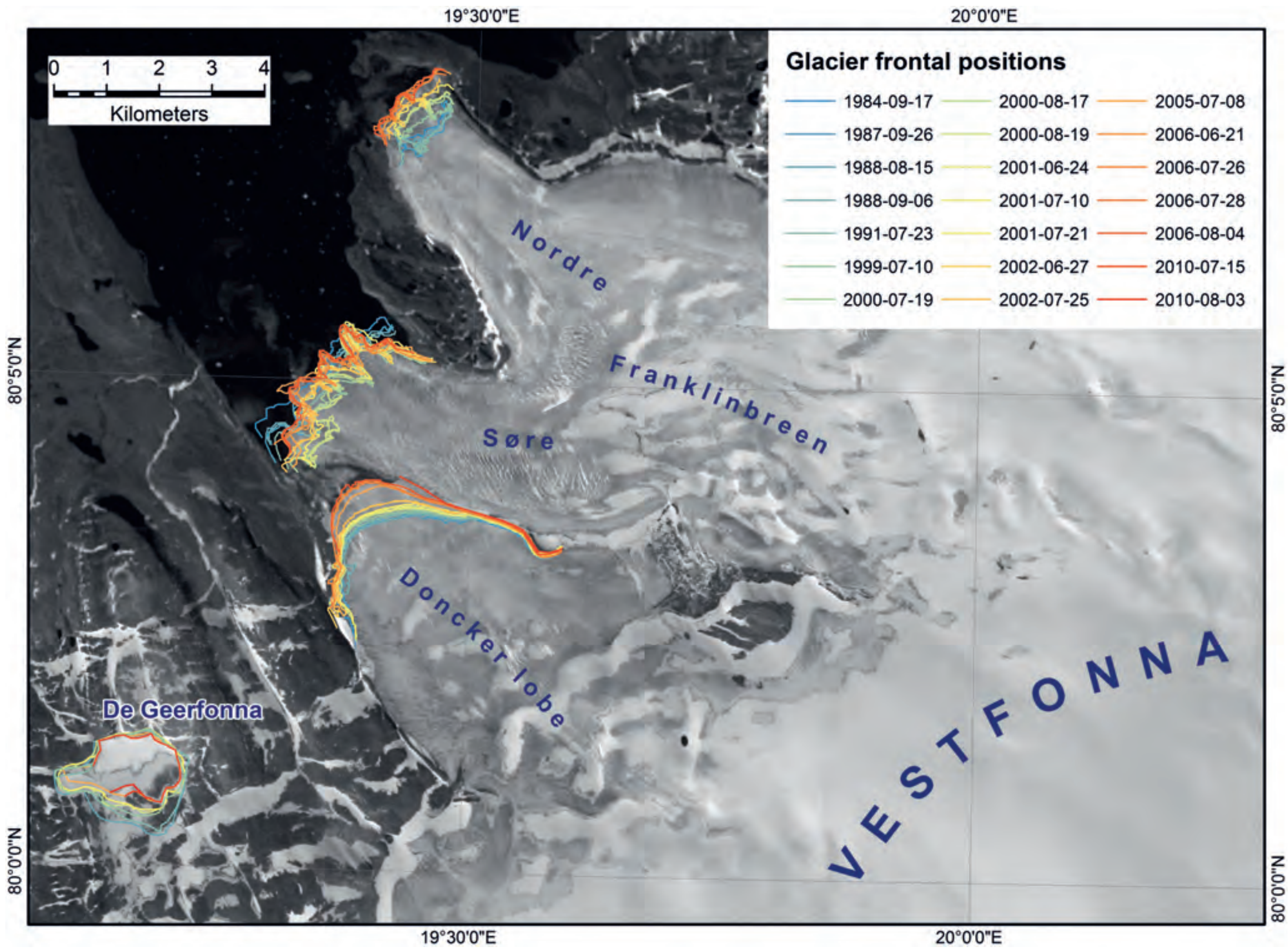

Figure 30. Changes of glacier frontal positions of Søre and Nordre Franklinbreen between 1984 and 2010. The background image is composed of two ASTER scenes from 15 July 2010 and 3 August 2010 as well as a LANDSAT scene from 26 July 2006 (© USGS/NASA, 2006/2010).

while Franklinbreen, the only major outlet glacier draining towards the north-west shows re-advance (Figure 30). This is consistent with an observed speed up and potential upcoming surge of this outlet. The glacier retreat on the southern coast also agrees with ICESat elevation change measurements. However, due to the glacier response time no direct relations between frontal retreat and surface mass balance can be drawn from the short observation period. The heterogeneous pattern of changes with on-going dynamic adjustments in some areas make the ice cap Vestfonna an ideal test site for future monitoring activities including novel techniques like differential interferometry from bi-static SAR systems.

Destabilisation of an Arctic ice cap triggered by a hydro-thermodynamic feedback to summer-melt

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Mass loss from glaciers and ice sheets currently accounts for two-thirds of the observed global sea-level rise and has accelerated since the 1990s, coincident with strong atmospheric warming in the Polar Regions. Continuous GPS measurements (Figure 31) and satellite synthetic aperture radar (Figure 32) were used to derive velocity maps from Basin-3, the largest drainage basin of the Austfonna ice cap, Svalbard. The observations demonstrate strong links between surface-melt and multiannual ice-flow acceleration. We identify a hydro-thermodynamic feedback that successively mobilizes stagnant ice regions, initially frozen to their bed, thereby facilitating fast basal motion over an expanding area (Figure 33). By autumn 2012, successive destabilization of the marine terminus escalated in a surge of Basin-3. The resulting iceberg discharge of 4.2±1-6 Gt/a over the period April 2012 to May 2013 triples the calving loss from the entire ice cap. Accounting for the seawater displacement by the terminus advance, the related sea-level rise contribution amounts 7.2±2.6 Gt/a. This rate matches the annual ice-mass loss from the entire Svalbard archipelago over the period 2003–2008, highlighting the importance of dynamic mass loss for glacier-mass balance and sea-level rise. The active role of external forcing contrasts previous views of glacier surges as purely controlled by internal mechanisms. Given sustained climatic warming and rising significance of surface melt, we hypothesize that the proposed hydro-thermodynamic feedback has implications for the future stability of ice-sheet regions, namely at presence of a cold-based marginal ice plug that currently prohibits fast drainage of inland ice. The possibility of large-scale dynamic instabilities such as the partial disintegration of ice sheets is acknowledged but not quantified in global projections of sea-level rise.

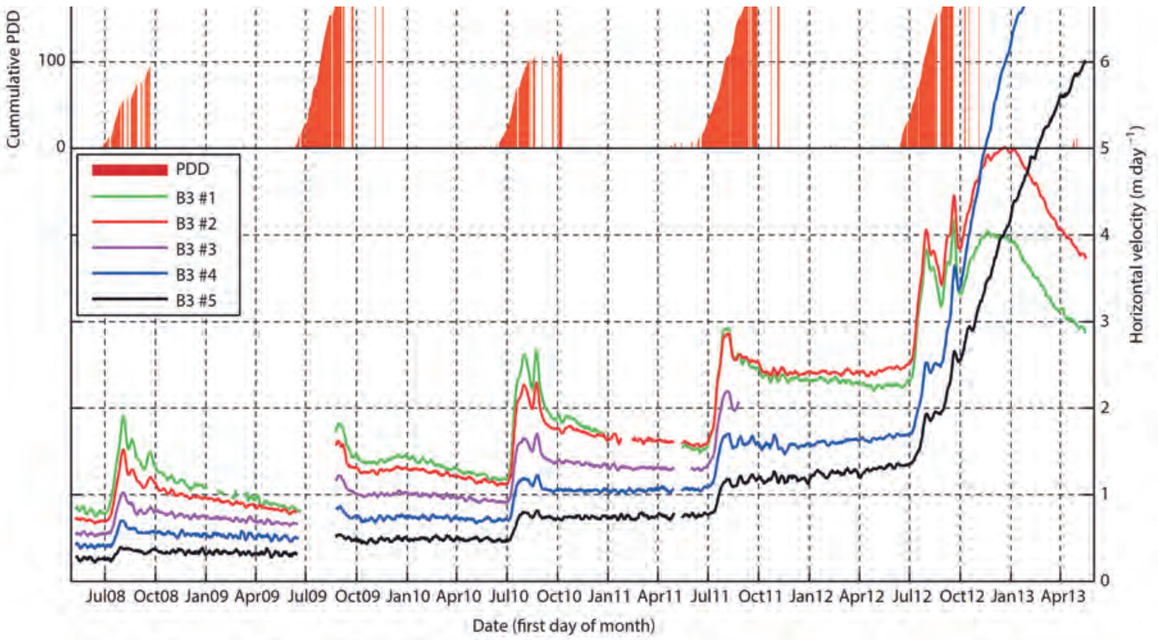

Figure 31. Flow velocities along the centreline of the fast-flow region of Basin-3, Austfonna, between May 2008 and May 2013. GPS stations are numbered from 1 at lowest to 5 at highest elevation. Red bars (upper panel) indicate potential melt days and cumulative positive degree days (PDD) for each summer, inferred from the temperature record of an automatic weather station.

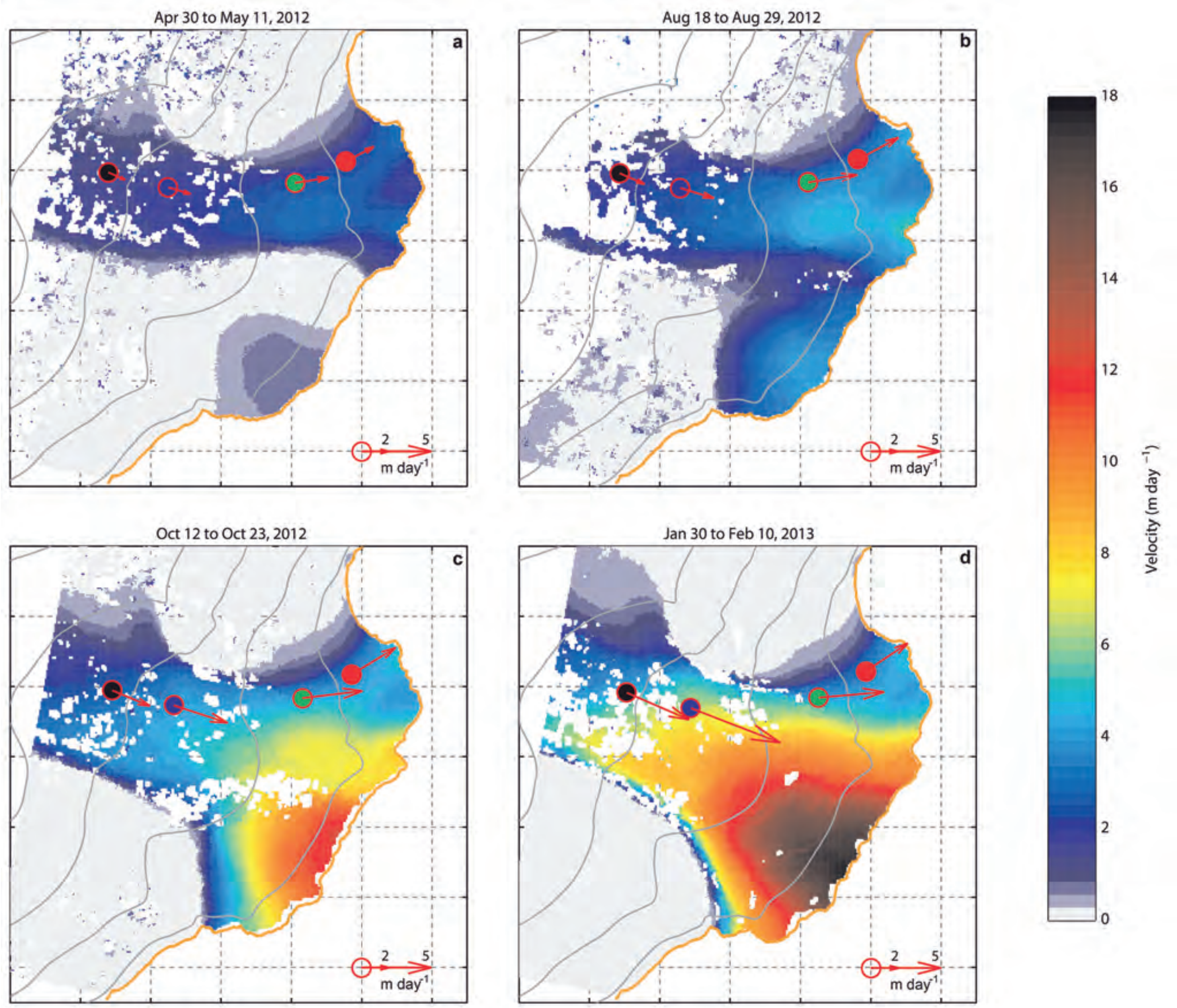

Figure 32. Surface velocity fields of Basin-3, Austfonna, derived from TerraSAR-X feature tracking; (a) April/May 2012; (b) August; (c) October; and (d) January/February 2013. Red circles represent mean position of GPS receivers over the particular repeat-pass period, fillcolor according to color-coding of receivers in Figure 31. The red arrows indicate associated GPS velocity vectors. Glacier elevation contours plotted in grey at 100m intervals, front position at time of repeat pass in orange.

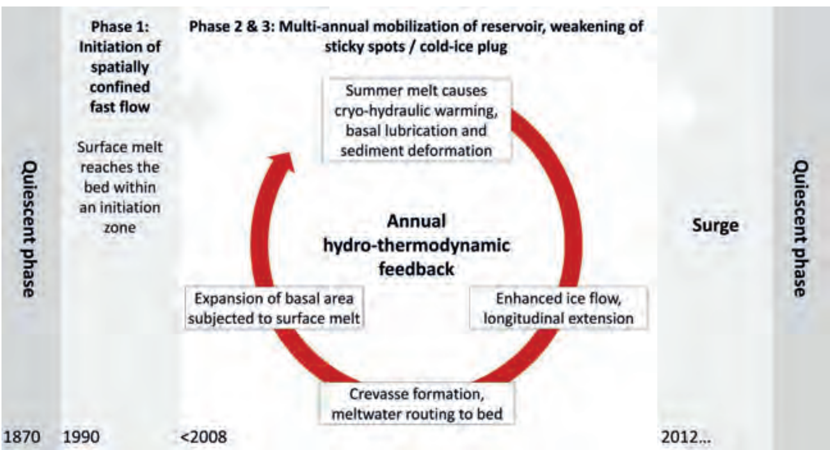

Figure 33. Schematic illustration of the proposed hydro-thermodynamic feedback to summer melt, imbedded within the surge cycle of Basin-3, Austfonna. The approximate start of each phase is indicated at the bottom. Phase 1 follows from long-term changes in glacier geometry, i.e. built-up of a reservoir, and associated changes in driving stress and basal thermal regime. The hydro-thermodynamic feedback loop operates over several years during phase 2 and 3, each loop coinciding with consecutive summer melt periods. Successive mobilization and destabilization initiates the surge. Dynamic thinning, reductions in driving stress and basal heat dissipation eventually terminates the surge.

Conclusions

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Understanding the dynamics of glaciers and ice sheets is a highly active frontier of science in which the diverse Arctic and North-Atlantic region plays a significant role due to the combination of accessibility, national priorities and global impact of the changes occurring. This report testifies to both the challenges and the progress faced by the scientists in assessing the stability and variations of land ice. In Greenland, our increasing ability to observe the accelerating mass loss using satellite remote sensing is challenging us to strengthen our ground- and ocean-based observation programmes in order to better understand the physical mechanisms and thus qualify our modelling of future sea level change. Such insight may come from glaciological campaigns and technical development carried out elsewhere, as is nicely illustrated with the case of the new Image GeoRectification And Feature Tracking toolbox (ImGRAFT) developed from work done at Engabreen, Norway, and subsequently applied to document the continued acceleration of major outlet glaciers from the Greenland Ice Sheet. A second example is the pioneering work done on Nordenskiöldbreen in Svalbard to observe and interpret ice velocities using in situ GPS, later applied to a number of outlet glaciers from the Greenland Ice Sheet to quantify seasonal variability of their velocities. The continued work with combining the GPS observations with satellite-derived velocity maps, this time applied to Austfonna, the largest ice cap on Svalbard, also led to a deeper understanding of glacier surge dynamics as being highly influenced by climate change through a hydro-thermodynamic feedback. In a parallel effort, the same methodology provided the first reliable characterization of ice velocities of Vestfonna, another large ice cap in Svalbard. Glaciers and ice caps in Iceland often provide an attractive combination of accessibility and extreme events, allowing scientists to study processes that may be more rare, yet important, elsewhere, such as sudden violent outbursts of subglacially stored meltwater known as jökullhlaups. In this way, Icelandic ice caps constitute a full size natural glaciological laboratory for testing methods, equipment and hypotheses. The above examples testify to the added value of Nordic collaboration by the demonstrated rapid transfer of methods and knowledge across the region.

Dynamic changes in ice flow have an important and often dominating impact on the mass balance of glaciers and ice sheets terminating in the ocean, as illustrated in particular by Austfonna on Svalbard and the Greenland ice sheet. As remarked by Howat and Eddy (2011) the retreat of the Greenland ice sheet over the last decade is the most widespread over the past half-century. The current synchronous retreat began in 1992 following a slow and relatively limited advance in 1985-1992 which occurred at the end of a 60 year cooling period, suggesting an asymmetric response to external forcing consistent with the contrasting mechanisms controlling advance and retreat (Howat and Eddy, 2011). Moon et al. (2012) examined the evolution of Greenland outlet glacier velocities over the period 2000-2010 and found a steady acceleration in the northwest, more variability in the southeast and relatively steady flow elsewhere with interregional variability showing a complex response to regional and local forcing. In a later study, Moon et al. (2014) classified the marine-terminating outlet glaciers in three types with distinct seasonal velocity modes, of which one was dominated by seasonal terminus retreat and the other two displaying different sensitivities to the interplay between water availability and subglacial conditions. Moon et al. (2014) pointed towards the need for more high temporal resolution glacier velocity time series, both ice-sheet wide and in-situ observations as shown in Ahlstrøm et al. (2013) to better characterize the response of the marine-terminating outlet glaciers to external forcing. Additionally, we need more subsurface ocean measurements near the outlet glaciers to improve our understanding of the ice-ocean interaction as well as more detailed fjord bathymetry and bedrock topography beneath the ice. This identified gap in out knowledge applies equally to all ice masses terminating in the ocean across the Arctic and North-Atlantic region.

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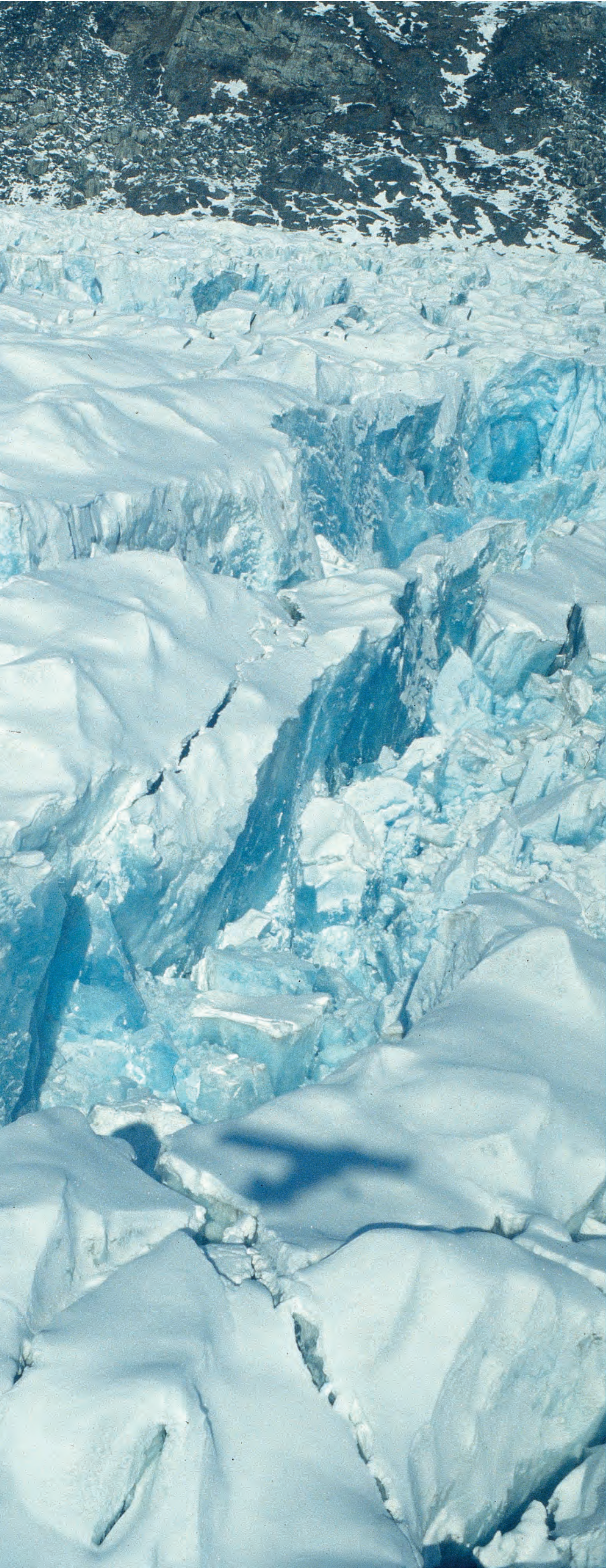

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