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Brief Communication: 2014 velocity and flux for five major Greenland outlet glaciers using ImGRAFT and Landsat-8

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Abstract

This study presents average velocity fields, mass flux estimates and central flowline profiles for five major Greenland outlet glaciers; Jakobshavn Isbræ, Nioghalvfjerdsbræ, Kangerdlugssuaq, Helheim and Petermann glaciers, spanning the period (August) 2013–(September) 2014. The results are produced by the feature tracking toolbox, ImGRAFT using Landsat-8, panchromatic data. The resulting velocity fields agree with the findings of existing studies. Furthermore, our results show an unprecedented speed of over 50 m day^{-1} at Jakobshavn Isbræ as it continues to retreat. All the processed data will be freely available for download at http://imgraft.glaciology.net.

1 Introduction

The Greenland Ice Sheet is currently losing mass at an accelerating rate (Rignot et al., 2011), and a significant part of this mass loss can be attributed to increased surface velocities leading to increasing discharge from outlet glaciers. The changes in ice flow velocity have been observed by satellite for the past two decades and display large spatial and temporal variations especially for marine-terminating glaciers (Moon et al., 2012). The processes controlling the variations are not completely understood, but are probably a combination of a warming atmosphere leading to increased surface melt (Andersen et al., 2010), increasing submarine melt rates (e.g. Holland et al., 2008), and changes in conditions at the terminus triggering thinning and acceleration (Nick et al., 2009).

About 20 % (by area Bevan et al., 2012) of the ice-sheet is drained by five glaciers (cf. map Fig. 1); Jakobshavn Isbræ, Nioghalvfjerdsbræ (also referred to as 79 North Glacier), Kangerdlugssuaq, Helheim and Petermann glaciers. Jakobshavn Isbræ has exhibited increasing acceleration and thinning in recent years (Joughin et al., 2012, 2014), leading to a contribution to global sea level rise of 1 mm during 2000–2011 (Howat et al., 2011). Smaller fluctuations in surface velocity have been observed since the 1990s showing seasonal variations with speedup in summer and slowdown in winter (Joughin et al., 2012). In contrast both Helheim and Kangerdlugssuaq were relatively stable until dramatic speedups occurred in 2002 (Helheim) and 2004 (Kangerdlugssuaq) followed by recent deceleration and apparent stability (Bevan et al., 2012). For Helheim the associated mass loss was off-set by an increase accumulation, while for Kangerdlugssuaq the lost mass corresponds to seven years of surface mass balance (Howat et al., 2011). On the other hand, the northern glaciers in this study appear to be influenced by different climatic conditions. Petermann experienced a large calving event in 2010 but in spite of this the ice-flow speeds have remained relatively stable or only slightly increasing (Bevan et al., 2012). Until recently Nioghalvfjerdsbræ exhibited the same stability with few variations in surface velocity (Bevan et al., 2012) or margin position (Joughin et al., 2010b). However, a recent study has shown that thinning and speedup are now also taking place in northeast Greenland (Khan et al., 2014). In short, there is an increasing need to continuously monitor the velocity of outlet glaciers on varying temporal scales if we are to predict their future contribution to global sea level rise.

In this study we use the newly developed ImGRAFT toolbox (Messerli and Grinsted, 2014) to retrieve surface velocities of Jakobshavn Isbræ, Kangerdlugssuaq, Helheim, Petermann, and Nioghalvfjerdsbræ. ImGRAFT is a feature tracking toolbox and is based on the Matlab programming suite (for more details see Messerli and Grinsted, 2014). We use LandSat 8 imagery from 2013 and 2014 to calculate surface velocities during the year from August 2013 to September 2014. Our results further demonstrate the capability of ImGRAFT to produce velocity maps over a variety of glaciers moving at different speeds. The fact that ImGRAFT is easy to use and freely available from the ImGRAFT website makes it suitable for other studies in need of updated surface velocity data on different temporal scales. The toolbox and the datasets presented here are available on the ImGRAFT website http://imgraft.glaciology.net.

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2 Data and method

This study explores the new Landsat 8 data acquired over Greenland since 2013. The highest resolution Landsat-8 band is used in this study; Panchromatic band-8, which has a surface resolution of 15 m.

The initial data selection criteria is based on the quality and coverage of the individual images. This stage of the processing is carried out through manual inspection of each individual scene. Cloud cover poses a challenge when working with optical imagery and can in some cases lead to data gaps if there are no suitable cloud-free images. Here, clouds in the scene are accepted as long as they do not directly obscure the region of interest. Whilst it is possible to use images with different viewing geometries, the resulting shift between the images needs to be corrected. We find that the best results are produced from images that have the same viewing geometry.

The velocity field is produced using feature tracking, whereby features such as crevasses and crevasse fields are tracked through time in sequences of image pairs. In order to track the features a minimum of two images is required. The first image is the template image where features are identified and second image is known as the search image. The search image is scanned, within a defined search window to find the best match of those features from the template image. In this study we apply the ImGRAFT toolbox by Messerli and Grinsted (2014). Although ImGRAFT was originally developed for terrestrial, oblique imagery this study demonstrates its versatility by adapting it to satellite imagery. ImGRAFT has a suit of algorithms in its toolbox, however, only the template matching algorithm is necessary here, because the satellite images are already available in GeoTIFF (Georeferenced Tagged Image File Format) format as a part of the L1T product from the USGS (United States Geological Survey) Earth Explorer database (http://earthexplorer.usgs.gov/).

In this study we experimented with an adapted template match algorithm at Jakobshavn Isbræ that incorporates a pre-guess location based on existing velocity data from the regions, for example SAR velocity data from the MEaSUREs project (Joughin et al., 2010a). The pre-guess helps to define the location of the search window. Not only does this speed up the feature tracking process but also it minimises the risk of mismatching features.

Once the feature tracking of all the images is complete the velocity fields are stacked to produce a mean velocity field. Only velocity fields with large spatial coverage are used to produce the mean velocity estimate and each velocity field is weighted according to the time period that it covers. If there is an overlap in time, the weighting is reduced for each overlapping period. The conservative error estimate for each displacement map is 2 pixels (30 m) or less. I.e. the error on any velocity field with a time interval greater than 15 days results in less than 2 m day^{-1} error in the velocity. This error is estimated by running the template matching algorithm on the bedrock flanking the glaciers and fjord. The velocity maps are then manually inspected for any detectable motion on the static rock features, as this provides an indication of the error in the displacement on the ice, due to the uncertainties in the georeferenced L1T products. In cases where there is a large displacement on static features, the scene pairs are discarded from the processing.

In addition to the velocity estimates and centreline flow profiles (hereafter referred to as flow profiles) we also produce mass flux estimates from ice flow through fixed flux gates (Fig. 1). We use thickness data for each of the five glaciers obtained from the CReSIS (Center for Remote Sensing of Ice Sheets) (https://data.cresis.ku.edu/data/grids/) website. The horizontal ice flow estimate used in the flux calculations is based on the mean velocity field calculated for each glacier, presented in Fig. 1. We assume a constant horizontal velocity with depth when estimating the flux, and define the flux gates as close as possible to the estimated grounding line. We estimate the grounding line position using a simple method outlined in Enderlin and Howat (2013), where we define the location as the point where the ice starts to float according to the CReSIS bed and ice thickness data. This method is used to estimate the grounding line location shown in Figs. 1 and 2, for Helheim and Kangerdlugssuaq. For Petermann and Nigoghalvfjerdsbræ, we use existing published grounding line locations (Rignot et al., 1997; Rignot and Steffen, 2008). Unfortunately due to the unprecedented retreat of Jakobshavn Isbræ, it is not possible to locate the grounding line with much certainty. We therefore estimate the position from Fig. 3 in Joughin et al. (2014) which shows the frontal seasonal evolution in relation to the bed topography. They also conclude that as of the end of 2013 that Jakobshavn Isbræ has retreated to a local topographic high, we interpret this as a possible grounding line location, especially as they stress that there is a very small floating tongue.

As discussed above, it is unavoidable to have gaps in the time-series of velocity fields and as a result the mean is influenced more by times where we have observations. This is partly compensated by weighting the mean, as explained above. However, to estimate the potential seasonal bias in the flux we adopt the following scheme: at all glaciers except one (Petermann) our observations composing the mean are primarily spring/summer (fast) velocities. Therefore we can make an estimate of the seasonal bias in the flux by filling missing time-periods with our minimum velocity data for each glacier. For Petermann where we mostly have winter (slow) velocities comprising the mean we fill the missing time-periods with our maximum velocity. We use this method because according to observations (Moon et al., 2014; Joughin et al., 2014) we most likely capture both the maximum and minimum flow speeds at all glaciers in the study. Once the data is filled we recompute the mean velocity field, and rerun the flux calculation. We report the seasonal bias as the difference between the original flux and this new estimate (Table 1). In all cases except one (Jakobshavn Isbræ) the bias small (Table 1). We attribute the notable flux bias at Jakobshavn Isbræ to the large (40 + %) range in seasonal velocities experienced at the glacier (Joughin et al., 2014; Moon et al., 2014), compared to the relatively low seasonality at the other glaciers in the study.

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3 Results and discussion

The velocity fields and flow profiles for the five glaciers are presented in Figs. 1 and 2 respectively. The velocities in the upper catchments for each glacier are very slow, on the order of a few metres per day. As a result longer time intervals between images generate the best results in these slow moving regions. These results give us confidence that ImGRAFT is able to track features over long (> 3 months) time spans, even over winter. The velocity fields presented are a weighted mean of individual velocity fields covering a long time frame from August 2013 (where possible) to September 2014. The velocity time periods are listed in the centreline flow profiles for each glacier in Fig. 2. A full list of all the images used in the study can be found in the Supplement.

The velocity fields and flow profiles display variations spatially and temporally. One interesting feature identified at Jakobshavn Isbræ and clearly visible in the flow profiles (Fig. 2), is the high range of speeds at the terminus compared to all other glaciers in the study. A range of 20 m day^{-1} 4 km upstream of the calving front is clearly visible between two velocity fields one and a half months apart. This rapid change in speed matches the observations of a recent study by Joughin et al. (2014). In our case the averaging periods were 21 and 16 days respectively, therefore no significant bias from a longer observational time interval is expected. For the latter period from 3–19 July at 4 km from the calving front the speed is 19 m day^{-1} above average, whereas the period 9 May–1 June is 2 m day^{-1} below the average at this distance. A recent study by Joughin et al. (2014) presents velocity fields from using TerraSAR-X data for years 2009 to 2013, documenting the rapid retreat of Jakobshavn Isbræ. The authors report the highest known recorded speed of any Greenlandic glacier, approximately 47 m day^{-1} in 2012, and suggest that the recent retreat of the grounding line into a deep (~ 1300 m) trough is the cause of these high velocities. Our data indicate yet a further speed up of Jakobshavn Isbræ in July 2014 with measured speeds peaking at 52 m day^{-1}. This was manually verified using a simple triangulation of selected features near the terminus, where the high speeds were measured.

Other glaciers investigated here do not exhibit the same range of speeds at the terminus as Jakobshavn Isbræ. Although Helheim and Kangerdlugssuaq glaciers both exhibit some variability at the calving front, neither consistently show such large ranges in speeds. It has been suggested this may be due to the ice mélange that is present for a large part of the year in the Sermilik fjord (Andresen et al., 2011) and Kangerdlugssuag fjord (Sundal et al., 2013). In the case of Petermann and Nioghalvfjerdsbræ the ranges are even smaller, this is most likely a result of the buttressing effect from their ice shelves (Joughin et al., 2010b). All the glaciers presented in this study including Jakobshavn Isbræ (beyond 15 km upstream of the calving front) display only slight seasonal variations.

At Kangerdlugssuaq there is a sharp change in speed of 6 m day^{-1} over a short distance of only 1.5 km, 12 km upstream of the calving front. The start of this transition zone coincides directly with the narrowing of the outlet where the ice from the large catchment is forced into the fjord. This narrowing can be clearly seen on the velocity map in Fig. 1 and in the sharp transition in the flow profile in Fig. 2. Helheim exhibits a similar effect of funnelling ice into the narrow outlet, it is visible as a step change in speed (Fig. 2). This effect is most likely enhanced at Helheim due to the confluence of the two large tributaries merging at 10 km (Fig. 1) from the calving front as they flow into the outlet.

Both Petermann and Nioghalvfjerdsbræ exhibit similar characteristics. They are the widest two glaciers in the study (> 20 km wide) and both terminate in small ice shelves (Joughin et al., 2010b; Münchow et al., 2014). A noticeable observation at Petermann is the distinct separation between the main trunk and the northern marginal slower flow which has been described in Münchow et al. (2014). The large tributary that flows into the main glacier forms a slower flowing part of the glacier tongue. Petermann and Nioghalvfjerdsbræ display highest speeds not at the terminus but at approximately 45 and 70 km from the calving front respectively. The peak in velocity in both cases coin-

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cides well with the location of the grounding line where the ice is no longer supported by the bed (Morlighem et al., 2014; Münchow et al., 2014). These glaciers are grounded in troughs that lie below sea level, suggesting that the outlets could increase their flux significantly in a future warming climate (Morlighem et al., 2014).

The flux estimates are presented in Table 1. Throughout, our flux estimates are in accordance with existing estimates, slight discrepancies are ascribed to slight differences in the time frame of data used, method and associated errors, as well as other individual factors such as the exact location of the flux gate. The current flux at the grounding line for Jakobshavn Isbræ is estimated to be approximately 30 $km^3 yr^{-1}$. This matches well with existing estimates by Howat et al. (2011), although Joughin et al. (2014) suggest that a tenfold increase in this estimate in the future is plausible. Helheim and Kangerdlugssuaq experienced their highest recorded fluxes in 2006 and 2005, respectively (Howat et al., 2011). Since then the flux has decreased which is also mirrored in the decline in speed near the terminus of both glaciers (Bevan et al., 2012). It took Helheim less than two years to return to pre-speed up flux (Howat et al., 2011; Bevan et al., 2012), and our results also support that ice flux values have returned to that of pre-speed up estimates. In contrast it has taken Kangerdlugssuaq nearly a decade to return to pre-speed up flux following the speed-up event, but we now find similar flux values to pre-speed up estimates. Although the range in flux was slightly higher at Kangerdlugssuaq compared to Helheim the variations were on the same order of magnitude, thus highlighting the different response times of each glacier. The flux estimates for both Petermann and Nioghalvfjerdsbræ match existing results from studies by Münchow et al. (2014) and Rignot et al. (2001). It is conceivable that the ice fluxes for Petermann and Nioghalvfjerdsbræ are likely to increase if thinning continues, allowing the grounding line to retreat in land. This is also a likely scenario for Jakobshavn Isbræ which lies in a deep trough 1300 m below sea level (Joughin et al., 2014).

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4 Conclusions

This study provides the latest 2014 velocity maps and flux estimates for five major Greenland outlet glaciers, and presents the first extensive results using the ImGRAFT feature tracking toolbox on satellite imagery. Our results match those of previous studies covering similar time-frames, locations and scales. A significant finding of this study is that Jakobshavn Isbræ shows little sign of slowing down, with speeds exceeding 50 m day^{-1} registered during July 2014, further increasing the previous upper limit recorded in 2012 (Joughin et al., 2014). Both Helheim and Kangerdlugssuaq have now returned to pre-speed up ice fluxes, following a peak in ice flux in 2006 and 2005 respectively. In the north we note little variability in speeds at Petermann and Nigohalvfjerdsbræ, however these two glaciers are also currently supported at their terminus by small ice shelves. Recent studies that have resolved the bed topography in detail have exposed two deep and long troughs extending far into the interior of the ice sheet at both these glaciers (Morlighem et al., 2014). This highlights the need for close monitoring of these outlets as they harbour a large potential for future GrIS mass loss.

The Supplement related to this article is available online at doi:10.5194/tcd-8-6235-2014-supplement.

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Table 1. Flux estimates for each of the glaciers from the mean velocity fields (see Fig. 1 for flux gate location). A conservative estimate of the seasonal bias in the flux is listed in the "bias" column in the table. A positive/negative bias indicates an over/under estimation of the flux. The dominant source of error in the flux gate values arise from the uncertainty in the thickness profile along the gate which we estimate to be on the order of 15 %.The drainage area is in percent of the entire GrIS area based on Bevan et al. (2012) estimates.

Glacier Name	Flux Estimate ($km^3\,yr^{-1}$)	Bias ($km^3\,yr^{-1}$)	No. of days covered by obs.	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

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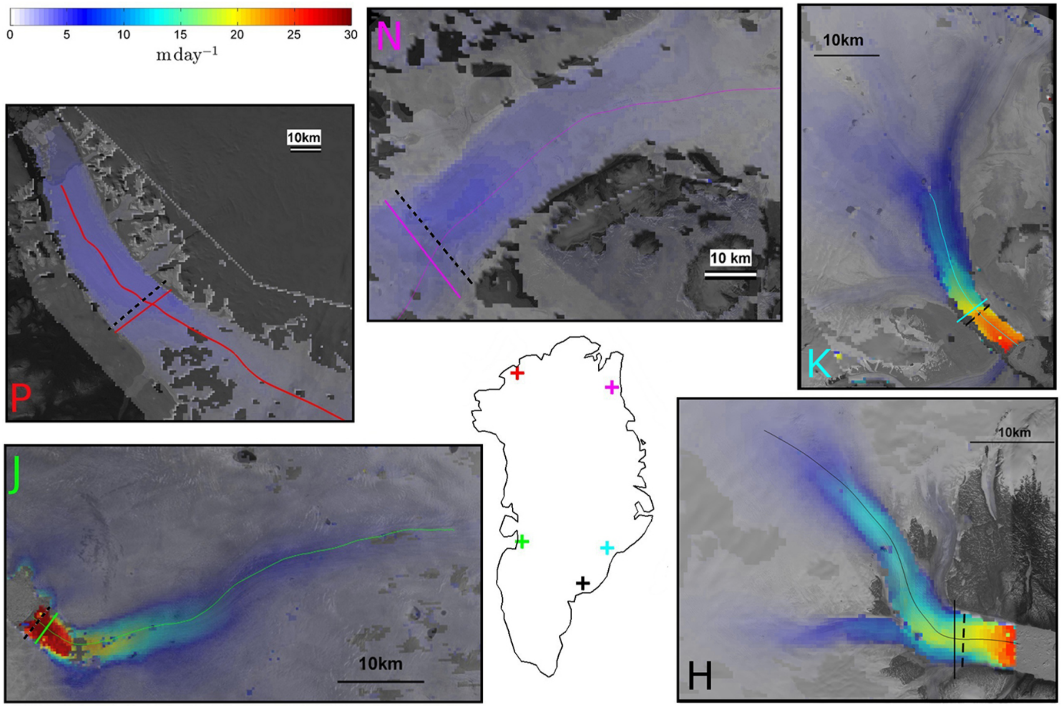

Figure 1. Mean velocity fields for each of the glaciers presented in this study: J = Jakobshavn Isbræ, P = Petermann, N = Nioghalvfjerdsbræ, K = Kangerdlugssuaq and H = Helheim. The dates of the individual velocity fields used to compose this average are listed in the supplementary material. The approximate grounding line location for each glacier is marked as a black dashed line on each velocity field.

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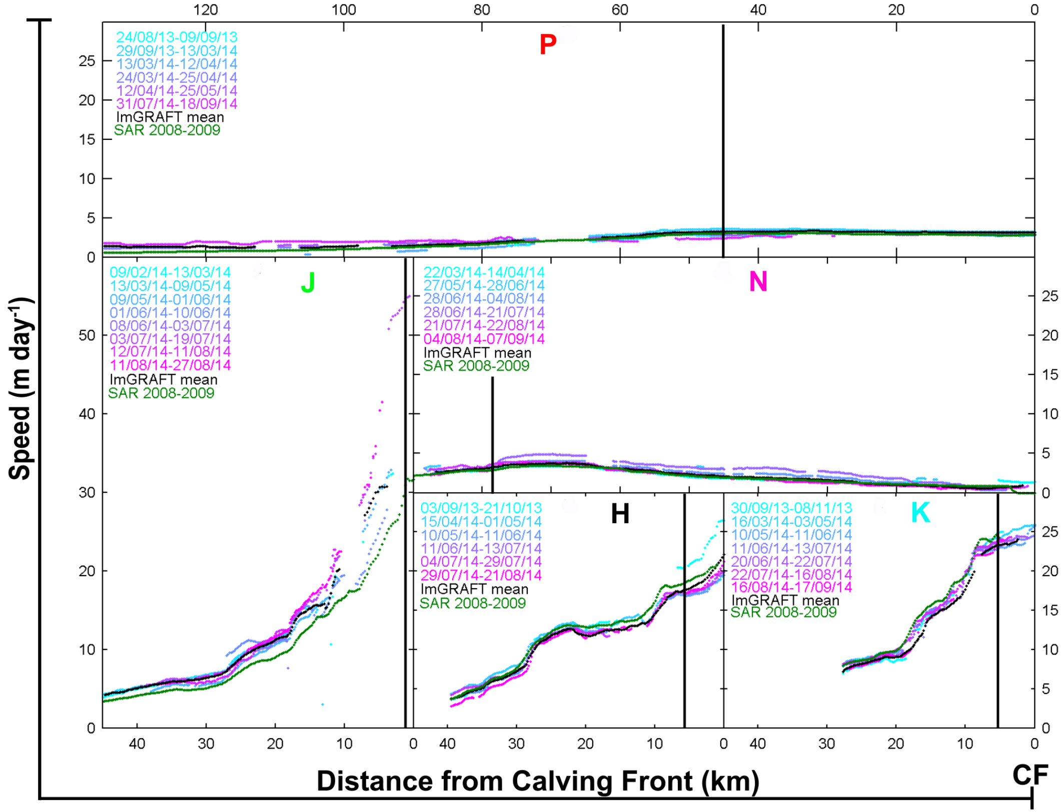

Figure 2. Centreline flowline profiles for each glacier for the range of dates listed. The ImGRAFT mean (black dots) is comprised of the velocity fields for the dates listed, however in the case of Jakobshavn, Kangerdlugssuaq and Helheim additional velocity fields are also used to estimate the mean. The SAR velocities for 2008–2009 (green dots) are from Joughin et al. (2010b). The black vertical bars represent each estimated grounding line location. Note the different y axis for Jakobshavn Isbræ.