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Glacier surface velocity mapping with Sentinel-2 imagery in Norway

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Summary: In this report, we summarize work carried out to map surface velocity of glaciers in mainland Norway from optical Sentinel-2 imagery over the period 2015-2018. All glaciers in mainland Norway were categorized based on the potential to extract surface velocity measurements using Sentinel-2 and feature tracking. In total, results were acquired over 91 glacier units, whereof 37 in northern Norway and 54 in southern Norway. This report also discusses advantages and challenges of using Sentinel-2 for mapping surface velocity of glaciers in mainland Norway.

Keywords: Glacier surface velocity, Sentinel-2, satellite imagery, feature tracking, glaciers, crevasses

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Copernicus Glacier Service Norway

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Preface

The project Copernicus Glacier Service ('Copernicus bretjeneste' in Norwegian) is a cooperation between the Norwegian Water Resources and Energy Directorate (NVE), the Norwegian Polar Institute and the Department of Geosciences, University of Oslo. The project is partly funded by the Norwegian Space Centre through the Copernicus programme of the European Space Agency (ESA). The project mainly focuses on using optical imagery from Sentinel-2, but also Landsat-8 and other sensors are considered.

This report is a summary of work carried out to map glacier surface velocity in mainland Norway from Sentinel-2 imagery in the period 2015-2018. The glacier velocity results are presented alongside with the advantages, limitations and challenges in the surface velocity mapping of glaciers in mainland Norway. Teodor Nagy has analysed the Sentinel imagery, acquired glacier surface velocity and written the report with contributions from Liss M. Andreassen. The glacier surface velocity dataset is available for downloading from NVE's website.

We would like to thank ESA for providing freely available Sentinel-2 imagery. We also want to thank Kartverket, the Norwegian mapping authority, for providing freely available high resolution orthophotos for mainland Norway via www.norgeibilder.no. Landsat 8 imagery was acquired via Earth Explorer tool built by USGS. Sentinel Hub Playground tool (https://apps.sentinel-hub.com/sentinel-playground/) was used for quick visualization of Sentinel-2 imagery.

Oslo, September 2019

Svein Taksdal
Director (acting)

Rune V. Engeset
Head of section

Sammendrag

I denne rapporten har vi brukt optiske bilder fra Sentinel-2 satellitten for å kartlegge brehastighet for perioden 2015-2018. Alle breer i Norge ble undersøkt og kategorisert basert på potensialet for å få hastighetsmålinger. Totalt ble resultater oppnådd for 91 breenheter, 37 i Nord-Norge og 54 i Sør-Norge. Denne rapporten beskriver metodikk for å beregne brehastighet fra Sentinel-2. Rapporten oppsummerer fordeler, utfordringer og begrensinger ved bruk slike bilder for å kartlegge brehastighet for norske breer.

Summary

In this report, we summarize work carried out to map glacier surface velocity in mainland Norway from Sentinel-2 imagery in the period 2015-2018. All glaciers in mainland Norway were categorized based on the potential to extract surface velocity measurements using Sentinel-2 images. In total, the velocity results were acquired over 91 glacier units, whereof 37 in northern Norway and 54 in southern Norway. This report also discusses the advantages, limitations and challenges when using Sentinel-2 imagery for mapping surface velocity of glaciers in mainland Norway.

Abbreviations

DEM Digital Elevation Model

et al. and others

ESA European Space Agency

GIS Geographical Information System

NVE Norges vassdrags- og energidirektorat (Norwegian Water Resources and Energy Directorate)

UAV Unmanned aerial vehicle

Abbreviations used in figures

L Landsat

S Sentinel

O/OR Orthophot

1 Introduction

1.1 Background

The velocity of glaciers is important for many aspects in glaciology. Quantifying glacier surface velocity on a larger spatial and temporal scale leads to a better understanding of dynamic response and mass balance evolution (Stocker-Waldhuber et al., 2019), glacier surging (e.g. Sund and Eiken, 2010), ice transport (e.g. Mouginot et al., 2019), and basal glacier conditions (e.g. Solgaard et al., 2018). Medium resolution optical satellite sensors such as Landsat-8 and Sentinel-2 have proved to be invaluable for observations of the cryosphere. The large amount of freely available optical imagery nowadays enables deriving glacier velocities at a higher spatial and temporal resolution than ever before. Glacier surface velocity extraction from optical imagery is well documented in multiple studies and has been determined for entire glacierized regions (e.g. Dehecq et al., 2015; Mouginot and Rignot, 2015), and for single glaciers (e.g. O'Neel et al., 2005; Redpath et al., 2013). Much attention to quantify glacier surface velocity has been focused on Greenland (e.g. Joughin et al., 2010; Joughin et al., 2014), Antarctica (e.g. Seehaus et al., 2018), the Himalayas (e.g. Dehecq et al., 2015), Svalbard (e.g. Strozzi et al., 2017), Alaska (e.g. Altena et al., 2019), and Patagonia (e.g. Muto et al., 2013).

Challenges in mapping surface velocities using optical imagery have been insufficient satellite sensor resolution, slow movement of glaciers, lack of trackable features, and cloud and snow cover. In particular, cloud cover has been identified as a major challenge in maritime regions, such as the west coast of Norway (Andreassen et al., 2008) and New Zealand (Mathieu et al., 2009). Increased ground resolution of the Sentinel-2 satellite missions together with a higher revisit rate makes it possible to also study smaller glaciers. Sentinel-2 imagery was used to derive surface velocity results for three larger outlet glaciers in Norway: Nigardsbreen, Engabreen, and Rembedalskåka (Klingenberg, 2017). Repeat aerial photography has been used for Engabreen (Jackson et al., 2005), and Nigardsbreen, Baklikbreen and Bergsetbreen (Wangensteen et al. 2006). Time-lapse cameras have also been used for Engabreen (Messerli and Grinsted, 2015). Prior to this, glacier surface velocity has primarily been quantified for individual glaciers in mainland Norway using field techniques and stake measurements, e.g. Storbreen (Liestøl, 1967), Hellstugubreen (Pytte, 1962) and Nigardsbreen (Østrem et al.,1976; Tønsberg, 2003).

Having a richer velocity dataset for mainland Norway from optical imagery can provide new insights into glacier dynamics. In particular, glacier surface velocity data for Jostedalsbreen, Vestre Svartisen and other large ice caps can be useful for modelling of future behaviour of the large ice caps in Europe.

1.2 Glaciers in Norway

Glaciers in mainland Norway (hereafter referred to as Norway) cover an area of 2692 ± 81km^2 and are divided into 3143 units (Andreassen et al., 2012) across southern Norway (1575 units) and northern Norway (1568 units) (Figure 1). The majority (ca. 73%) of the glacier units are smaller than 0.5km^2, though 110 glacier units that are larger than 5km^2 account for ca. 48% of the glacier area in Norway (Andreassen et al., 2012). Among these are the largest glaciers: Jostedalsbreen (474 km^2), Vestre Svartisen (219 km^2), and Søndre Folgefonna (164 km^2) (Andreassen et al., 2012). The largest glaciers have multiple glacier outlets, which tend to move fast enough for movement to be detectable in optical imagery. Many of the distinct glacier outlets in Norway are free of snow, or have minimal snow cover during parts of the melting season, enhancing the possibility to track glacier features, most often crevasses, but also large ogives, moraines and bands of debris cover. Smaller and less steep glaciers may offer little trackable features due to limited movement. The smallest glacier and ice patches may have stagnant ice with little or no movement.

1.3 Report aims

This report examines the suitability of using Sentinel-2 imagery for deriving glacier surface velocities in Norway and presents a glacier surface velocity product using Sentinel-2 imagery from the period 2015-2018. The report discusses advantages, challenges, and limitations of using Sentinel-2 optical imagery to map glacier surface velocity for Norway. The limitations of using Sentinel-2 imagery are discussed in detail with specific examples.

Figure 1: A map of Norway showing glacierized areas in blue. The black frames indicate subsets shown in Figure 13. Abbreviations: FOL: Folgefonna, JOS: Jostedalsbreen, SVA: Svartisen.

2 Data and methods

2.1 Satellite imagery and feature tracking

Glacier surface velocity can be acquired using a wide range of data sources. For the new glacier surface velocity product presented in this report, we used exclusively optical imagery from the Sentinel-2 missions. The Sentinel-2A satellite was launched into an orbit on 23/06/2015 (Paul et al., 2016) and was followed by the Sentinel-2B satellite on 07/03/2017, doubling the data availability (Castriotta and Knowelden, 2017). The combination of the Sentinel 2A-2B constellation yields an observation every five days at the equator and more frequently in higher latitudes, which makes the Sentinel 2A-2B constellation superior to other missions including Landsat 8 with longer revisit times (Li and Roy, 2017). Sentinel-2A and Sentinel-2B satellites currently provide the highest ground resolution (10m) of freely-available imagery. The Sentinel-2A and Sentinel-2B missions carry a multi spectral instrument (MSI), which provides 13 reflective wavelength bands; four 10m visible and near-infrared (NIR) bands, six 20m near-infrared and short-wave infrared (SWIR) bands, and three 60m bands (Zhang et al., 2018) (Figure 2). In comparison, the most recent Landsat mission, Landsat 8, carries an operational land imager (OLI) and thermal infrared sensor (TIRS) and has nine reflective wavelength bands designed for land use, with the highest panchromatic band ground pixel resolution being 15m (Loveland and Irons, 2016). Sentinel-2 10m ground resolution imagery provides enhanced detail of glacial features such as crevasses compared to Landsat 8 15m band (Figure 3). To derive surface velocities, presence of features such as crevasses is crucial. More features generally lead to higher likelihood of results as demonstrated in earlier studies (Klingenberg, 2017; Nagy et al., 2019).

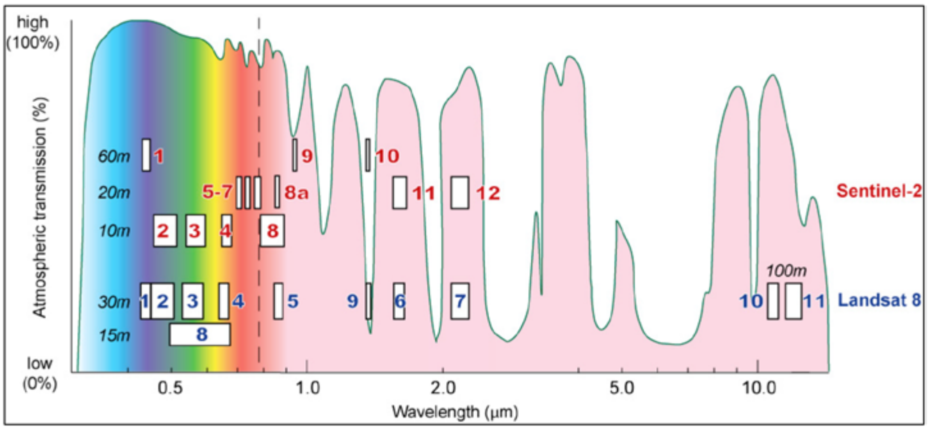

Figure 2: A graph showing wavelength and ground pixel resolution of all Sentinel-2 and Landsat 8 bands. Adapted from Kääb et al. (2016).

To acquire displacement information from the imagery, we used the Sentinel-2 Displacement Toolbox (SenDiT) (Nagy et al., 2019). SenDiT is a semi-automatic, open-source toolbox optimized for retrieval of displacement maps from Sentinel-2 bands with 10m ground resolution. SenDiT enables a quick generation of displacement maps in the user-defined spatiotemporal window. Most importantly, SenDiT combines data download, feature tracking, and output generation. The number of input parameters is kept to a minimum yet still allows for the full versatility of SenDiT. After installation of the toolbox, it only requires a text file input composed of 21 lines, specifying the spatial, temporal, cloud and feature tracking criteria. The toolbox uses the Image Correlation software (IMCORR) (Fahnestock et al., 1992) and its structure is described in detail by Nagy et al. (2019). The degree of flexibility of SenDiT is higher than offered by other services such as CPOM, GoLIVE, and MEASURE, which provide velocity maps for fixed spatiotemporal parameters. The automated processing and the quick turnaround is superior to other feature tracking tools such as ImGRAFT, CIAS, or COSI-Corr. However, results obtained with SenDiT still need to be checked and postprocessed using manual filtering.

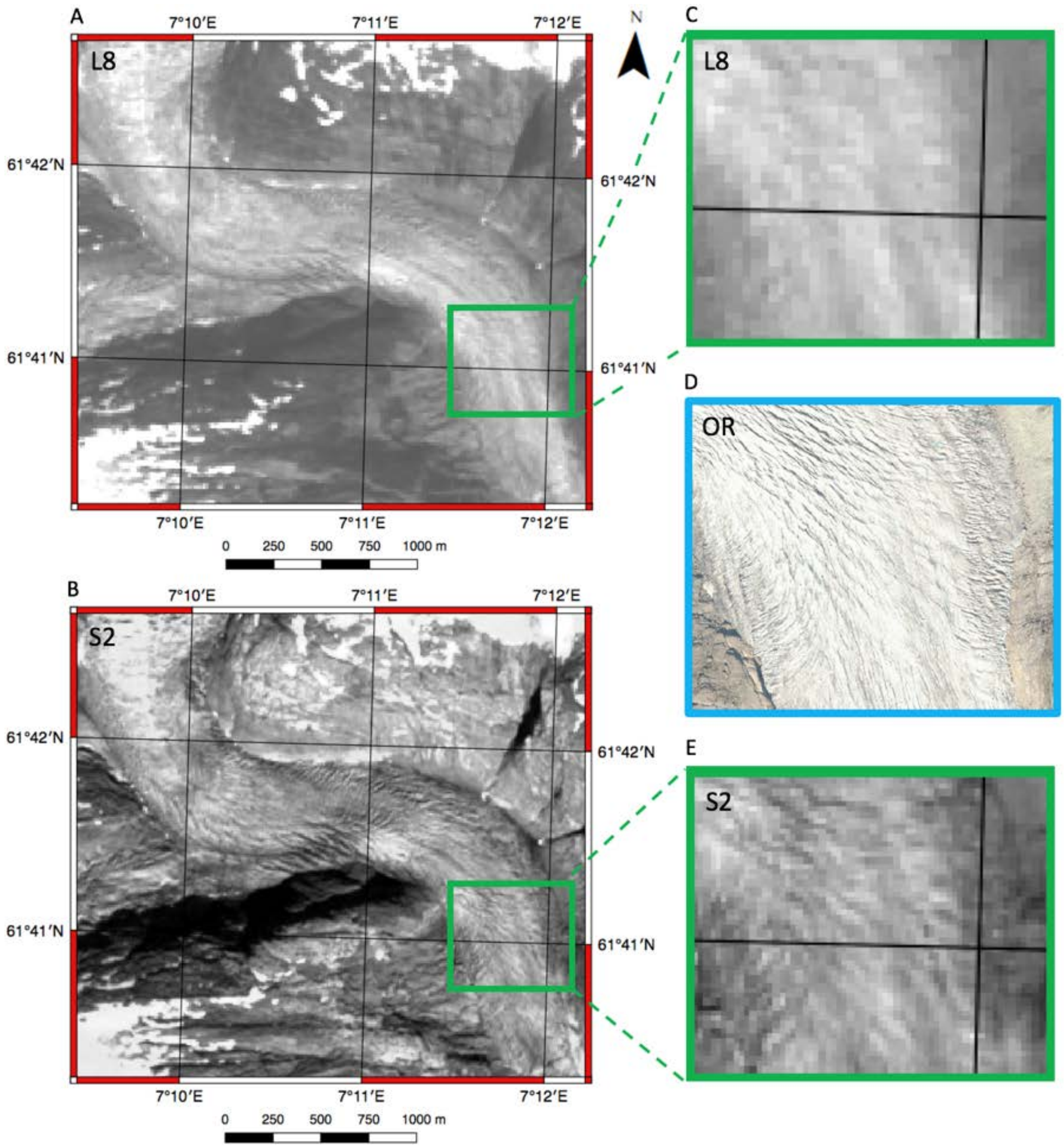

Figure 3: Adapted from Nagy et al. (2019). Comparison of Landsat 8 (L8) with Sentinel-2 (S2) and orthophoto (OR) of Nigardsbreen tongue and terminus using imagery acquired on 22/08/2017 (S2 and L8) and 26/08/2017 (OR). (A) L8 band 8 image of 15m ground resolution over the area of interest; (B) S2 band 8 image of 10m ground resolution over the area of interest; (C) Close-up of the image A displaying minimal signs of crevassing; (D) Close-up of orthophoto displaying heavy crevassing in the upstream and lateral sections at 0.25 m ground resolution; (E) Close-up of the image B displaying clear crevassing in the upstream and lateral parts.

2.2 Methods and data sources for glacier surface velocity mapping

There are several methods and data sources available for glacier surface velocity measurements (Table 1). In-situ mapping can be done with stakes, time-lapse cameras, or UAVs. Glacier velocity measurements are not a standard part of the mass balance program carried out by NVE, but are done routinely for Austdalsbreen terminus and occasionally on other glaciers using stake measurements (e.g. Kjøllmoen et al., 2018). Despite high accuracy, the main disadvantage of the stake measurements is a low spatial coverage and high costs associated with fieldwork. Time-lapse cameras and UAV orthophotos can also be used, but only for spatially limited areas. As already mentioned, Sentinel-2 imagery captures the glacier surface features in more detail than Landsat 8 (Figure 3). The Sentinel-2 revisit time at the same orbit of 5 days is superior to Landsat 8's 16 days. Denser image coverage increases chances of working with cloudless imagery and Sentinel-2 is therefore preferable to Landsat 8. High resolution acquisitions (<5m) from optical satellites such as SPOT 5 have previously been used (Altena and Kääb, 2017), but are costly. An alternative to optical imagery are radar acquisitions. Their advantage is independence of sun illumination and cloud cover as well as detectability of relatively slow flow (Schellenberger et al., 2016). However, decorrelation is often problematic for faster flowing glaciers with changeable surface features. InSAR (Interferometric synthetic aperture radar) and radar offset tracking mapping compliment the use of optical imagery (e.g. Wangensteen et al., 2005). Both InSAR and offset tracking of radar images have yielded results over some of glaciers in mainland Norway (Schellenberger and Kääb, 2017).

Table 1: Advantages and disadvantages of methods used for mapping of glacier surface velocity.

Mapping method	Advantages	Disadvantages
In-situ stake mapping	Very high accuracy. Monitoring of movement over very slow flowing glaciers.	Risk associated with movement/transport of personell on the glacier. Limited spatial and multi-temporal coverage potential. Laborious fieldwork, costs associated with fieldwork.
Time-lapse camera	Very high accuracy. Flexible temporal scale of observations.	Very limited spatial scale. Laborious fieldwork, costs associated with fieldwork. Time-consuming and expertise-requiring data processing.
UAV orthophotos	Very high accuracy. Temporal and spatial independency.	Low spatial and multi-temporal coverage potential. Laborious fieldwork. Time- consuming data processing. Costs associated with fieldwork, UAV purchase and maintenance.
Landsat 5, 7, 8 optical imagery	Large spatial coverage.	Quality depending on weather and snow/ice conditions. Coarser than Sentinel-2.

	Good multi-temporal coverage, freely and readily available data.	
Sentinel-2 optical imagery	Large spatial coverage. Improved multi-temporal coverage. Highest freely available imagery resolution. Freely and readily available data.	Quality depending on weather and snow/ice conditions.
High resolution optical imagery (<5m)	Flexible spatial coverage. Very good detectability of features.	High costs associated with purchase of imagery.
Radar imagery	Good performance in homogenous and stable areas. Good detectability of relatively slow velocity. Independent of sun illumination and cloud cover.	Easily decorrelated signal due to change in feature pattern, water content and fast flow of glaciers. Time-demanding post-processing and interpretation of results

2.3 Selection of satellite imagery

For the glacier surface velocity product generation, all Sentinel-2 images for the period June – October in 2015 to 2018 were visually reviewed to identify suitable images. All the 36 glacierized regions in Norway as defined by Andreassen et al. (2012) were inspected. To select images for feature tracking the following criteria were used:

1) Presence of trackable features
2) Time span of the image pair
3) Cloud cover

Presence of trackable features

The feature appearance is determined by the ground resolution of the satellite sensor (Figure 3). The features most often seen on glacier surfaces are crevasses and crevasse induced shadowing, ogives, lateral and medial moraines, reintroduced englacial debris, rockslides and boulders (Figure 4). Other types of features include ash layers, vegetation and manmade objects such as weather stations or large tents, but they are less common in mainland Norway. Applying feature tracking on snow covered parts of the glaciers is difficult due to lack of differences in intensity values. Therefore, we looked for snow free parts (ablation areas) to get trackable features. The relative orientation of features is also important as features such as medial and lateral moraines that are stretched in the flow direction of glaciers are often hard to track even with the best Sentinel-2 or Landsat 8 resolution, as features within the moraines are usually too fine to distinguish in the neighbouring pixel values. On the other hand, crevasses, ogives, debris layers or ash layers that are perpendicular to the flow of the glacier were found to offer potentially good tracking targets.

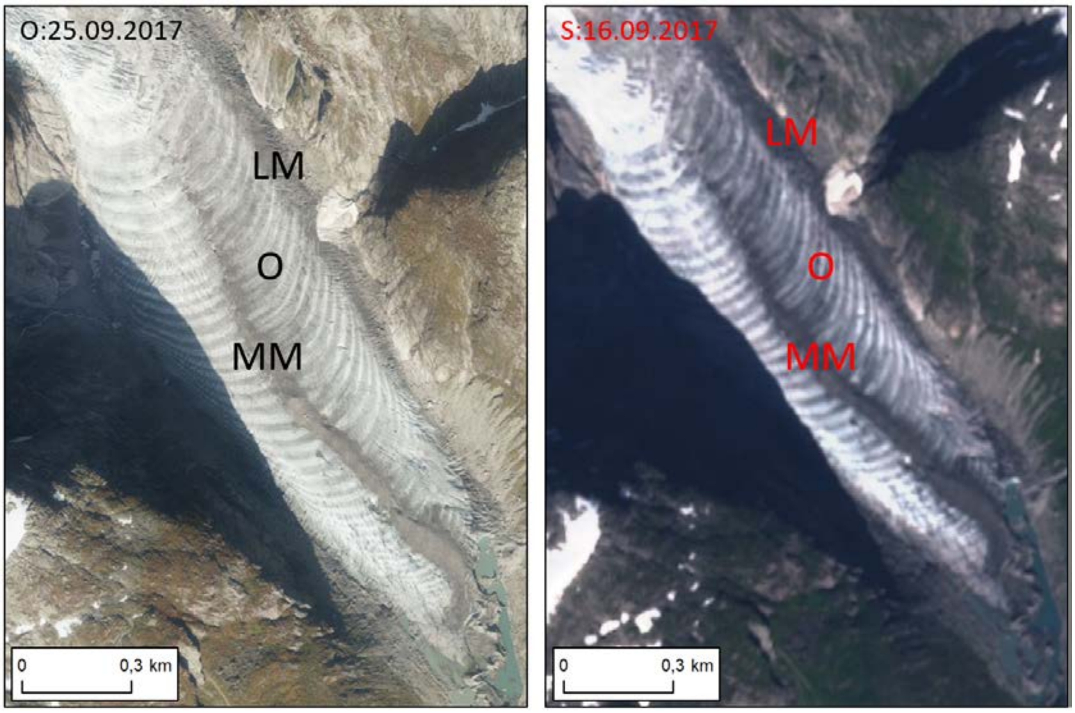

Figure 4: Illustration of visible surface features in orthophoto (left) and Sentinel-2 imagery (right) on Austerdalsbreen, outlet of Jostedalsbreen. LM: lateral moraine, MM: medial moraine, O: ogives.

Time span of the image pair

The day difference between the two paired images must be long enough to observe displacement, yet short enough for the features not to change and maintain similarity. Due to the varying nature of glacier surface velocity, a variable time span is used. The ideal time window was chosen after visually assessing the speed of the glacier. Large time spans may result in decorrelation of the features through change of pattern, change of extent, or complete disappearance due to snow. Commonly, selected time spans were on the order of weeks and months for fast moving glaciers and months to a year or two for slower moving glaciers. To compare the imagery and derive velocity on a yearly scale, it is ideal to use images from the similar periods of the year, as same features tend to become visible on the surface at certain time during the seasons. However, the time of appearance of a feature will vary due to interannual variations in summer melt and winter accumulation (Figure 5).

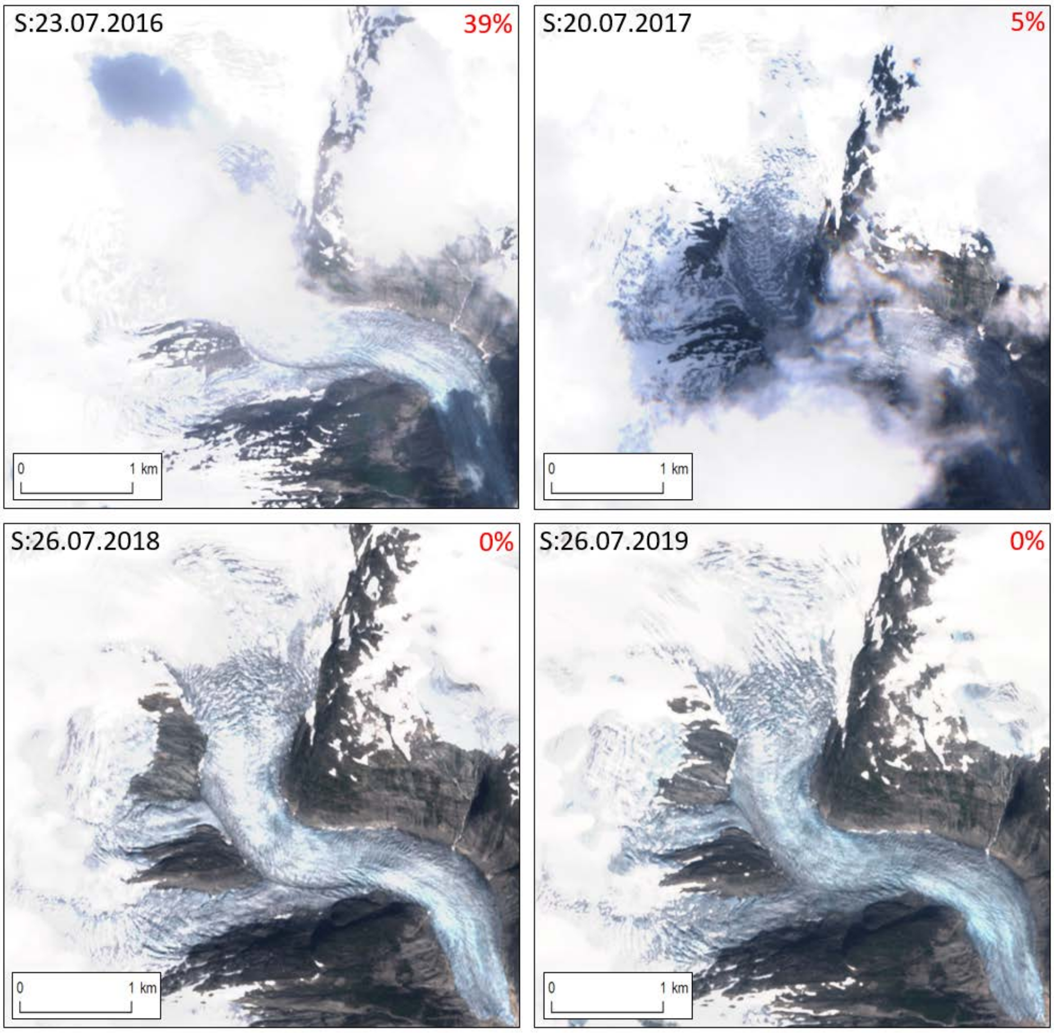

Figure 5: A comparison of feature visibility and snow cover on Nigardsbreen, outlet of Jostedalsbreen, using Sentinel-2 images from July in the period 2016-2019. Clouds cover part of the tongue on 20/07/2017. Note also cloud and cloud shadow on 23/07/2016. Overall cloud percentage of the scene given by ESA is in red.

Regardless of the time span of the image pair, many of the spatially small and/or flat glaciers move too slow for movement to be detected. An example of such a glacier is Gråsubreen, which has a long time series of mass balance observations (1962-). The in-situ positional measurements from 2015-2017 at 11 stakes indicate velocities of 0.4 – 4.2 m/year (< 2m/year for 8 of 11 stakes) (Kjøllmoen et al., 2018). The slow flow of the glacier ice also often correlates with the absence of large crevasses, which are the most commonly tracked features (Figure 6). No results were acquired for Gråsubreen as its flow is too slow to be detected in yearly or bi-annual pairs and no or few trackable features were present.

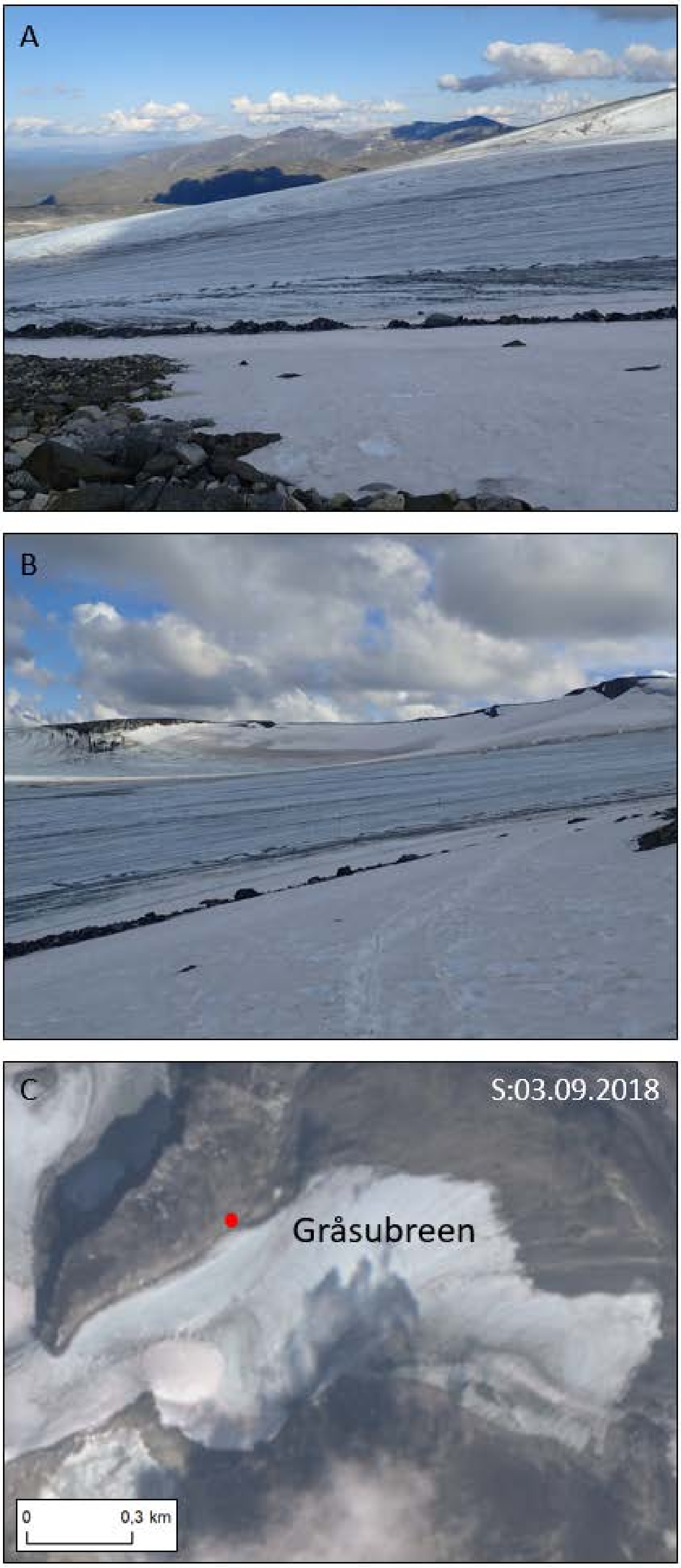

Figure 6: A and B: In-situ photos of Gråsubreen from 24/07/2019 displaying uniform nature of glacier ice with little crevassing. C: Sentinel-2 colour image of Gråsubreen from 03/09/2018 showing uniform nature of ice with a limited number of features. The red dot approximates the position, from which photos A and B were taken. Photos (AB): Liss M. Andreassen. Notice cloud shadow on the Sentinel imagery (C).

Cloud cover

Clouds over the glaciers is a problem when using optical imagery for glacier surface velocity mapping as optical sensors cannot collect surface reflectance through clouds. Manual selection is laborious but is often better than using strict cloud percentage thresholds to avoid omitting potentially good images that can have little or no cloud cover over the glaciers of interest, despite a high overall cloud percentage for the scene (calculated by ESA). The cloud cover over Nigardsbreen was more prominent in a 2017 acquisition with overall 5% cloud cover, than in a 2016 acquisition with 39% cloud cover (Figure 5). Therefore, we manually selected imagery to get as many suitable scenes as possible. Figure 7 shows that an image with a relatively high cloud cover percentage (48%) can contain regions with no or minimal cloud cover (in green). Nagy et al. (2019) showed that even an image with a cloud coverage percentage >75% can give results over parts of glaciers, such as over Tunsbergdalsbreen (Figure 8).

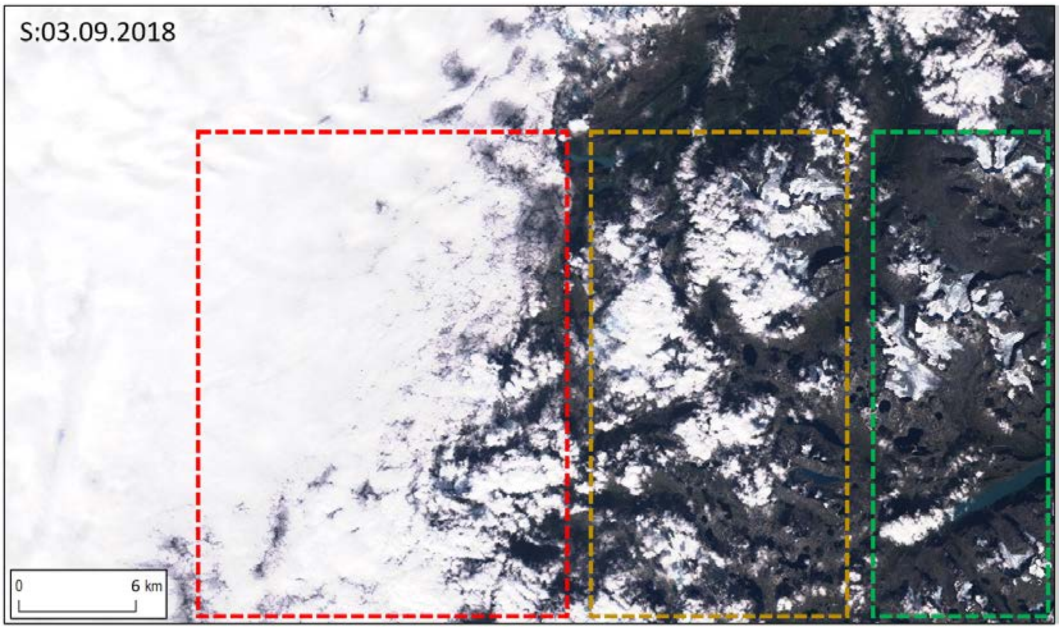

Figure 7: Illustration of varying cloud cover conditions within a single Sentinel-2 image with an overall cloud cover percentage of 48% over Jotunheimen region. Red box: All glaciers are affected by clouds. Orange box: Some glaciers are visible, others are covered in clouds. Green box: Glaciers are completely visible.

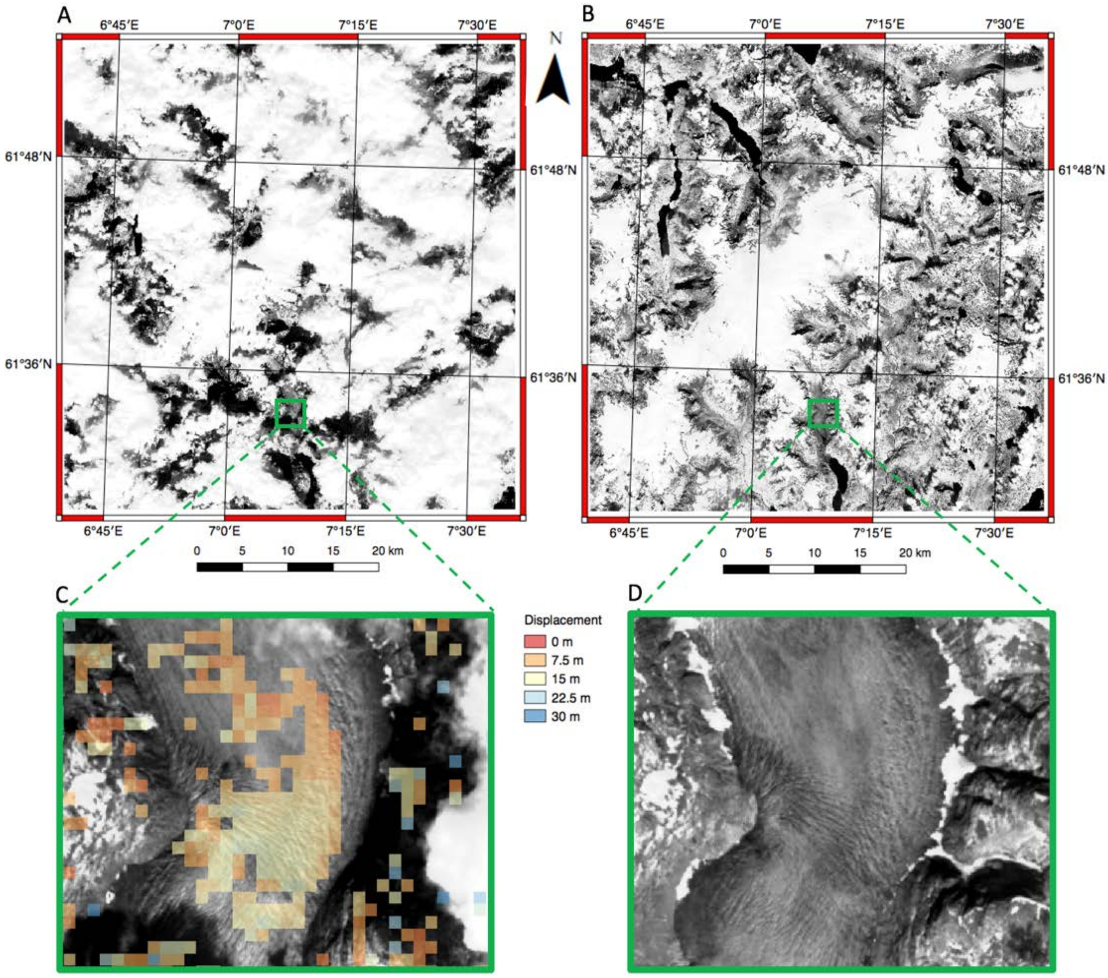

Figure 8: Adapted from Nagy et al. (2019). (A) Sentinel-2 image of Jostedalsbreen from 11/09/2016 with >75% cloud cover; (B) Sentinel-2 image of Jostedalsbreen from 23/07/2016 with minimal cloud cover; (C) Displacement map using pair 23/07/2016–11/09/2016 over a close-up image of a section of Tunsbergdalsbreen with less cloud coverage than overall scene of 11/09/2016; (D) Close-up image of a section of Tunsbergdalsbreen with minimal snow cover and no cloud cover.

2.4 Main errors in image matching

The two main errors in matching optical satellite imagery are the relative co-registration accuracy error and the orthorectification error. Errors in image matching can also be due to a satellite sensor malfunction such as the scan line corrector failure of Landsat 7 sensor in 2003. Some of the Sentinel-2A acquistions up to June 2016 are found to be affected by satellite platform vibrations induced by onboard dynamic components (jitter) (Kääb et al., 2016; Nagy et al., 2019). This resulted in a formation of bands of differential displacement within a few image pairs from over the stable ground areas. We avoided using imagery with the Sentinel-2 sensor malfunction for the glacier velocity product.

Orthorectification error

Orthorectification is the process of using a DEM to remove the image distortion caused by variations in topography. The quality of orthorectification depends mainly on the resolution and quality of the DEM. Sentinel-2 images used for the glacier velocity product were provided as orthorectified products. The images were orthorectified by ESA using the Planet DEM 90, and other non-specified DEMs for the areas outside the Shuttle Radar Topography Mission (SRTM) coverage (North of 60° latitude) (Kääb et al., 2016). The Planet DEM 90 is of 90m resolution, and it is mainly derived from SRTM DEM, which was acquired in February 2000 (Ressl et al., 2018). There are two errors that contribute to vertical offsets between the terrain and its approximation by a DEM: a) measurement or production errors where DEM elevation does not agree with terrain elevation at the time of acquisition of the elevation data; and b) changes in terrain elevation over time between elevation measurement and satellite scene acquisition (Kääb et al., 2016). To quantify glacier displacement over time, the latter error is the most prominent one, often encountered as glaciers can loose tens of meters of elevation between the DEM acquisition date and the satellite scene acquisition and orthorectification date. When co-registering two images from the same relative orbit, the DEM effects will get eliminated. Using imagery from two different relative (usually neighbouring) Sentinel-2 orbits may amount to an error of several tens of meters at the glacier termini (Kääb et al., 2016; Nagy et al., 2019). Therefore, we only used image pairs composed of imagery from the same relative orbit.

Relative co-registration accuracy

The relative co-registration accuracy of the two images in an image pair is the main source of error in the glacier velocity product. The error manifests itself as a relatively uniform and unidirectional shift, visible over the stable ground. The magnitude range of the co-registration error in the used image pairs was estimated from the stable area and used as the main error estimate for the given pair. Figure 9 illustrates a typical uniform nature of co-registration error over the stable area south of Nigardsbreen. The magnitude of displacement over the stable area in the selected subregions is in the range 2-6m and the direction is in the range 220-270°. Overall, we estimated a co-registration error to be most often in the range 2-8m for most image pairs, but we found a co-registration error reaching the magnitude of up to 12m for some of the pairs.

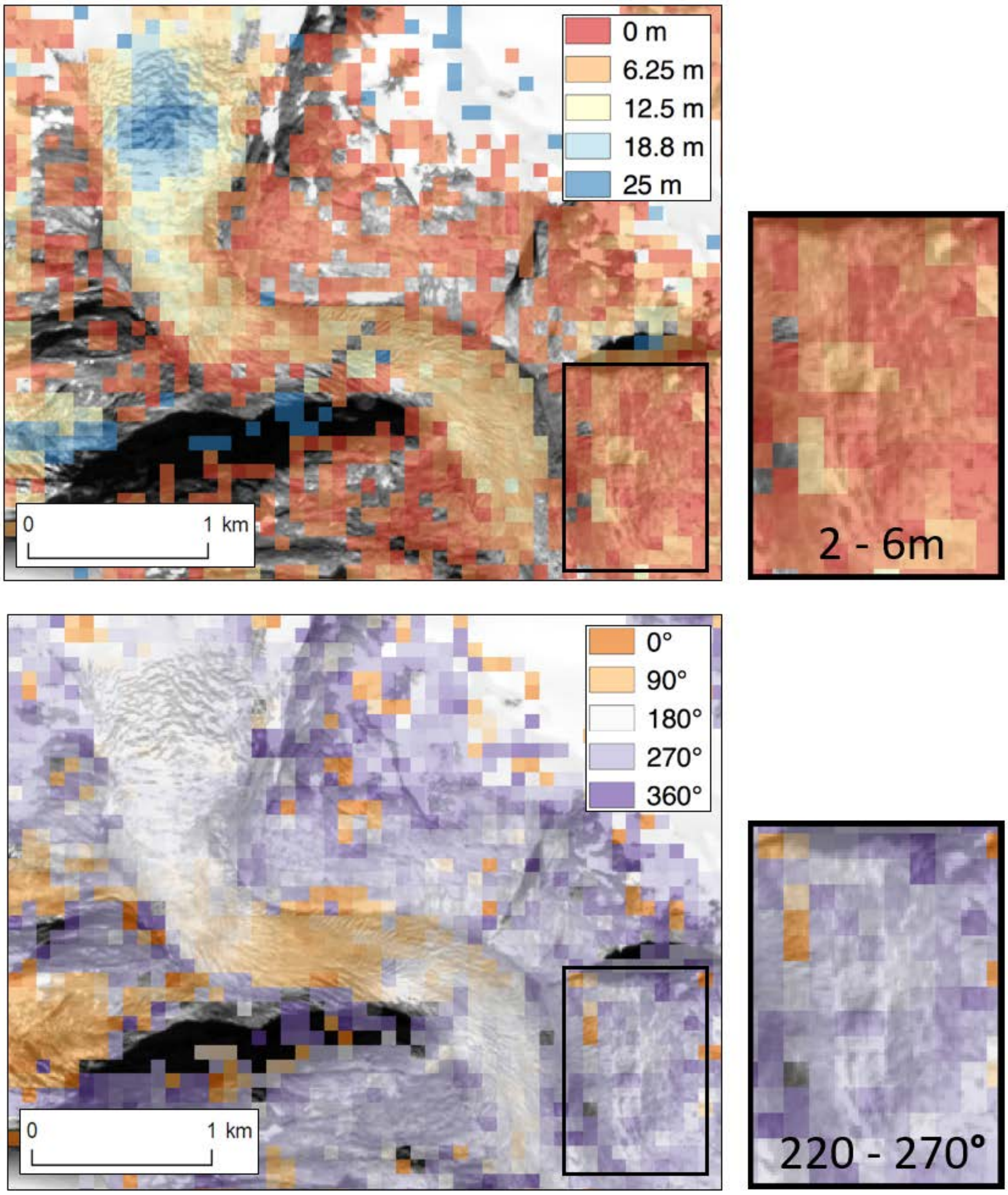

Figure 9: Maps of displacement magnitude and displacement direction over Nigardsbreen and adjacent areas of stable ground with close-ups of the stable areas and estimated approximate magnitude and direction of movement. The data was acquired from the Sentinel-2 pair 22/08/2017-16/09/2017 (25 days temporal difference).

2.5 Filtering and post-processing

It was necessary to filter the results manually as the glacier movement in a region or of an ice cap can differ both in magnitude and direction. The displacement magnitude and direction can also vary within a single glacier, e.g for Nigardsbreen where flow is fast and dominantly in N-S direction in the icefall upstream, while slower and in W-E direction further downstream (Figure 10). To detect and remove outliers, the magnitude and azimuth of the displacement were used alongside with DEMs of the glacier areas, and high resolution orthophotos to understand the flow direction of the ice (Figure 10). The derived glacier velocity dataset was manually filtered for each of the image pairs and for each glacier unit separately.

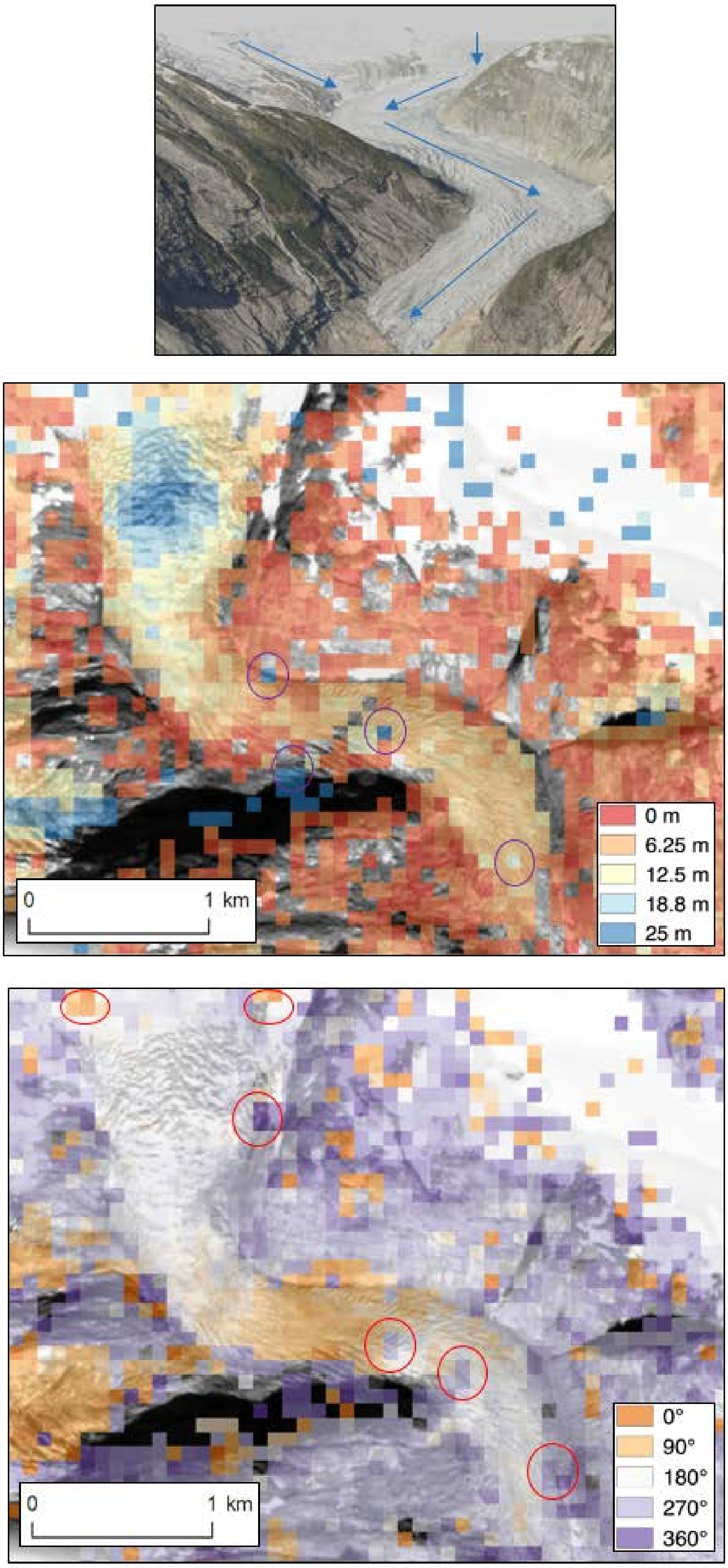

Figure 10: Illustration of outliers detected using displacement magnitude (in purple) and displacement direction (in red) over Nigardsbreen using the image pair 22/08/2017-16/09/2017. The 3D representation of the glacier flow (blue arrows) uses a high-resolution orthophoto of Nigardsbreen from 26/08/2017. The outliers were removed from the final dataset.

3 Results

3.1 Glacier surface velocities

After dataset filtering, we remained with ca. 25200 point results over 91 glacier units. For the investigated period 2015 to 2018, the maximum number of multitemporal point measurements at one point was eight for certain points of Engabreen, Tunsbergdalsbreen and Austerdalsisen. These glaciers have some of the longest and widest outlets, a large number of distinct crevasses, large accumulation basins, and they move relatively fast due to steep terrain. Therefore, they are likely to provide spatiotemporally dense observation series. The final glacier velocity product has results mainly over the snow-free parts of the glaciers that offer trackable features such as crevasses (Figure 12).

In total, 91 glacier units yielded results whereof 37 in northern Norway and 54 in southern Norway. This represents ca. 10% of the glacier units that are larger than 0.5km^2. Out of the 91 units, 53 units were part of the four largest ice caps in Norway (Jostedalsbreen, Vestre Svartisen, Søndre Folgefonna, Østre Svartisen). Jostedalsbreen itself had results for over 30 glacier units (Figure 13).

Recorded surface velocities of over 1m/day were found for interannual pairs capturing displacement in the melting season for the following glaciers: Kjenndalsbreen, Briksdalsbreen, Bergsetbreen, Nigardsbreen, Bondhusbrea, Buerbreen, Austerdalsisen. The maximum velocity was 1.65m/day for Nigardsbreen. The seven aforementioned glaciers are characterised by steep ice fall sections resulting in fast ice flow. The range of the day difference of the image pair was: 10-60 days for the melting season (summer) image pairs, 290-400 days for the yearly pairs, and 675-715 days for the bi-yearly pairs.

3.2 Categorization of glaciers

All glaciers were classified into categories according to their potential for glacier surface displacement measurements (Table 2). Six categories were defined. The top category (1) was assigned to glaciers that provided best results and had a consistently large number of well-defined features for tracking and observable magnitude of movement (Figure 11, Figure 13, Table 2). Nigardsbreen and several of its neighbouring glaciers are examples of glaciers in that category (Figure 12).

In total, 57 out of 91 glacier units were assigned the top category status. These glacier units are almost certain to provide results in the coming years given favourable cloud cover conditions. The median size of the unit in the top category was 9.97km^2, which illustrates that the best results were derived from the larger glacier units. The remaining 34 of 91 glacier units with obtained results from 2015-2018 were classified as category 2. Further 88 units were classified as having a potential to provide results in the future due to either the feature richness, size, shape of the outlet, slope or a combination of them (category 3-4). Moreover, 678 glaciers were considered to be not likely to provide results in the future (category 5). Finally, all glaciers with area <0.5 km^2 were classified as too small (category 6).

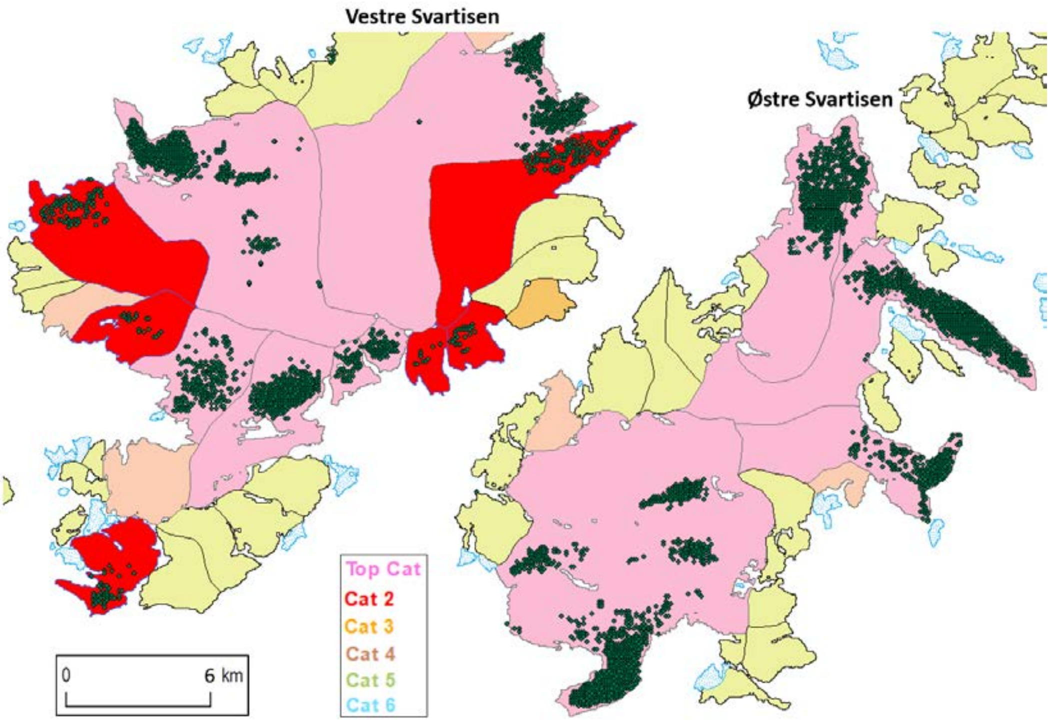

Figure 11: A map of Vestre (western) and Østre (eastern) Svartisen showing point velocity distribution and categorization of the glacier units. The glacier outlines are based on the 1999-2006 glacier area inventory (Andreassen et al., 2012).

Table 2: Division of the glacier units into categories 1-6 where 1 contains the glaciers best suited for obtaining results using feature tracking. The units are defined by Andreassen et al. (2012). 'n' is the sum of glacier units in each category. Top Cat – Top Category.

Category	**n**	**Description**
1(Top Cat)	57	Provided results and are well-suited to provide results in the future
2	34	Provided results and are likely to provide results in the future
3	28	Did not provide results but may provide results in the future
4	60	Did not provide results and are rather unlikely to provide the results in the future
5	678	Did not provide results and will unlikely provide results in the future
6	2286	Too small (<0.5km^2)
1 – 6	3143	

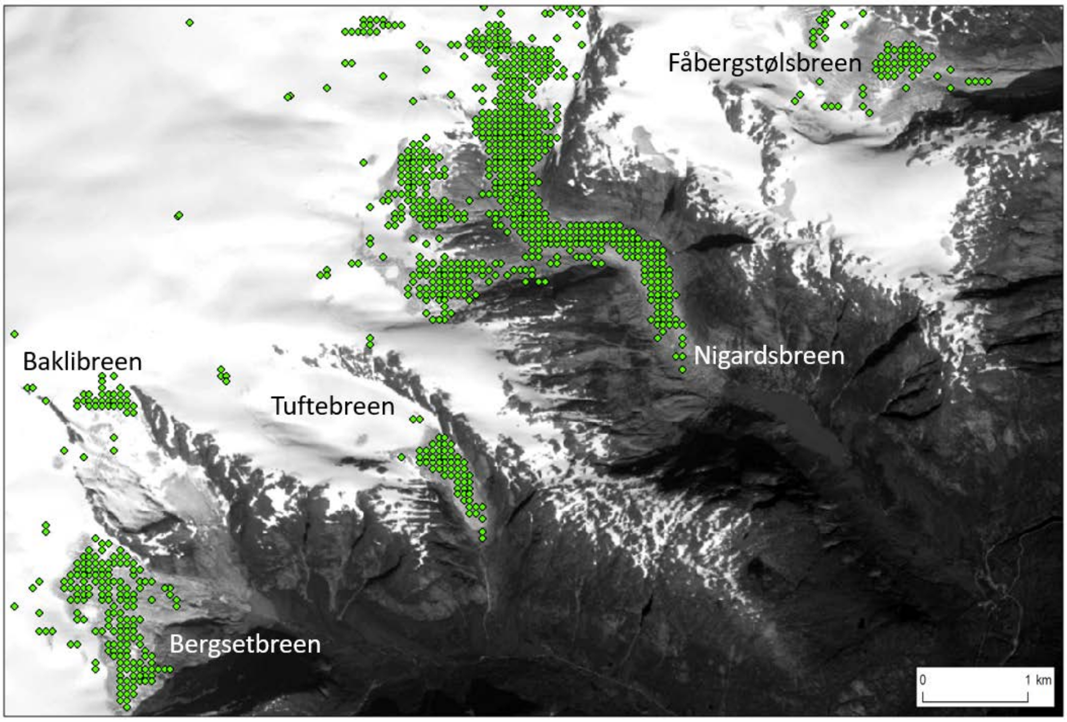

Figure 12: Distribution of glacier velocity points derived of Nigardsbreen and its neighbouring glaciers (all in Top category) over a Sentinel-2 image (band 8) from 22/08/2017. Results are mainly obtained over snow-free and feature-rich ice

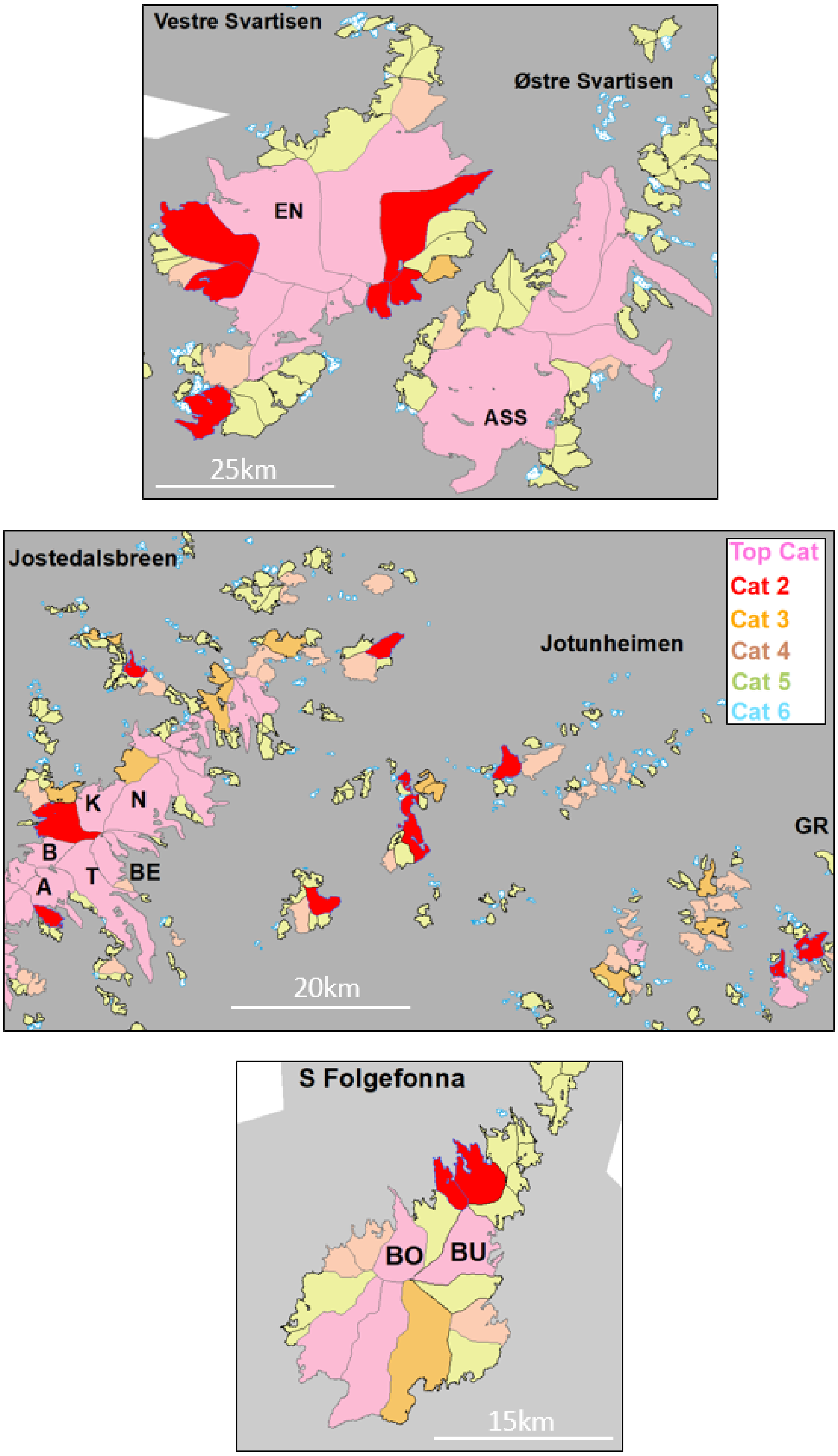

Figure 13: Classification of glacier units of three subset regions (see Figure 1 for location) based on the suitability to perform feature tracking. The glaciers mentioned in the report are in black. Abbreviations: EN: Engabreen; ASS: Austerdalsisen; K: Kjenndalsbreen; B: Briksdalsbreen; A: Austerdalsbreen; T: Tunsbergdalsbreen; BE: Bergsetbreen; N: Nigardsbreen; GR: Gråsubreen; BO: Bondhusbrea; BU: Buerbreen.

3.3 Accuracy of the results

Despite its time demand, it was considered best to filter the results manually. Application of strict automatic cut-off points would result in omitting a large part of the final dataset. To assess the performance of the feature tracking, a comparison of the stake and SenDiT derived data was performed by Nagy et al. (2019) showing that SenDiT derived velocities compared well to stake data for Nigardsbreen, Rembedalskåka and Engabreen (Table 3, Figure 14). The three stakes that were selected maximized a spatial overlap with feature tracking results, as well as a temporal overlap over the surveyed periods. The stake velocities were found to be within the error margin of the feature tracking measurements for Nigardsbreen and Rembedalskåka (Table 3). Partial disagreement between the measured stake velocity and results of Sentinel-2 image matching for Engabreen were likely due to a reduced spatial and temporal overlap between the two measurements (Table 3).

When considering sources of movement in a displacement map, the main components are: true movement over a number of days of the pair; relative co-registration error; and orthorectification error. We minimized the orthorectification error by using image pairs with two images from the same orbit. The main source of the error in the surface velocity dataset derived from Sentinel-2 imagery was therefore the relative co-registration accuracy of the image pairs (Figure 10). The relative co-registration accuracy was estimated for each of the pairs using mean displacement across a small subset area over stable terrain free of snow, cloud, ice and water bodies.

Table 3: Comparison of velocities from Sentinel-2 feature tracking and stake in-situ measurements for three stakes with best spatiotemporal overlap. Adapted from Nagy et al. (2019).

Glacier	Point	Period (stake)	Velocity (m/day)	Flow Direction (°)	Distance to FT res. (m)	Period (Sentinel)	Velocity (m/day)	Flow Direction (°)
Nigardsbreen	N1	23.08.2017–18.10.2017	0.567+/−0.005	162	44.07	27.08.2017–16.09.2017	0.624+/−0.175	172
	N2				38.60		0.580+/−0.175	187
Rembedalskåka	R1	15.09.2016–24.05.2018	0.141+/−0.0005	241	104.01	22.08.2017–28.07.2018	0.130+/−0.009	236
	R2				116.59		0.148+/−0.009	238
Engabreen	E1	18.10.2016–25.10.2018	0,122+/−0.0004	358	266.77	22.08.2016–26.09.2017	0.155+/−0.016	341
	E2				306.54		0.149+/−0.016	358

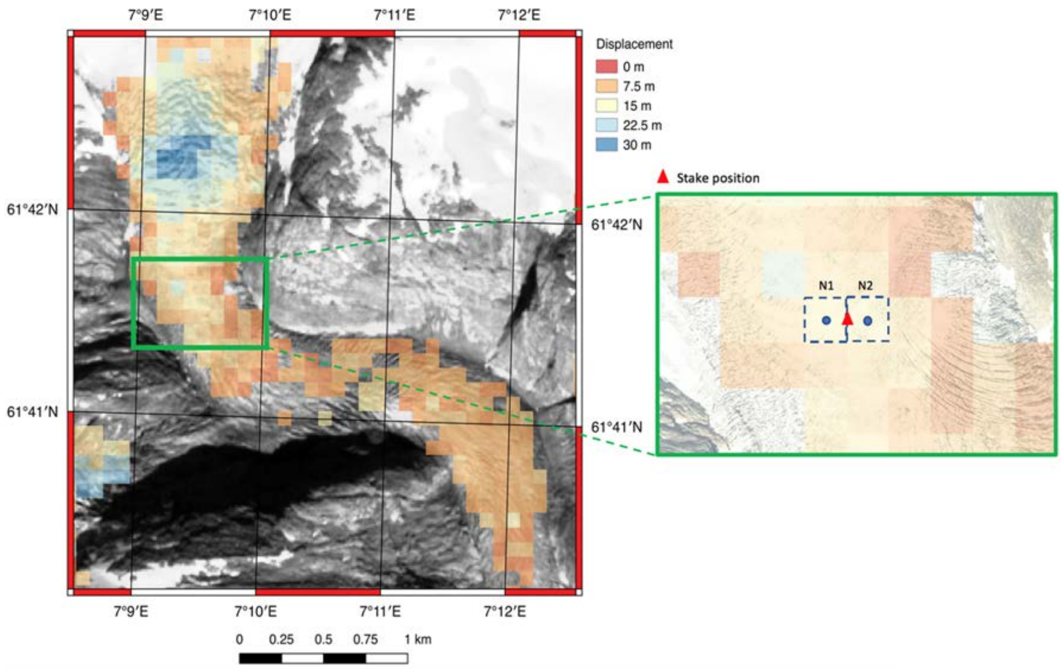

Figure 14: Adapted from Nagy et al. (2019). A filtered displacement map of the pair 22/08/2017-16/09/2017 over Nigardsbreen with a close up of a position of the stake and points N1 and N2 (Table 3).

3.4 Glacier velocity dataset

The final glacier velocity dataset is stored in NVE's geodatabase and made available for viewing in NVE's digital glacier atlas (NVEs BreAtlas). The dataset has a list of attributes filled out for each point including its estimated displacement magnitude, displacement azimuth, temporal window of surveying and calculated velocity in m/day (Table 4). The dataset can be downloaded from http://www.nve.no/glacier.

Table 4: Table listing the glacier velocity database attributes and their description per time of report. The database contains a couple more attributes that are relevant for measuring surface velocity from other sources than Sentinel-2 imagery, e.g. stake number, that are not listed here.

Attribte name	**Attribute description**
X	X coordinate
Y	Y coordinate
Velocity_md	Calculated velocity in m/day
Diff_days	Day difference of the image pair
Data_src	Source of image or data for glacier velocity mapping
Rel_orbit	Relative orbit of image acquisition
Proc_desc	Description of processing method
Filtering	Description of filtering method
Dato1	Date of earlier image
Dato2	Date of later image
Direction	Calculated displacement azimuth in degrees
LengdeVektor	Calculated displacement magnitude in meters
CorrelationStrength	Imcorr software output parameter (the higher the number, the stronger the correlation)
RegionNumber	Region (by Andreassen et al. 2012), in which velocity point is located
ProductID	Period of the inventory (2015-2018)
ShiftDirection	Estimated displacement azimuth in the stable area subset
ShiftMagnitude	Estimated displacement magnitude in the stable area subset
Beregnet_av	Person responsible for undertaking measurements
BREID_1	ID of a glacier unit, in which the velocity point is located

4 Conclusion

This report presented how glacier surface velocities was derived using feature tracking on Sentinel-2 images over the period 2015-2018. Using Sentinel-2 imagery is superior to using Landsat 8 imagery due to the higher temporal and spatial resolution. Many of the glaciers in Norway have trackable features, especially in the steep, relatively fast flowing sections. The features typically become visible during the melting season, depending on winter snow and melting conditions on the glaciers that will vary from year to year. Crevasses and crevasse induced shadowing are the most prominent features that are trackable on the glaciers in mainland Norway. Ogives are also fairly common and are often useful as they are perpendicular to the ice flow. Snow cover directly limits the feature tracking. The main reasons for not being able to obtain results are persistent snow, cloud cover, absence of trackable features and too slow ice flow (e.g. Gråsubreen). Favourable cloud conditions in the image pairs are needed. Using strict thresholds for cloud cover percentage runs a risk of omitting potentially good images, with high cloud cover percentage, but relatively little or no cloud cover over the glaciers of interest. Therefore, visual inspection is recommended to select the Sentinel-2 scenes suitable for glacier surface velocity mapping. The time period between two paired images is crucial for successful feature tracking. If the time span is too short, observable movement is difficult to detect. If the time span is too large, the crevasse pattern, appearance and extent as well as snow conditions can change. Commonly, time spans are on the order of weeks and months for fast moving glaciers and months to a year or two for slower moving glaciers. Typical time spans for mainland Norway were 10-60 days to derive inter-seasonal velocities and 290-400 days for annual velocities.

To calculate the glacier velocities we used a semi-automatic, open-source toolbox (SenDiT) that combines data download, feature tracking, and output generation. The results were checked carefully by visual inspection and manually filtered for each image pair and each glacier unit to remove outliers or unreliable results. In total, the final glacier surface velocity dataset has ca. 25200 velocity points over 91 glacier units. Velocity fields are mainly obtained over glacier tongues and steep icefalls with few results available from the higher feature-poor parts of the glaciers. The coverage varies from glacier to glacier. Some larger glaciers such as Tunsbergdalsbreen, Austerdalsisen, Nigardsbreen and Engabreen with well defined features have results from multiple pairs.

All glacier units in Norway were categorized into classes depending on their suitability for glacier velocity mapping using Sentinel-2 imagery. Of the 91 glacier units with velocity point results, 57 were classified in the top category meaning that they are best suited to provide results in future studies given favourable cloud conditions, whereas the other 34 units with obtained results were classified in the next best category and classified as likely to provide results in future studies. Further 88 glacier units were identified as having a potential to provide results in the future. Remaining glaciers have less potential due to their size, slow flow or lack of trackable surface features.

By using image pairs composed of two images from the same orbit we minimized the orthorectification error. Thus, the relative co-registration accuracy error between two images was the principal error component, and estimated to most often range from 2 to 8m, but reaching up to 12m for some of the pairs. Overall, we found Sentinel-2 useful for glacier surface velocity mapping, yielding a relatively rich dataset over 2015-2018. The dataset can be used for modelling and can be repeated for assessing changes in glacier dynamics. Given the limitations in sensor quality (10m resolution), glacier properties (size, speed, feature richness), and external factors (cloud cover, snow cover), Sentinel-2 is a good source of data for glacier surface velocity mapping in mainland Norway. The data are freely available with regular and frequent acquisitions, but can be limited by cloud cover. For mapping velocities in parts of glaciers where we did not obtain results, other methods such as stake measurements, time lapse cameras or interferometric synthetic aperture radar can be a better choice. Mapping can also be improved in the future with new higher resolution sensors improving feature detectability.

5 Data availability

The dataset is made freely available for download at: https://www.nve.no/glacier/ as part of the Copernicus Glacier Service (Copernicus bretheneste) project.

References

Altena, B. and Kääb, A.: Weekly Glacier Flow Estimation from Dense Satellite Time Series Using Adapted Optical Flow Technology, Front. Earth Sci., 5, 1–12, https://doi.org/10.3389/feart.2017.00053, 2017.

Altena, B., Scambos, T., Fahnestock, M., and Kääb, A.: Extracting recent short-term glacier velocity evolution over Southern Alaska and the Yukon from a large collection of Landsat data, The Cryosphere, 13, 795-814, https://doi.org/10.5194/tc-13-795-2019, 2019.

Andreassen, L. M., Winsvold, S. H., Paul, F., and Hausberg, J. E.: Inventory of Norwegian Glaciers, NVE Rapport 38, Norwegian Water Resources and Energy Directorate, https://doi.org/10.5167/uzh-73855, 2012.

Andreassen, L. M., Paul, F., Kääb, A., and Hausberg, J. E.: Landsat derived glacier inventory for Jotunheimen, Norway, and deduced glacier changes since the 1930s, The Cryosphere, 2, 131-145, https://doi.org/10.5194/tc-2-131-2008, 2008.

Castriotta, A.G. and Knowelden, R.: Sentinel Data Access 2017 annual report. Unpublished.

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

Fahnestock, M., Scambos, T., and Bindschadler, R. A.: Semi-automated ice velocity determination from satellite imagery, EOS, 73, 493, 1992.

Jackson, M., Brown, I. A., and Elvehøy, H.: Velocity measurements on Engabreen, Norway, Ann. Glaciol., 42, 29–34, https://doi.org/10.3189/172756405781812655, 2005.

Joughin, I., Smith, B., Howat, I., Scambos, T., and Moon, T.: Greenland flow variability from ice-sheet-wide velocity mapping, J. Glaciol., 56, 415–430, https://doi.org/10.3189/002214310792447734, 2010.

Joughin, I., Smith, B., Shean, D.E., and Floricioiu, D. Brief Communication: Further summer speedup of Jakobshavn Isbrae, Cryosphere, 8, 209–214, https://doi.org/10.5194/tc-8-209-2014, 2014.

Kääb, A., Winsvold, S. H., Altena, B., Nuth, C., Nagler, T. and Wuite, J.: Glacier Remote Sensing Using Sentinel-2. Part I: Radiometric and Geometric Performance, and Application to Ice Velocity, Remote Sensing, 8(7), 598, https://doi:10.3390/rs8070598, 2016.

Klingenberg, T. F.: Evaluation of Sentinel-2: Case Study of Land Cover Classification and Ice Velocity, Masters thesis, p. 118, 2017.

Li, J. and Roy, D.P.: A global analysis of Sentinel-2A, Sentinel-2B and Landsat-8 data revisit intervals and implications for terrestrial monitoring, Remote Sens., 9, 902, 2017.

Liestøl, O.: Storbreen glacier in Jotunheimen, Norway, Norsk Polarinstitutt Skrifter, 141, p. 63, 1967.

Loveland, T.R. and Irons, J.R.: Landsat 8: The plans, the reality, and the legacy, Remote Sens. Environ., 185, 1–6, 2016.

Mathieu, R., Chinn, T., and Fitzharris, B.: Detecting the equilibrium-line altitudes of New Zealand glaciers using ASTER satellite images, New Zealand Journal of Geology and Geophysics 52 (3), 1–14, https://doi.org/10.1080/00288300909509887, 2009.

Messerli, A., Grinsted, A.: Image georectification and feature tracking toolbox: ImGRAFT, Geosci. Instrum. Methods Data Syst., 4, 23–34, 2015.

Mouginot, J., and Rignot, E.: Ice motion of the Patagonian Icefields of South America: 1984-2014. Geophys. Res. Lett. 42, 1441–1449, https://doi.org/10.1002/2014GL062661, 2015.

Mouginot, J., Rignot, E., Bjørk, A. A., Van den Broeke, M., Millan, R., Morlighem, M., Noël, B., Scheuchl, B., and Wood, M.: Forty-six years of Greenland Ice Sheet mass balance from 1972 to 2018, Proceedings of the National Academy of Sciences, https://doi.org/10.1073/pnas.1904242116, 2019.

Muto, M., and Furuya, M.: Surface velocities and ice-front positions of eight major glaciers in the southern Patagonian Ice Field, South America, from 2002 to 2011, Remote Sens. Environ., 139, 50–59, https://doi.org/10.1016/j.rse.2013.07.034, 2013.

Nagy, T., Andreassen, L.M., Duller, R.A. and Gonzalez, P.J.: SenDiT: A Sentinel-2 Displacement Toolbox with application to glacier surface velocities. Remote Sensing, 11, 1151, 2019.

O'Neel, S., Pfeffer, W.T., Krimmel, R., and Meier, M.: Evolving force balance at Columbia Glacier, Alaska, during its rapid retreat, J. Geophys. Res., 110, F03012, https://doi.org/10.1029/2005JF000292, 2005.

Østrem, G., Liestøl, O. and Wold, B.: Glaciological investigations at Nigardsbreen, Norway, Norsk Geografisk Tidskrif (Norwegian Journal of Geography), 30(1), 187–209, 1976.

Paul, F., Winsvold, S.H., Kääb, A., and Nagler, T.: Glacier remote sensing using Sentinel-2. Part II: Mapping glacier extents and surface facies, and comparison to Landsat-8, Remote Sens., 8, 575, 2016.

Pytte, R.: Hellstugubreen: En glasiologisk undersøkelse, Masters thesis, p. 86, 1964.

Redpath, T. A. N., Sirguey, P., Fitzsimons, S.J., and Kääb, A.: Accuracy assessment for mapping glacier flow velocity and detecting flow dynamics from ASTER satellite imagery: Tasman Glacier, New Zealand, Remote Sens. Environ, 133, 90–101, https://doi.org/10.1016/j.rse.2013.02.008, 2013.

Schellenberger, T., Van Wychen, W., Copland, L., Kääb, A., and Gray, L.: An inter-comparison of techniques for determining velocities of maritime arctic glaciers, Svalbard, using Radarsat-2 wide fine mode data, Remote Sens., 8, 785, https://doi.org/10.3390/rs8090785, 2016.

Schellenberger, T., and Kääb, A: Prodex project report, unpublished, 2017.

Seehaus, T., Cook, A. J., Silva, A. B., and Braun, M.: Changes in glacier dynamics in the northern Antarctic Peninsula since 1985, Cryosphere, 12, 577-594, https://doi.org/10.5194/tc-12-577-2018, 2018.

Solgaard, A., Messerli, A., Schellenberger, T., Hvidberg, C., Grinsted, A., Jackson, M., and Dahl-Jensen, D.: Basal conditions at Engabreen, Norway, inferred from surface measurements and inverse modelling, Journal of Glaciology, 64(246), 555-567, https://doi.org/10.1017/jog.2018.45, 2018.

Stocker-Waldhuber, M., Fischer, A., Helfricht, K., and Kuhn, M.: Long-term records of glacier surface velocities in the Ötztal Alps (Austria), Earth Syst. Sci. Data, 11, 705-715, https://doi.org/10.5194/essd-11-705-2019, 2019.

Strozzi, T., Paul, F., Wiesmann, A., Schellenberger, T., and Kääb, A.: Circum-Arctic changes in the flow of glaciers and ice caps from satellite SAR data between the 1990s and 2017. Remote Sensing, 9, 947, https://doi.org/10.3390/rs9090947, 2017.

Sund, M. and Eiken, T.: Recent surges on Blomstrandbreen, Comfortlessbreen and Nathorstbreen, Svalbard, Journal of Glaciology, 56(195), 182-184, https://doi.org/10.3189/002214310791190910, 2010.

Tønsberg, O. M.: Kartlegging av dynamikken på en fremrykkende bre - Nigardsbreen, Sør-Norge - vha GPS og fotogrammetri, Masters thesis, p. 65, 2003.

Wangensteen, B., Weydahl, D. J., Hagen, J. O.: Mapping glacier velocities on Svalbard using ERS tandem DInSAR data, Norsk Geogr. Tidsskr. / Nor. J. Geogr., 59, 276–285. 2005.

Wangensteen, B., Tønsberg, O. M., Kääb, A., Eiken, T., and Hagen, J. O.: Surface Elevation Change and High Resolution Surface Velocities for Advancing Outlets of Jostedalsbreen. Geografiska Annaler, Series A: Physical Geography, 88(1), 55–74. doi:10.1111/j.0435-3676.2006.00283, 2006.

Zhang, H. K., Roy, D. P., Yan, L., Li, Z., Huang, H., Vermote, E., Skakun, S., and Roger, J.: Characterization of Sentinel-2A and Landsat-8 top of atmosphere, surface, and nadir BRDF adjusted reflectance and NDVI differences, Remote Sens. Environ., 215, 482–494, 2018.

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