Continuous Monitoring of Ice Motion and Discharge of Antarctic and Greenland Ice Sheets and Outlet Glaciers by Sentinel-1 A & B

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ABSTRACT

The Sentinel-1 acquisition planning for polar regions provides almost uninterrupted observations of the Greenland Ice Sheet margin, key regions in Antarctica and other polar ice masses. The satellite constellation has thereby changed the landscape for satellite Earth observation (EO) in the polar regions, providing excellent opportunities for operational monitoring of key climate variables including ice velocity and glacier discharge. Based on Sentinel-1 SAR imagery, an archive of ice velocity maps covering the polar regions has been generated, encompassing the entire mission duration. The ice velocity maps, complemented with ice thickness and other EO datasets, form the basis for deriving ice flow, discharge fluctuations and trends at sub-monthly to multi-annual time scales, providing key input for ice dynamic and climate modelling. Our results underscore the value of long-term comprehensive monitoring of the polar ice masses, which is vital to gain insight for predicting their response to ongoing climate and ocean warming.

***Index Terms*—** Sentinel-1, Copernicus, Greenland, Antarctica, ice velocity, ice discharge, SAR, interferometry

1. INTRODUCTION

Ice velocity and the associated strain rate, which is a measure of the ice deformation rate, are key variables for estimating ice sheet discharge and mass balance. These parameters are essential input for glacier models aiming at quantifying ice dynamical processes. Changes in flow velocity and velocity gradients are indicators for shifting boundary conditions in response to atmospheric and/or oceanic warming. Remote sensing techniques utilizing synthetic aperture radar (SAR) and optical satellite data are the only feasible means to obtain accurate region-wide surface velocities of the remote Greenland and Antarctic glaciers on a regular basis. SAR has the advantage of being applicable year-round, day and night, and at all weather conditions, making it well suited for the polar regions.

The launch of European Union's Copernicus Sentinel-1A by the European Space Agency (ESA) in April 2014, followed by Sentinel-1B two years later, in combination with a dedicated polar acquisition plan, set the basis for the regular provision of SAR data over Greenland and Antarctica. This allowed a transition from the previous campaign style acquisitions to operational monitoring of essential climate variables including ice sheet velocity and ice discharge. We developed an automatic system for generating ice sheet velocity and ice discharge based on Sentinel-1 data and generated an extensive archive of ice velocity and derived products for studying the ongoing ice dynamical changes in the polar regions [1]. The products have been developed and validated within the ESA Antarctic and Greenland Ice Sheet CCI projects. The production was partly shifted to the Copernicus Climate Change Services C3S.

2. DATA SETS & METHOD

The primary input for the retrieval of ice velocity are repeat-pass SAR data from the Sentinel-1A and B constellation, acquired in Interferometric Wide (IW) swath mode. Sentinel-1 carries a C-band SAR instrument acquiring high-resolution SAR images over a 250 km swath with a ground range resolution of about 5 m x 20 m, well suited for comprehensive velocity retrievals over large ice bodies [2]. We use 6- and 12-day repeat-pass single look complex (SLC) images acquired over Greenland and Antarctica to derive ice flow velocity fields using the offset tracking (OT) and SAR interferometry (InSAR) techniques. The differential InSAR method has a sensitivity in respect to displacement that is one to two orders of magnitude higher than that of OT. However, acquisitions of crossing ascending/descending orbits are required to determine 2D surface velocity. Previous to the launch of Sentinel-1A and 1B, such data were not systematically acquired over the ice sheets. On request of the C3S services and science community, ESA developed a Sentinel-1 acquisition plan for Greenland and Antarctica providing unprecedented coverage and temporal sampling. This enabled the continuous monitoring of ice velocities, including the systematic use of InSAR for improved products particularly in zones of moderate flow velocities.

For Greenland, a continuous record of ice velocities along the ice sheet margins is available, starting in October 2014, augmented by annual ice sheet wide velocity maps related to dedicated acquisition campaigns in winter. In 2019, additional tracks were added to the regular acquisition scheme, covering the slow-moving interior of the Greenland ice sheet, and allowing the systematic application of SAR interferometry.

In Antarctica, the acquisition planning initially focused on a few key regions, including the Antarctic Peninsula, the Amundsen Sea Sector and Lambert Glacier/Amery Ice Shelf. In 2015, a continent-wide mapping campaign allowed the retrieval of ice sheet wide velocity fields up to the polar gap at 78.6°S. Since July 2017, the acquisition planning expanded to include the nearly entire ice sheet margin at 6- to 12-day intervals, thereby enabling the generation of dense time series for outlet glaciers that were previously only sparsely covered. Figure 1 shows the multi-annual average ice velocity maps from OT for Greenland and Antarctica.

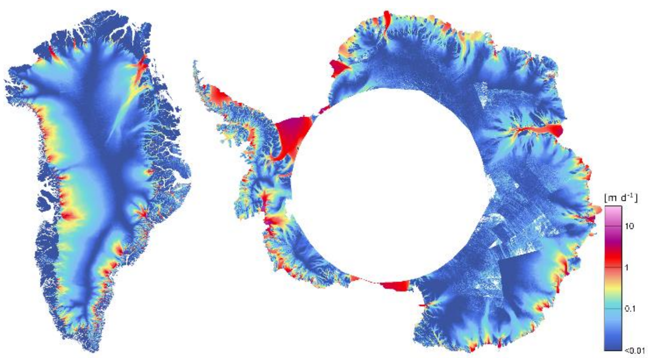

Figure 2: Ice sheet wide maps of the magnitude of the velocity for Greenland (left) and Antarctica (right) derived from Sentinel-1 applying Offset Tracking. Note: figures not to scale.

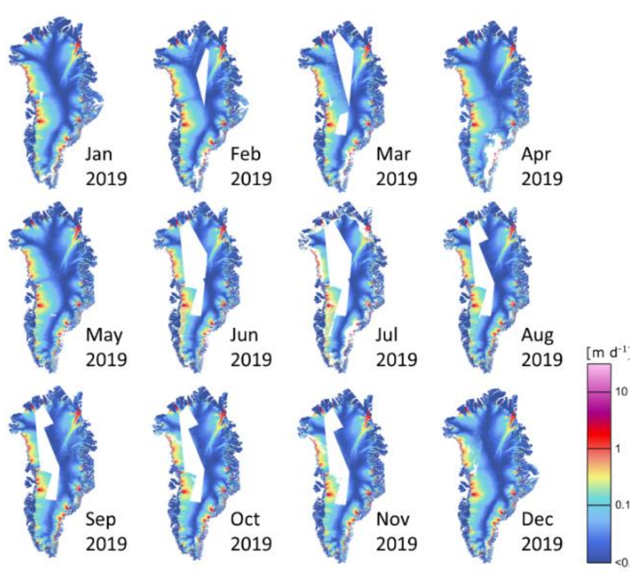

Figure 1: Monthly Greenland Ice Sheet wide velocity maps for 2019. White areas are regions without data acquisitions in the corresponding month.

3. ICE VELCOCITY PRODUCTS

We generated a dense archive of ice velocity maps covering both Greenland and Antarctica, encompassing the entire Sentinel-1 mission epoch until now, spanning more than 6 years. The ice velocity maps include annual and monthly mosaics of the Greenland (Figure 2) and Antarctic Ice Sheets as well as dense time series with a temporal sampling of 6 and 12 days covering the ice sheet margins. The maps are provided on a 200 m (Antarctica) and 250 m (Greenland) grid in polar stereographic projection.

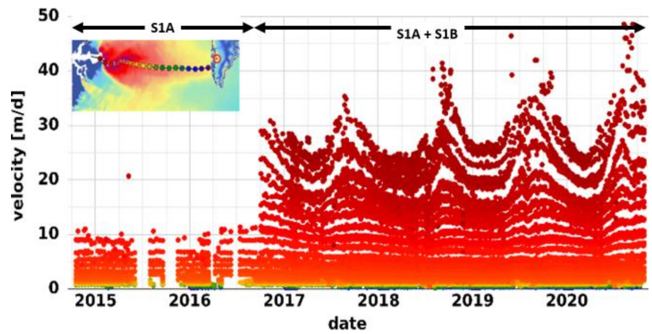

Figure 3: Ice velocity time series at fixed points (2.5 km apart) along the central flow line of Jakobshavn Glacier (see inset). Till October 2016 only 12-day repeat data from Sentinel-1A were available, which did not allow the measurement of fast flow.

For those outlet glaciers of Greenland and Antarctica that are continuously observed by Sentinel-1, the dense time series enables the observation of velocity fluctuations at different temporal scales, ranging from weekly to interannual variations. Figure 3 shows an example for the temporal variation of ice velocity along the central flow line of Jakobshavn Glacier, West Greenland. Till October 2016 Sentinel-1A data were acquired every 12 days, which did not allow the retrieval of velocities on the fast-moving areas close to the glacier terminus that reaches velocities up to 40 m/d. The combination of Sentinel-1A and B data with 6-day intervals enables the retrieval of velocities close to the glacier terminus, revealing strong seasonal variations of the ice flow.

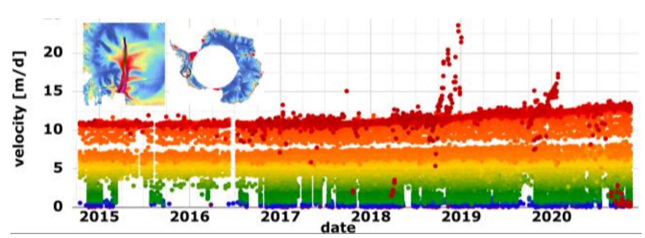

Figure 4: Ice velocity time series at fixed points (5 km apart) along the central flow line of Pine Island Glacier, West-Antarctica (see inset). Points with very high velocity indicate iceberg calving events.

Figure 4 shows the time series of ice velocity along the Pine Island Glacier, one of the major outlet glaciers in West Antarctica. The seasonal variation is small compared to Greenland glaciers, but Sentinel-1 observations reveal an increase of velocity in the recent years that has been triggered by oceanic warming in the Amundsen Sea.

Complementary to the standard operational velocity maps, based on OT, we produced a high resolution 50 m ice velocity map for Greenland applying SAR interferometry (Figure 5). This map is based on Sentinel-1 6-day repeat pass image pairs acquired during the 2018/19 and 2019/20 winter mapping campaigns. It is complemented by 12-day pairs acquired during winter 2017 for filling gaps. The interferometric processing was adapted to reduce the phase jumps at bursts boundaries. These phase discontinuities are characteristic of SAR operating in Terrain Observation by Progressive Scans (TOPS) acquisition mode for areas with a motion component in along-track direction [3][4]. Thanks to its high sensitivity to motion, InSAR greatly reduces the noise level in the velocity measurements compared to OT. The improvement is particularly visible in the slow-moving interior (1-10 cm/d). Furthermore, though not corrected for ionospheric phase delay, the InSAR velocity is not affected by ionospheric streaks that affect OT. InSAR captures ice velocities up to about 1.5 m/d, and thus also captures some parts of the outlet glaciers (Figure 5). Therefore, this product provides essential data for the precise delineation of ice drainage basins and ice divides. On fast moving outlet glaciers, where InSAR fails, or in regions without crossing orbit data, OT velocity products complement the InSAR velocity maps.

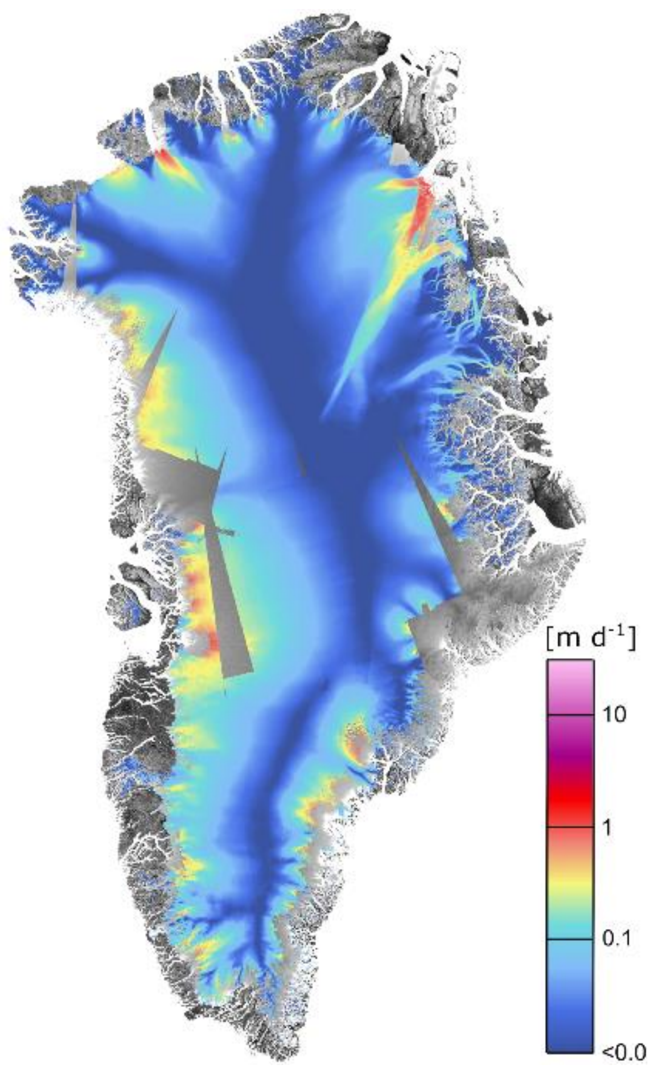

Figure 5: Sentinel-1 InSAR ice velocity map, of Greenland 2018-20, with 50 m pixel spacing, generated from Interferometric Wide swath mode data acquired in TOPS mode (background: Sentinel-1 backscatter map).

4. ICE DISCHARGE

Glacier and ice sheet discharge (or mass flux) and its variability can be derived from time series of ice velocity if suitable ice thickness data (e.g. from Radio Echo Sounding or bathymetric data) are available. The discharge, ϕ, is calculated from the product of the depth averaged ice velocity and ice thickness at the calving front or at the flux gate at the grounding line according to

$$\phi = \rho_{ice} \int_{x=0}^{x=l} H(x)\vec{v}\,(x)d\vec{x}$$

where ρ_{ice} is the density of ice, v is the depth averaged velocity magnitude normal to the flux gate and H is the ice thickness at the gate with width l. We used gridded ice thickness from the IceBridge BedMachine Greenland, (IDBMG4 v4) dataset [5][6] complemented with denser flight track data from the NASA Operation IceBridge flight campaigns [7] to calculate monthly ice discharge for major outlet glaciers. Figure 6 shows as example the monthly ice discharge in Gt/y of the Academy Glacier, North-East Greenland, revealing seasonal variability with maximum discharge in summer overlaid on a long-term increase.

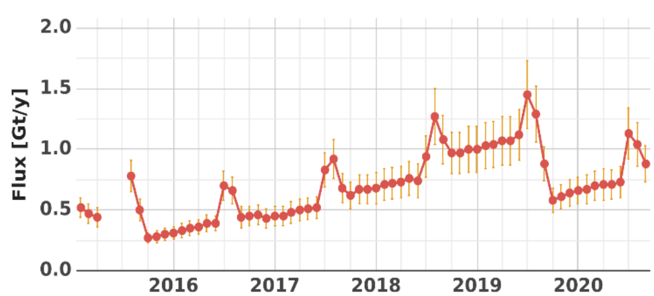

Figure 6: Monthly ice discharge rates for Academy Glacier in NE Greenland since 2015.

5. SUMMARY AND OUTLOOK

The Sentinel-1 satellites, following a dedicated, dense acquisition plan for polar land ice masses, enable the most comprehensive, continuous survey of ice sheet velocities, a unique resource for capturing changes in flow dynamics and ice discharge at temporal scales ranging from days to years. The potential constellation of three Sentinel-1 satellites, S1A, S1B and S1C, in the near future will further enhance the capabilities for the detailed and comprehensive survey of ice flow of polar ice sheets and ice caps. Offset tracking is used for generating the baseline ice velocity products all year around for the operational Copernicus Climate Change services (C3S). These products are complemented by high resolution velocity products from SAR interferometry, which are limited in coastal zones to the period without surface melt and can be produced for the dry snow zones all year round. Over 6-day time spans the interferometric coherence at C-Band is preserved on the slow-moving interior sections of the ice sheets most of the time. Coherent image pairs are obtained also on other sections with velocities below about 1.5 m/d. Further Copernicus based advancements for monitoring ice sheet parameters, particularly ice velocity and grounding line, can be expected from the High Priority Copernicus Expansion Mission ROSE-L (Radar Observing System for Europe L-Band SAR) which is in preparation for launch and operation in the second half of this decade, complementary to the Sentinel-1 mission.

6. ACKNOWLDEGEMENTS

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