ANALYSIS OF THE VELOCITY CHANGES OF THE JAKOBSHAVN GLACIER BASED ON SAR IMAGERY

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ABSTRACT: The study analyzes the changes in dynamics of the Jakobshavn Glacier in summer and winter in 2017 and 2021. Satellite radar observations and the available database were used for this. Moreover, the influence of the time baseline between SAR images on the quality of the results was also investigated. The velocities computed from Sentinel-1 images and the offset-tracking technique were compared with the MEaSUREs database information. The results showed that Jakobshavn Glacier accelerated in 2021 up to 39.0 m d^{-1}. However, this value may be underestimated due to the resolution of Sentinel-1 data. The results therefore confirm the acceleration of the glacier melting process, which may be a result of the observed climate changes on our planet.

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Introduction

Melting of glaciers and global ice mass loss are well-known problems nowadays due to plenty of existing studies focusing on the consequences of climate change (Joughin et al. 2010; Vizcaino et al. 2015, Golledge et al. 2019, Wu et al. 2020). Both processes have accelerated in recent years (Hugonnet et al. 2021). The problem of melting glaciers occurs not only in polar regions like the Arctic or Antarctic (Rignot et al. 2014, Lemos et al. 2018a, Tuckett et al. 2019, Joughin et al. 2020) but also in mountains (Zhou et al. 2014, Gatti et al. 2018, Du et al. 2019). The melting of glaciers consequently leads to an increase in sea-level (Aschwanden et al. 2019, Golledge 2020). Greenland is a major contributor to sea-level rise and the velocity of the flow of outlet glaciers is one of the factors influencing the rate of ice mass loss (King et al. 2020). Therefore, persistent monitoring of glacier velocities and their responses to changing conditions is necessary for an accurate estimation of the mass balance.

This study is focused on the biggest and fastest glacier in Greenland, called Jakobshavn. Due to the significant velocities of ice displacement observed for many years, it became an object of interest for researchers (Sohn et al. 1998, Luckman, Murray 2005, Farness, Jezek 2008). The glacier velocity near the terminus position reached 6700

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m a^{-1} in 1985 (Joughin et al. 2004). The velocity was estimated by tracking crevasse displacements on airborne imagery. Until 1992, the Jakobshavn Isbrae was slowing down. The InSAR results showed that in 1992 its maximum speed was 5700 m a^{-1}, but then it started to accelerate rapidly until 2003, reaching even 12600 m a^{-1}. It was caused by the warming of the ocean tides (Holland et al. 2008). Further studies confirmed observed phenomenon in the years 2004–2007 (Joughin et al. 2008). The long-lasting acceleration period in Jakobshavn glacier history resulted in the record velocity noted in the 2012–2013 summer periods. The maximum velocity at the terminus exceeded 17000 m a^{-1} (Joughin et al. 2014). In 2016, the glacier slowed down until 2018 (Khazendar et al. 2019). However in summer 2019, the acceleration at the level of 1500 m a^{-1} was observed (Joughin et al. 2020). New research can confirm acceleration in the dynamics of glacier movements.

Although the regular observation of glaciers is important, it may be challenging due to unfavourable weather conditions, high velocities, and sometimes hindered access to such places. Nevertheless, current easier access to satellite data allows for persistent monitoring of these regions. Especially useful are radar sensors, which acquire data regardless of weather conditions (Lee, Pottier 2009). Currently, SAR satellites are useful tools in cryosphere monitoring, as they are used for observation of displacements of ice masses, assessing grounding line position, or glacier mapping (Winsvold et al. 2018, Friedl et al. 2020, Samsonov et al. 2021). SAR data is used in a variety of techniques to estimate surface movements, including radar interferometry (InSAR) and offset-tracking methods. The main difference between those two methods is that InSAR uses information about the phase of the radar signal (Massonnet, Feigl 1998, Hanssen 2001), while the offset-tracking technique is based on intensity information (Strozzi et al. 2002). Application of the InSAR method in regions where dynamic movements of land surface occur may lead to a loss of coherence (Trouvé et al. 2005). Wherefore, the offset-tracking method is mainly used in ice-covered areas, where velocities are significant and major displacements appear in the horizontal plane. This technique is widely used to obtain glacier surface velocities (Yan et al. 2013, Strozzi

et al. 2017, Gomez et al. 2019, Fang et al. 2020, Neckel et al. 2020) but also displacement values in mining areas (Huang et al. 2016, 2020, Zhao et al. 2021) or even in the areas of landslides (Cai et al. 2017; Sun et al. 2017) or sand dunes (Mahmoud et al. 2020). The accuracy of this method is determined as 1/10-1/30 of the pixel size (Fan et al. 2019). There are also other algorithms for glacier velocity calculations. Some studies show the potential of applying optical imagery and the feature tracking method to monitor such areas, but a collection of useful optical imagery sets is challenging due to polar night or mountainous areas (Guo et al. 2013, Kääb et al. 2016). Another algorithm used in glacier monitoring is autoRIFT, which is also based on normalized cross-correlation but employs progressive window sizes (Lei et al. 2021). Another approach is dense image matching (Schubert et al. 2013). However, compared to cross-correlation techniques, it is less valuable for glaciological purposes and monitoring of large areas.

When the Sentinel-1 mission was released, SAR imagery became a popular data source for different studies, including glacier areas (Nagler et al. 2015). Data is collected at regular intervals and open access is provided. Because observations of surface movements have become easier and timelier (Torres et al. 2012), it led to launching new projects focusing on the usage of satellite data, also for glacier monitoring, such as GIMP (Greenland Ice sheet Mapping Project). Its main objective is to monitor changes in ice sheets and selected glaciers in Greenland (Joughin et al. 2010). Results are distributed by the National Snow and Ice Data Centre (NSIDC) as a part of the MEaSUREs program. This program is coordinated by NASA and its main aim is to share data about the Earth with the scientific community. The MEaSUREs database contains glacier velocities calculated based on TerraSAR-X radar images. Both, the Sentinel-1 imagery and the MEaSUREs database were used in this research.

In spite that there are some research projects collecting information about glacier movements through the years (Joughin et al. 2010), an update of databases is performed with a delay. In some areas, including the Jakobshavn glacier, the pace of velocity changes is high. Considering that glacier flow velocities affect ice mass balance, constant

monitoring of such areas is necessary. Therefore, the presented research focuses on two objectives:

– determine the dynamics in 2021 year of the Jakobshavn glacier's movements and compare the results with selected previous period;
– compare the obtained results with the available database and verify the existing algorithm.

This study shows a comparison of velocities between winter and summer in 2017 and 2021 for the Jakobshavn glacier. This analysis was conducted to deliver a new information about the current velocity of this glacier. Velocities were calculated by the offset-tracking technique using Sentinel-1 SAR acquisition and open-source SNAP (SeNtinel Application Platform) software. In order to obtain the most reliable results, velocities from 2017 were calculated for different time baselines and compared with values from the MEaSUREs database. Therefore, it was possible to assess the influence of the time baseline on the quality of the results. Assessment of current velocities of the Jakobshavn glacier may enable an analysis of its response to climate changes and deliver reliable data for glaciological society. Moreover, an interruption of the slowing-down process is a stimulus to study more carefully which factors triggered such changes, and accurate velocity monitoring is needed for these purposes.

Materials and Methods

Study area

The study area of this research is the Jakobshavn Glacier, located in the western part of Greenland (Fig. 1). Jakobshavn covers an area of about 110 000 km², its length is more than 65 km, and the thickness of the ice masses is about 2 km.

SAR data used in the study

A total of 10 SAR images were used for velocity calculations. They were registered by the Sentinel-1 (S-1) twin satellites that deliver satellite imagery every 6 days almost all over the world. The data were collected for the winter and summer periods of 2017 and 2021 (Table 1). Calculations were performed in 6 intervals with the 6-day baseline for each period and additionally 24- and 30-day baselines in 2017. To implement the offset-tracking method the Ground Range Detected (GRD) products were used with a pixel spacing of 10 × 10 m and a resolution of 20 × 22 m (ESA n.d.). The GRD products are preprocessed SAR data that has been multi-looked and projected to the ground range using an Earth ellipsoid model. Data were acquired in two descending passes: pass 127 for images from 2017 and pass 25
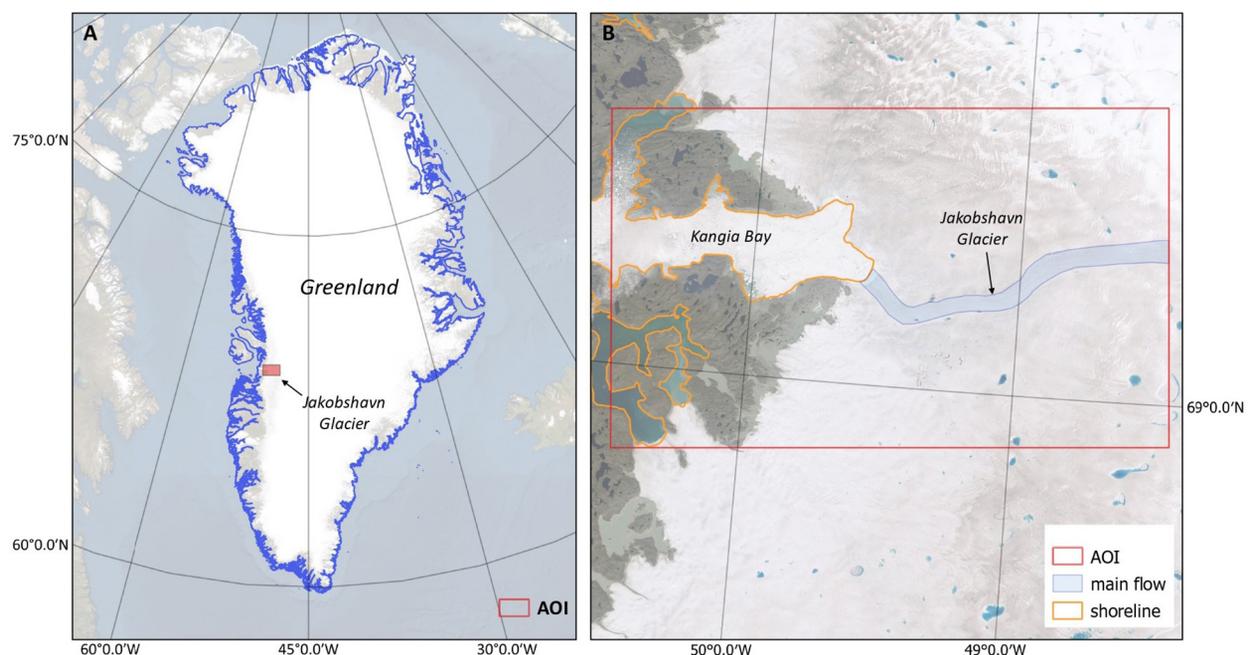

Fig. 1. Location of the area of interest (AOI): A) position of the Jakobshavn glacier on the Greenland map, B) precise location of the glacier near Kangia Bay.

Table 1. Description of data used in the study.

No.	Data of image acquisition	Orbit number	Time baseline [days]	Period
1	31.01.2017	127	6	Winter 2017
	06.02.2017	127		
2	31.01.2017	127	24	
	24.02.2017	127		
3	30.07.2017	127	6	August 2017
	05.08.2017	127		
4	30.07.2017	127	30	
	29.08.2017	127		
5	03.01.2021	25	6	Winter 2021
	09.01.2021	25		
6	01.08.2021	25	6	August 2021
	07.08.2021	25		

for 2021 data. The images were registered using Interferometric Wide mode (IW) with dual horizontal polarization (HH).

MEaSUREs data

Acquired datasets from the MEaSUREs program (Making Earth System Data Records for Use in Research Environments) consist of displacement maps for a selected glacier in GeoTIFF format. Calculations were performed on the basis of SAR images, which were acquired by twin satellites TerraSAR-X/TanDEM-X from the German Aerospace Center (DLR). Delivered raster data have a temporal resolution of 11 days and spatial resolution of 100 × 100 m. They contain velocities along the x and y-axis with estimated errors for these values, as well as the resultant velocity in m a^{-1}. In this research, two datasets were used. They represent the velocities of Jakobshavn Glacier in February and August 2017 (Fig. 2). The datasets are not published continuously but are updated regularly (e.g. for 1.5 years). The current available version delivers information about glaciers' velocities until May 2021 (Joughin et al. 2021).

The spatial distribution of displacements for these periods is similar. The glacier terminus slightly retreats in the summer months and the velocities are higher. In August, the maximum velocity reaches more than 39 m d^{-1}, while during February it is about 31 m d^{-1}. The greatest velocities are near the terminus position.
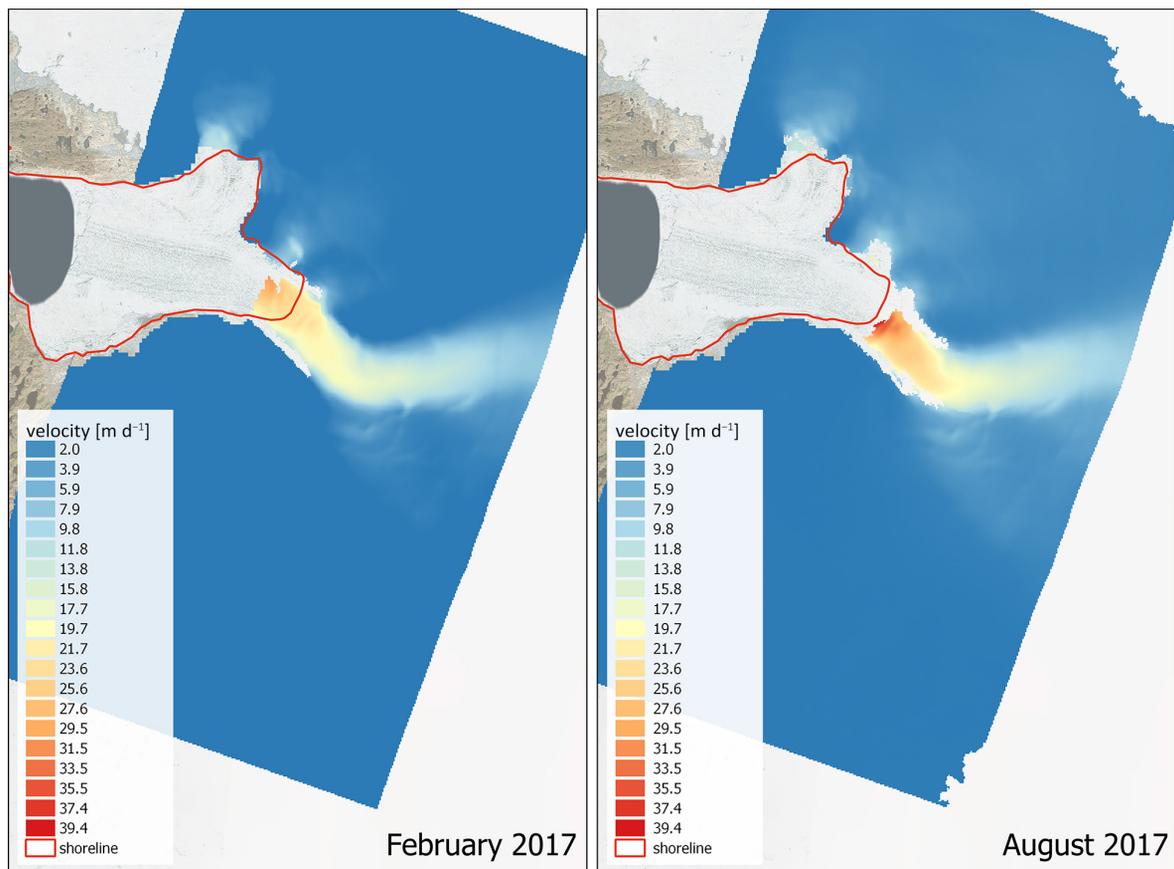

Fig. 2. Velocities of the Jakobshavn Glacier from the MEaSUREs database.

Processing

To obtain the velocities of a glacier, the intensity SAR data from Sentinel-1 satellites were used. The displacements of the Jakobshavn glacier were calculated with the offset-tracking method. This technique allows detecting sub-pixel offsets between two images covering the same area using normalized cross-correlation (Strozzi et al. 2002, Xu et al. 2020). Calculations were performed using open-source SNAP (Sentinel Application Platform) software, provided by the European Space Agency (ESA), for six periods using the same input parameters (Table 2).

In the first step of processing, for each Sentinel-1 image, a file containing information about precise orbits was attached. In the next step, the pairs of the SAR images were co-registered using the digital terrain model ACE30. Afterward, the offset-tracking procedure was applied. The corresponding pixels were searched in both SAR intensity images. The search area was determined by the size of the registration window, which depends on the maximum velocity which can occur in the selected region and the time interval between images. In those limited areas, corresponding points, called Ground Control Points (GCP), are searched. In a further step, distances between these points are calculated in range and azimuth direction, and therefore maximum velocities and their directions are computed. In the last step of processing in the SNAP software, the terrain correction was applied. Georeferenced displacement maps were exported into GeoTIFF format.

To carry out spatial analyses, results from S-1 images and displacement maps from the MEaSUREs database were imported into Quantum GIS (QGIS) software and converted into one coherent reference system. In the next step, a grid of points covering the majority of a glacier was created. For each point, velocity values were extracted from the MEaSUREs database as well as from long- and short-time SNAP calculations.

Table 2. Parameters for the offset-tracking procedure.

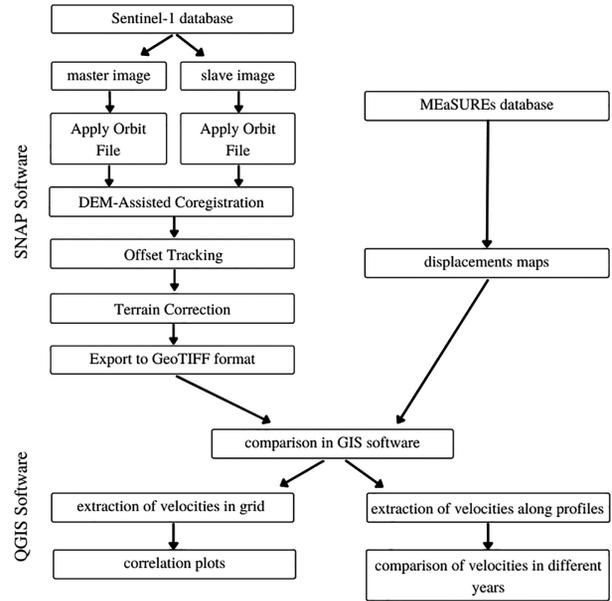| Parameters	
DTM	ACE30
Grid size	20 × 20 pxl (200 × 200 m)
Searching window	128 × 128 pxl
Max velocity	40 m d^{-1}

Fig. 3. Workflow.

On the ground of these data, correlation plots for summer and winter 2017 were created. In the last stage of analysis, 4 profiles were created for the Jakobshavn glacier: one along the main flow and 3 perpendicular profiles. Plots enabled analysis of changes in glacier velocity between 2017 and 2021. The steps of data processing and analysis are presented in the workflow diagram (Fig. 3).

Results

The results of this research are 6 velocity maps for Jakobshavn Glacier obtained by the offset-tracking technique for February 2017, August 2017, January 2021, and August 2021 (Fig. 4). For February and August 2017, two maps for each month were created, containing velocities calculated over a short and long time interval. The obtained results differ not only in the value of the calculated speed but also in the spatial extent where it was possible to locate glacier movements.

In February 2017, two calculating intervals were tested to check the influence of time baseline on the quality of the obtained results. The velocities were calculated at 6- and 24-day intervals. For both periods, the area of detected movements also covers part of the sea-ice floating in the Kangia Bay. For a shorter time baseline, the maximum glacier speed is 31.4 m d^{-1} and in the longer interval, it reaches 27.5 m d^{-1}. For a 24-day

period, velocities are lower in the whole area of the Jakobshavn glacier. Moreover, the continuity of results is disturbed, and more noises appear. The maximum values appear near the terminus but there is no visible cut-off between the glacier tongue and sea-ice cover.

The results of the calculations in both intervals were compared with the velocities from the MEaSUREs database. The correlation plots were created for each pair (Fig. 5). The correlation coefficient for a long interval is 0.25 and for a 6-day period is 0.67. The correlation plot for the 24-day baseline is characterized by a large dispersion of points. A shorter calculation interval results in a significant increase in R^2 value.

For August 2017, velocities were also calculated for two intervals: 6- and 30-days (Fig. 6) and compared to the values from the MEaSUREs
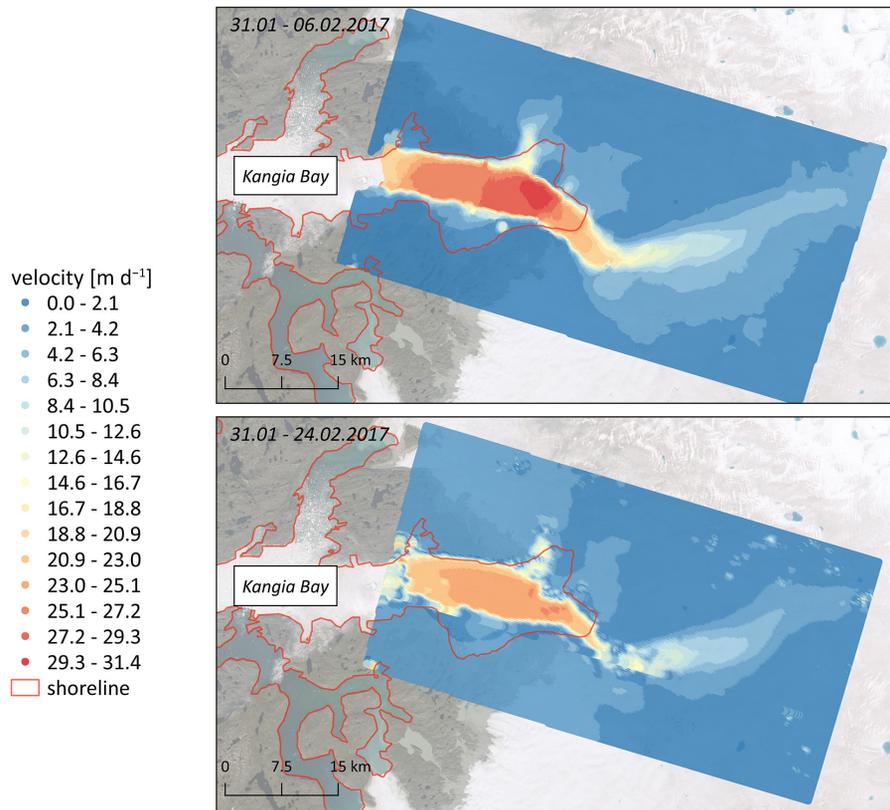

Fig. 4. Velocities for winter 2017 obtained from short and long intervals.
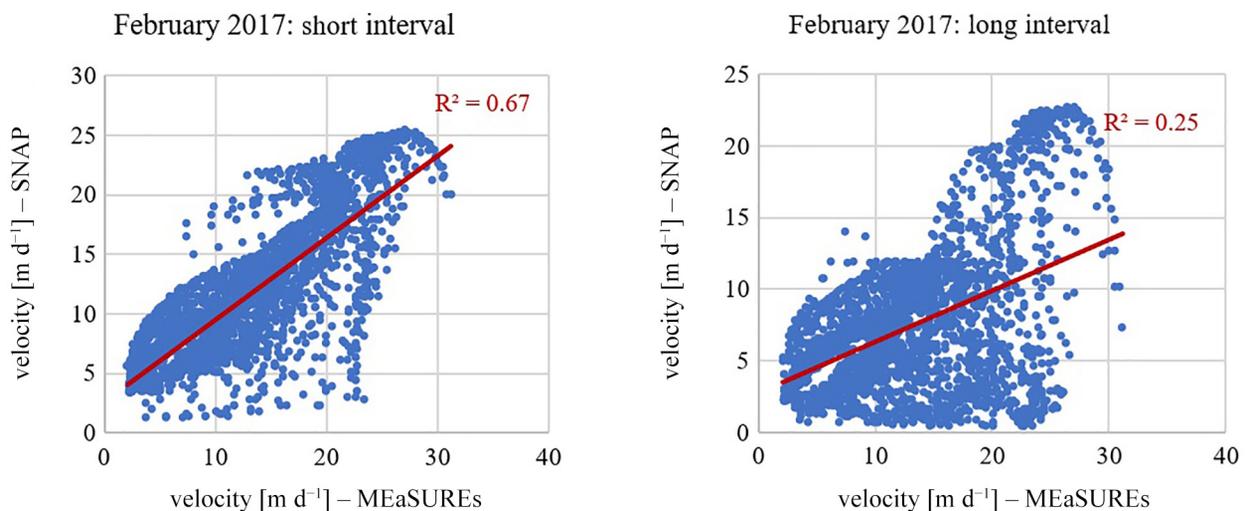

Fig. 5. Correlation plots for winter 2017.

database (Fig. 7). A shorter baseline showed a maximum velocity of 25.0 m d^{-1}. The shape of the glacier and the spatial extent of displacements is similar to data presented in the MEaSUREs database. In the map created for a longer period, a large number of noises are visible. It was also impossible to determine velocities near the glacier terminus. The maximum speed is less than 23.0 m d^{-1}. The correlation plots for summer 2017 present similar results to those from the winter (Fig. 7). The 30-day interval shows lack of correlation between velocities from the SNAP and the MEaSUREs database. The correlation coefficient for 6-day calculations is equal to 0.78. For both periods summer and winter 2017, a significant increase in data quality is visible with a shorter time interval. Velocities from 6-day calculation periods show a higher correlation with values from
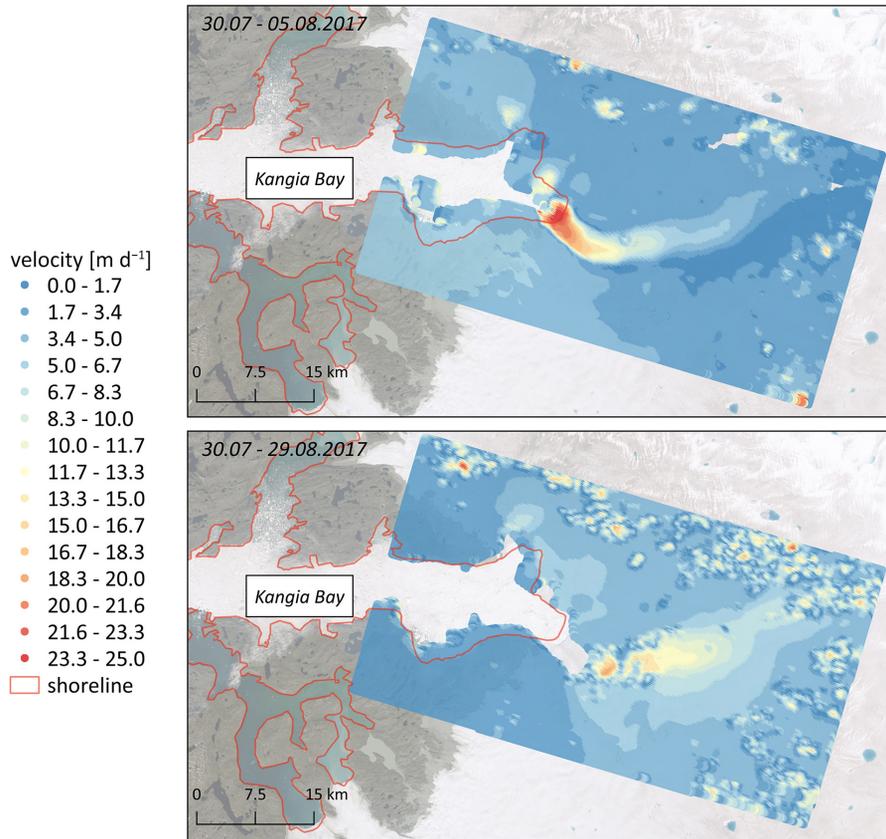

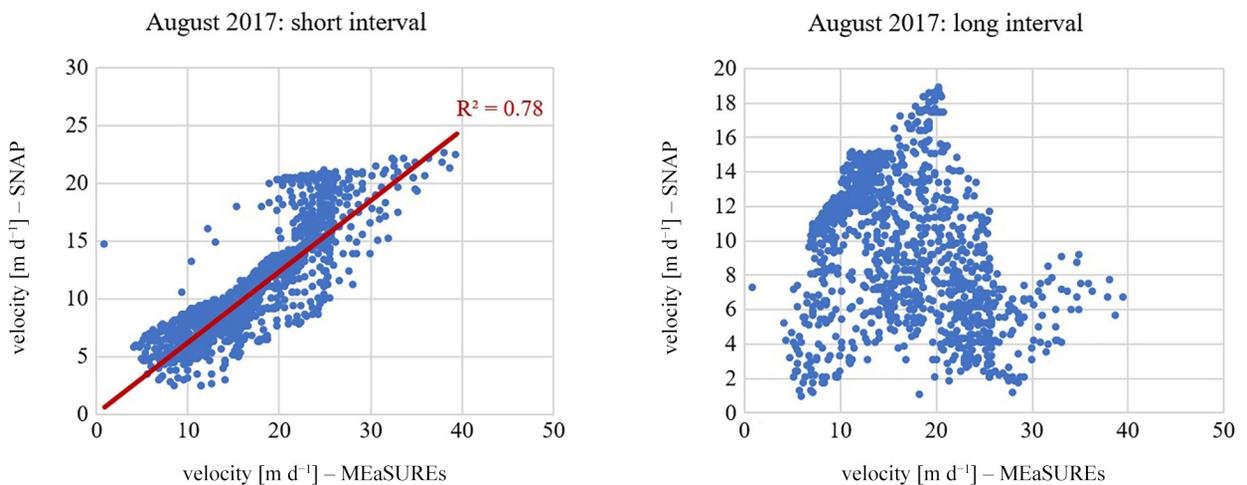Fig. 6. Velocities for summer 2017 obtained from long and short calculation intervals.

Fig. 7. Correlation plots for summer 2017.

independent datasets. They also contain fewer noises and present more reliable results near the terminus and borders of a glacier. However, for both seasons, Sentinel-1 data present an underestimation of displacement values compared to TerraSAR-X/TanDEM-X results.

The MEaSUREs database contains information about the velocity of selected glaciers but it is not updated regularly. To obtain information about velocity of glacier in newer period, it was necessary to calculate displacement using only Sentinel-1 data. Tests for 2017 datasets showed that shorter intervals deliver more reliable results, so calculations in winter and summer 2021 were performed at 6-day intervals. The maximum velocities for both seasons are similar. In January, it is 38.0 m d^{-1} and in August, about 39.0 m d^{-1} (Fig. 8). However, in the map from summer, it is visible that high displacement values are located in a large part of a glacier located near Kangia
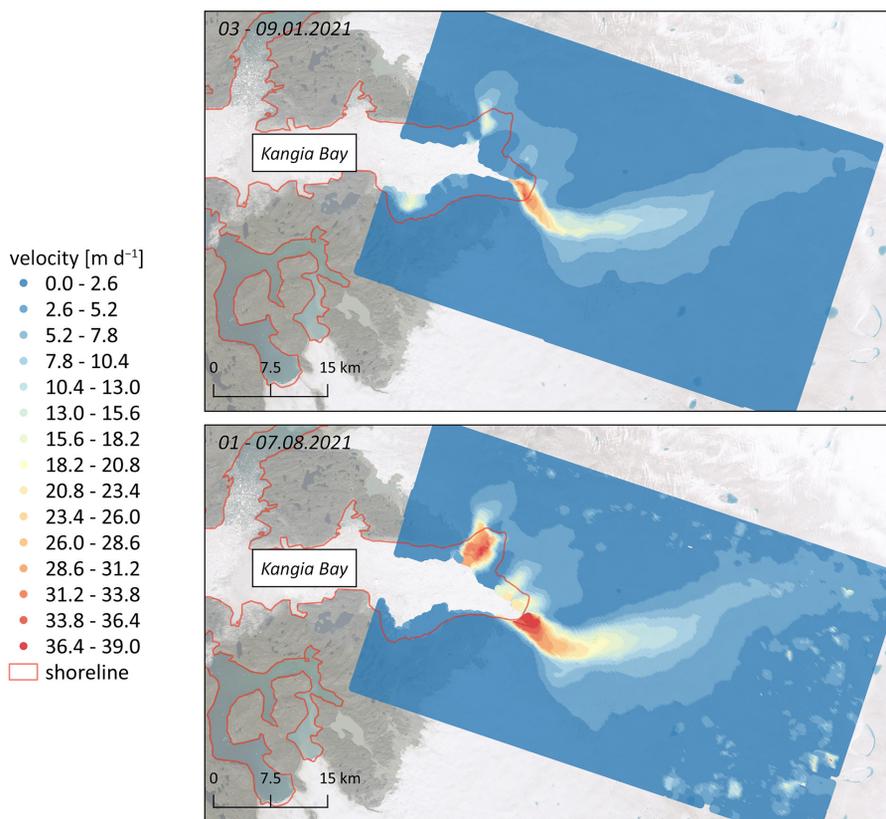

Fig. 8. Velocities of the Jakobshavn Glacier in winter and summer 2021.
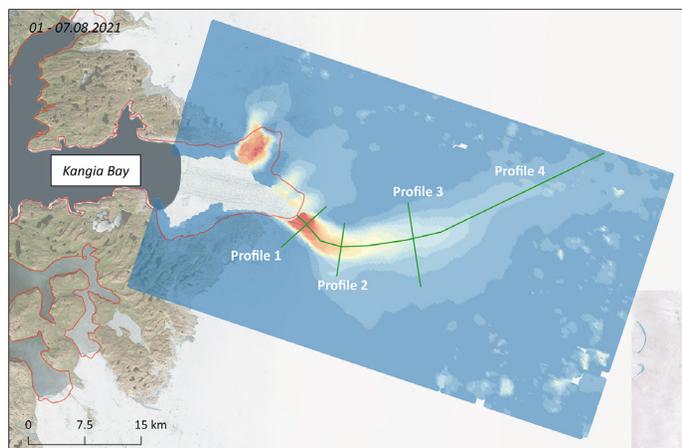

Fig. 9. Location of profiles.

Bay. Moreover, data from August 2021 present another small part of moving ice cover in the west-north part of the map. In winter 2021, no significant movements were registered in this part. For both seasons, the spatial distribution of maximum velocities is similar compared to the MEaSUREs database.

To describe changes in glacier dynamics, velocities along 4 profiles were compared between 2017 and 2021 (Fig. 9). One profile was selected along a line representing the flow of a glacier. 3 profiles were created transverse to the flow line: near the terminus position, in the area of the middle and low values of velocities. Profiles were created for the winter and summer months. A comparison was performed on the 2017 SNAP

results, the MEaSUREs database, and velocities in 2021 obtained from the SNAP software.

Profile 1, located near the front of a glacier, shows slight acceleration of a glacier. The maximum velocity in this part of the glacier increased by about 5.0 m d^{-1}, taking into account only the results from SNAP. The 2nd profile shows that velocities calculated based on Sentinel-1 images did not change significantly. Values from the MEaSUREs database present similar velocities but they are horizontally shifted compared to SNAP results. For the winter months, profile 3 shows similar changes in the glacier velocity in 2017 and 2021 (Fig. 10). The last profile was analyzed along with the main flow direction of the glacier. The mean deviation between SNAP
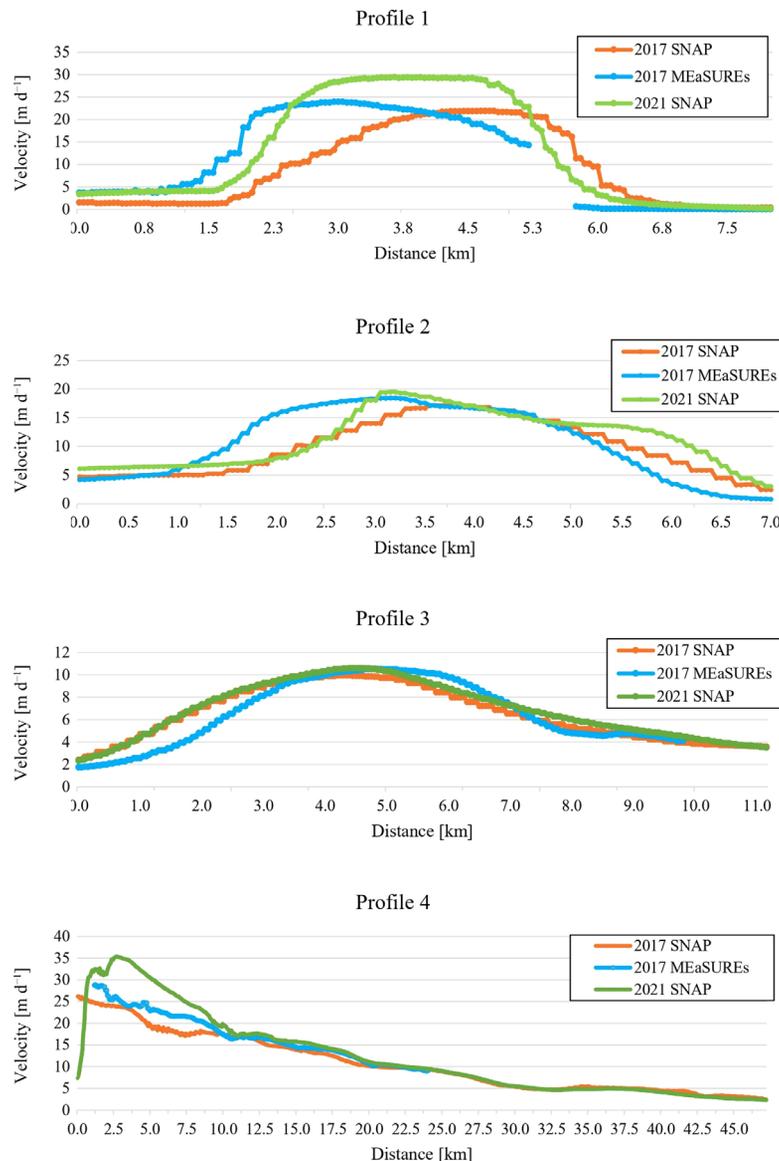

Fig. 10. Winter profiles presenting velocity values.

velocities from 2017 and 2021 was 2.3 m d⁻¹ and between MEaSUREs database 2.5 m d⁻¹. For most of the glacier length, velocities did not change in analyzed periods. The biggest deviations are observed closer to the terminus position. The Jakobshavn glacier increased its velocity in 2021. The maximum velocity along profile 4 reaches in 2021 more than 10 meters more related to similar period in 2017.

Similar profiles were analyzed for velocities in August 2017 and 2021 (Fig. 11). In each of the 4 profiles, a speedup of the Jakobshavn glacier is visible. However, deviations between SNAP values from 2017 and 2021 are greater than in comparison with MEaSUREs velocities. In the first profile, maximum velocity has changed by

almost 20 m d⁻¹ between SNAP calculations. Compared to the MEaSUREs database, the maximum velocity of the glacier increased by almost 10 m d⁻¹. Profiles 2 and 3 also show an increase in velocity values in August 2021. SNAP velocities are higher even about 8–10 m d⁻¹ but comparison with independent database also shows acceleration at the level of a few m d⁻¹. Profile 4, presenting changes in the velocity alongside the main flow of the glacier, shows a speedup along the entire glacier in summer 2021. In the front part of a glacier, the increase in velocity reaches even 20 m d⁻¹. Values from the MEaSUREs database from 2017 show smaller changes in velocity. However, the velocity has changed by almost 10 m d⁻¹ in areas of the greatest velocities.
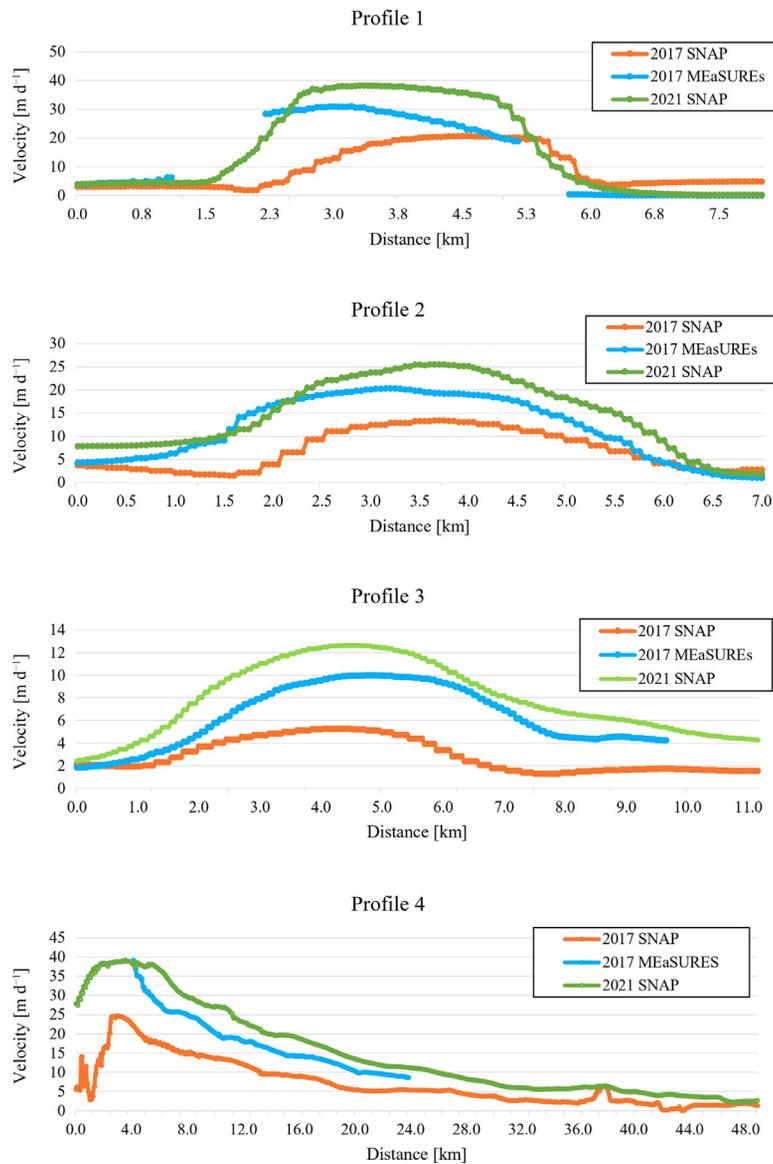
Fig. 11. Summer profiles presenting velocity values.

Discussion

The presented study shows that calculations using the offset-tracking technique deliver more reliable results for shorter time baselines. Velocities based on shorter intervals show a higher correlation with values from the MEaSUREs database. Fast changes in glacier structure probably resulted in the poor quality of the results from the long interval. However, even for a short time baseline, there are differences between these two sources. It probably results from the different pixel sizes of SAR images. Cross-correlation algorithm aggregates the information from lower resolution of Sentinel-1. Thus, the satellite signal is averaged over a larger area, which results in underestimating the maximum values compared to the results for TerraSAR-X data. The results also reveal an acceleration of the Jakobshavn glacier in 2021 compared to 2017. The acceleration is visible between calculations in the SNAP software, which were conducted on the same input processing parameters. The velocity change at the level of several or even a dozen meters between those two periods is significant. According to previous studies, the velocity of the Jakobshavn glacier had been decreasing until 2018 (Khazendar et al. 2019). In 2017, a slow-down period was observed (Riel et al. 2021) and even the seasonal variability of ice speed diminished (Lemos et al. 2018b), which is also visible in the presented velocity maps. In 2019, this downward trend (Joughin et al. 2020) was disturbed, but there were no more studies confirming the trend reversal. The results of this research for 2021 indicate that the Jakobshavn glacier started to accelerate again, and 2019 was probably the turning point. Moreover, in summer 2021, the calculated maximum velocity reached 39.0 m d^{-1}, which is in agreement with a prediction from 2020 (Willis et al. 2020). The expected value of ice velocity was 14.4 km a^{-1}, which corresponds to approx. 39.5 m d^{-1}. What is more, a yearly analysis of the Greenland ice sheet also confirmed that the Jakobshavn Isbræ has accelerated again between 2020 and 2021 (Mottram et al. 2021).

Conclusion

In this research, results obtained for 2017 allowed comparison of existing algorithms used in glacier dynamics studies. Results from Sentinel-1 data present underestimation of displacement compared to the MEaSUREs database results. Furthermore, the use of open-source software and Sentinel-1 data in this research allowed confirmation of the acceleration trend for the Jakobshavn glacier. However, due to fact of low resolution of Sentinel-1 data, it should be supposed that the maximum value of the velocity in 2021 is greater than obtained result 39.0 m d^{-1}. Taking into account the possible underestimation of the results for the Sentinel-1 data, the obtained results can be important in research of glacial dynamics, as the results of climate change. It is also important to deeper analyze the possible causes of such acceleration because it can result in further thinning and melting of a glacier. In further research, the possible causes of velocity changes should be analyzed, including weather conditions such as temperature and precipitation, or sea temperature. Nonetheless, the variability of velocity changes is one of the crucial aspects in glacial changes studies.

Author's contribution

Ł.M. – 70% – data preparation and processing, research methodology, analysis, preparation of the manuscript; H.R. – 10% – writing, review and editing; W.W.T. – 20% – writing, data analysis, review and editing. All authors have read and agreed to the published version of the manuscript.

References

Aschwanden A., Fahnestock M.A., Truffer M., Brinkerhoff D.J., Hock R., Khroulev C., Mottram R., Khan A.S., 2019. Contribution of the Greenland Ice Sheet to sea level over the next millennium. *Science Advances* 5(6). DOI 10.1126/SCIADV.AAV9396.

Cai J., Wang C., Mao X., Wang Q., 2017. An adaptive offset tracking method with SAR images for landslide displacement monitoring. *Remote Sensing* 9(8): 830.

Du W., Liu X., Guo J., Shen Y., Li W., Chang X., 2019. Analysis of the melting glaciers in Southeast Tibet by ALOS-PAL-SAR data. *Terrestrial, Atmospheric and Oceanic Sciences* 30: 7–19.

ESA. n.d. *Sentinel-1 SAR technical guide*. Online: https://sentinels.copernicus.eu/web/sentinel/technical-guides/sentinel-1-sar/products-algorithms/level-1-algorithms/ground-range-detected (accessed 11 October 2021).

Fan J., Wang Q., Liu G., Zhang L., Guo Z., Tong L., Peng J., et al., 2019. Monitoring and analyzing mountain glacier surface movement using SAR data and a terrestrial laser scanner: A case study of the Himalayas north slope glacier area. *Remote Sensing* 11(6): 625.

Fang L., Ye Z., Su S., Kang J., Tong X., 2020. Glacier surface motion estimation from SAR intensity images based on subpixel gradient correlation. *Sensors* 20(16): 4396.

Farness K., Jezek K.C., 2008. *Velocity trends for Jakobshavn glacier, Greenland for the years 2000, 2004, 2005, and 2006 including procedure manuals*. Byrd Polar Research Center, The Ohio State University. Online: https://kb.osu.edu/handle/1811/54467 (accessed 14 January 2022).

Friedl P., Weiser F., Fluhrer A., Braun M.H., 2020. Remote sensing of glacier and ice sheet grounding lines: A review. *Earth-Science Reviews* 201: 102948.

Gatti R.C., Dudko A., Lim A., Velichevskaya A.I., Lushchaeva I.V., Pivovarova A.V., Ventura S., Lumini E., Berruti A., Volkov I.V., 2018. The last 50 years of climate-induced melting of the Maliy Aktru glacier (Altai Mountains, Russia) revealed in a primary ecological succession. *Ecology and Evolution* 8(15): 7401–7420.

Golledge N.R., 2020. Long-term projections of sea-level rise from ice sheets. *Wiley Interdisciplinary Reviews: Climate Change* 11(2): e634.

Golledge N.R., Keller E.D., Gomez N., Naughten K.A., Bernales J., Trusel L.D., Edwards T.L., 2019. Global environmental consequences of twenty-first-century ice-sheet melt. *Nature* 566(7742): 65–72.

Gomez R., Arigony-Neto J., De Santis A., Vijay S., Jaña R., Rivera A., 2019. Ice dynamics of union glacier from SAR offset tracking. *Global and Planetary Change* 174: 1–15.

Guo W., Liu S., Wei J., Bao W., 2013. The 2008/09 surge of central Yulinchuan glacier, northern Tibetan Plateau, as monitored by remote sensing. *Annals of Glaciology* 54(63): 299–310.

Hanssen R., 2001. *Radar interferometry – Data interpretation and error analysis*, 1st edn., Vol. 2. Springer Netherlands, Dordrecht. DOI 10.1007/0-306-47633-9.

Holland D.M., Thomas R.H., De Young B., Ribergaard M.H., Lyberth B., 2008. Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters. *Nature Geoscience* 1(10): 659–664.

Huang J., Bai Y., Lei S., Deng K., 2020. Time-series SBAS pixel offset tracking method for monitoring three-dimensional deformation in a mining area. *IEEE Access* 8: 118787–118798.

Huang J., Deng K., Fan H., Yan S., 2016. An improved pixel-tracking method for monitoring mining subsidence. *Remote Sensing Letters* 7(8): 731–740. DOI 10.1080/2150704X.2016.1183177.

Hugonnet R., McNabb R., Berthier E., Menounos B., Nuth C., Girod L., Farinotti D., Huss M., Dussaillant I., Brun F., Kääb A., 2021. Accelerated global glacier mass loss in the early twenty-first century. *Nature* 592(7856): 726–731.

Joughin I., Abdalati W., Fahnestock M., 2004. Large fluctuations in speed on Greenland's Jakobshavn Isbræ glacier. *Nature* 432(7017): 608–610.

Joughin I., Shean D.E., Smith B.E., Floricioiu D., 2020. A decade of variability on Jakobshavn Isbræ: Ocean temperatures pace speed through influence on mélange rigidity. *Cryosphere* 14(1): 211–227.

Joughin I., Howat I.M., Fahnestock M., Smith B., Krabill W., Alley R.B., Stern H., Truffer M., 2008. Continued evolution of Jakobshavn Isbrae following its rapid speed-up. *Journal of Geophysical Research: Earth Surface* 113(F4): 4006.

Joughin I., Smith B.E., Howat I.M., Scambos T., Moon T., 2010. Greenland flow variability from ice-sheet-wide velocity mapping. *Journal of Glaciology* 56(197): 415–430.

Joughin I., Smith B.E., Shean D.E., Floricioiu D., 2014. Brief communication: Further summer speedup of Jakobshavn Isbræ. *Cryosphere* 8(1): 209–214.

Joughin I, Howat I.M., Smith B., Scambos T., 2021. *MEaSUREs Greenland Ice Velocity: Selected Glacier Site Velocity Maps from InSAR*, Version 4. [Jakobshavn Glacier]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. DOI 10.5067/GQZQY2M5507Z.

Kääb A., Winsvold S.H., Altena B., Nuth C., Nagler T., Wuite J., 2016. Glacier remote sensing using Sentinel-2. Part I: Radiometric and geometric performance, and application to ice velocity. *Remote Sensing* 8(7): 598. DOI 10.3390/rs8070598.

Khazendar A., Fenty I.G., Carroll D., Gardner A., Lee C.M., Fukumori I., Wang O., Zhang H., Seroussi H., Moller D., Noël B.P.Y., van der Broeke M.R., Dinardo S., Willis J., 2019. Interruption of two decades of Jakobshavn Isbrae acceleration and thinning as regional ocean cools. *Nature Geoscience* 12(4): 277–283.

King M.D., Howat I.M., Candela S.G., Noh M.J., Jeong S., Noël B.P.Y., van den Broeke M.R., Wouters B., Negrete A., 2020. Dynamic ice loss from the Greenland ice sheet driven by sustained glacier retreat. *Communications Earth & Environment* 1(1): DOI 10.1038/s43247-020-0001-s.

Lee J.S., Pottier E., 2009. *Polarimetric radar imaging: From basics to applications*. CRC Press. DOI 10.1201/9781420054989.

Lei Y., Gardner A., Agram P., 2021. Autonomous repeat image feature tracking (autoRIFT) and its application for tracking ice displacement. *Remote Sensing* 13(4): 1–20.

Lemos A., Shepherd A., McMillan M., Hogg A.E., 2018a. Seasonal variations in the flow of land-terminating glaciers in central-west Greenland using sentinel-1 imagery. *Remote Sensing* 10(12): 1878.

Lemos A., Shepherd A., McMillan M., Hogg A.E., Hatton E., Joughin I., 2018b. Ice velocity of Jakobshavn Isbræ, Petermann Glacier, Nioghalvfjerdsfjorden, and Zachariæ Isstrøm, 2015–2017, from Sentinel 1-a/b SAR imagery. *Cryosphere* 12(6): 2087–2097.

Luckman A., Murray T., 2005. Seasonal variation in velocity before retreat of Jakobshavn Isbræ, Greenland. *Geophysical Research Letters*, 32(8): 1–4.

Mahmoud A.M.A., Novellino A., Hussain E., Marsh S., Psimoulis P., Smith M., 2020. The use of SAR offset tracking for detecting sand dune movement in Sudan. *Remote Sensing* 12(20): 3410.

Massonnet D., Feigl K.L., 1998. Radar interferometry and its application to changes in the earth's surface. *Reviews of Geophysics* 36(4): 441–500.

Mottram R., Stendel M., Box J., Mankoff K., Ahlstrøm A., 2021. What happened to Greenland's ice sheet in 2021? *World Economic Forum*, 1 December. Online: https://www.weforum.org/agenda/2021/12/greenland-ice-sheet-environment-climate-change/ (accessed 31 January 2022).

Nagler T., Rott H., Hetzenecker M., Wuite J., Potin P., 2015. The sentinel-1 mission: New opportunities for ice sheet observations. *Remote Sensing* 7(7): 9371–9389.

Neckel N., Zeising O., Steinhage D., Helm V., Humbert A., 2020. Seasonal observations at 79°N glacier (Greenland) from remote sensing and in situ measurements. *Frontiers in Earth Science* 8: 142.

Riel B., Minchew B., Joughin I., 2021. Observing traveling waves in glaciers with remote sensing: New flexible time series methods and application to Sermeq Kujalleq (Jakobshavn Isbræ. Greenland. *Cryosphere* 15(1): 407–429.

Rignot E., Mouginot J., Morlighem M., Seroussi H., Scheuchl B., 2014. Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. *Geophysical Research Letters* 41(10): 3502–3509.

Samsonov S., Tiampo K., Cassotto R., 2021. SAR-derived flow velocity and its link to glacier surface elevation change and mass balance. *Remote Sensing of Environment*, 258: 112343.

Schubert A., Faes A., Kääb A., Meier E., 2013. Glacier surface velocity estimation using repeat TerraSAR-X images: Wavelet- vs. correlation-based image matching. *ISPRS Journal of Photogrammetry and Remote Sensing* 82: 49–62.

Sohn H.-G., Jezek K.C., van der Veen C.J., 1998. Jakobshavn Glacier, west Greenland: 30 years of spaceborne observations. *Geophysical Research Letters* 25(14): 2699–2702.

Strozzi T., Luckman A., Murray T., Wegmüller U., Werner C.L. 2002. Glacier motion estimation using SAR off-set-tracking procedures. *IEEE Transactions on Geoscience and Remote Sensing*, 40(11): 2384–2391.

Strozzi T., Paul F., Wiesmann A., Schellenberger T., Kääb A., 2017. Circum-arctic changes in the flow of glaciers and ice caps from satellite SAR data between the 1990s and 2017. *Remote Sensing* 9(9): 947.

Sun L., Muller J.-P., Chen J., 2017. Time series analysis of very slow landslides in the three gorges region through small baseline SAR offset tracking. *Remote Sensing* 9(12): 1314.

Torres R., Snoeij P., Geudtner D., Bibby D., Davidson M., Attema E., Potin P., Rommen B., Floury N., Brown M., Traver I.N., Deghaye P., Duesmann B., Rosich B., Miranda N., Bruno C., L'Abbate M., Croci R., Pietropaolo A., Huchler M., Rostan F., 2012. GMES Sentinel-1 mission. *Remote Sensing of Environment* 120: 9–24.

Trouvé E., Vasile G., Gay M., Grussenmeyer P., Nicolas J.M., Landes T., Koehl M., Chanussot J., Julea A., 2005. Combining optical and SAR data to monitor temperate glaciers. *International Geoscience and Remote Sensing Symposium (IGARSS)*, Vol. 4, pp. 2637–2640.

Tuckett P.A., Ely J.C., Sole A.J., Livingstone S.J., Davison B.J., Melchior van Wessem J., Howard J., 2019. Rapid accelerations of Antarctic Peninsula outlet glaciers driven by surface melt. *Nature Communications* 10(1): 1–8.

Vizcaino M., Mikolajewicz U., Ziemen F., Rodehacke C.B., Greve R., Van Den Broeke, M.R., 2015. Coupled simulations of Greenland Ice Sheet and climate change up to A.D. 2300. *Geophysical Research Letters* 42(10): 3927–3935.

Willis J., Carroll D., Gardner A., Khazendar A., Wood M., Holland D., 2020. *Glacier forecast: Jakobshavn Isbrae primed for thinning and acceleration*. Preprint, ResearchSquare, pp. 1–23.

Winsvold S.H., Kääb A., Nuth C., Andreassen L.M., Van Pelt W.J.J., Schellenberger, T., 2018. Using SAR satellite data time series for regional glacier mapping. *The Cryosphere* 12: 867–890.

Wu Z., Zhang W.H., Liu Y.S., Ren D., Xun J.Z., Bai J.X., 2020. Analysis of the response of glaciers to climate change based on the glacial dynamics model. *Environmental Earth Sciences* 79(19): 1–10.

Xu X., Ma C., Lian D., Zhao D., 2020. Inversion and analysis of mining subsidence by integrating DInSAR, offset tracking, and PIM technology. *Journal of Sensors* 2020(8): 1–15. DOI 10.1155/2020/4136837.

Yan S., Guo H., Liu G., Fu W., 2013. Monitoring Muztagh Kuksai glacier surface velocity with L-band SAR data in southwestern Xinjiang, China. *Environmental Earth Sciences* 70(7): 3175–3184.

Zhao G., Wang L., Deng K., Wang M., Xu Y., Zheng M., Luo Q., 2021. An adaptive offset-tracking method based on deformation gradients and image noises for mining deformation monitoring. *Remote Sensing* 13(15): 2958.

Zhou J., Li Z., Guo W., 2014. Estimation and analysis of the surface velocity field of mountain glaciers in Muztag Ata using satellite SAR data. *Environmental Earth Sciences* 71(8): 3581–3592.