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ORIGINAL PAPER

POLAR LANDSCAPE TRANSFORMATIONS OF SELECTED GLACIERS IN SOUTHWESTERN SPITSBERGEN BASED ON SENTINEL-1 AUTORIFT PIXEL TRACKING

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ABSTRACT

Polar landscape is a unique system comprising interrelated elements of natural environment. Great glacial valleys reveal the bedrock and become deserted, giving new appearance to areas once dominated by snow and ice. Such a landscape transformation process is described here for three southwestern Spitsbergen glaciers investigated in the years 2018-2022. Changes of glacier surface relief are due to the velocity of glacier movement on the bedrock. The velocities were calculated from SAR data, with the use of AutoRift and Geogrid being part of the ISCE suite. The article identifies the time-variability and the repeatability of the process and compares surface velocities for different types of glaciers. It demonstrates that the velocities significantly differ depending on the type of the glacier, the bedrock and the atmospheric conditions. It also discusses the impact of wind velocity, precipitation and humidity on the velocity of ice mass movement on the surface. Despite some differences in glacier velocities, the article demonstrates deformation of the surface in changing climatic parameters for each of the described objects.

1. INTRODUCTION

The polar landscape, with its glaciers, mountains, rivers, lakes, the coastline and general surrounding, is unique and also subjected to transformations in time. The rate of such changes largely depends on the climate. Global warming is particularly noticeable in these regions and manifests itself in the regression of glaciers (Robinson, 2022). The variability of the ice sheet is one of the indicators of the landscape transformations. The flow of the ice sheet results in constant transformations of the polar environment, which was relatively stable in previous periods. The regression of glaciers has consequences for both polar and global climate (Constable et al., 2022). Modifications of the ice sheet indicate a constant, cyclical increase of temperatures and is expected to continue. Over the last years, the deterioration of glaciers has intensified drastically, from several centimeters to several or even several hundred meters per day, depending on the type, location, exposition and other glaciological, morphological and geomorphological parameters (Błaszczyk et al., 2009). The transformation process is influenced by a number of structural factors, such as hydraulic characteristics and mass balance, external factors such as temperature and humidity, and geomorphological factors, such as the appearance and disappearance of glacial rivers and lakes. All of the Svalbard glaciers are in retreat (Sasgen et al., 2022). The location of the Svalbard archipelago makes it especially vulnerable to the impacts of the aforementioned changes (Isaksen et al., 2016). Between 1936 and 2010, the surface area of Svalbard's glaciers decreased by 10.4 %, while their volume declined by 14.8 % (Geyman et al., 2022). The glacier retreat rate has increased significantly in recent years (Nuth et al., 2013). One of the degradation parameters is the velocity of ice flow towards the terminus, as it is of major importance for glacier retreat (Noël et al., 2020; Błaszczyk et al., 2013). For water-terminating glaciers, an increase in ice flow velocity leads to a higher calving rate (Strozzi et al., 2022). The terminus of a valley glacier melts slowly and successively, exposing diverse bedrock. Empty trough valleys are subject to geomorphological transformations, the permafrost becomes degraded, and the sediments cause changes in the terrain relief (Dutta et al., 2023). Simultaneously, as valley glaciers retreat, they expose depressions in which glacial lakes are formed (Stachniak et al., 2022). Between the glacier and the moraines, glacial rivers flowing from under the terminus form extensive flooded plains with additional currents, smaller or bigger lakes, islands, hills and hillocks. The slopes of trough valleys show sedimentary cones which change along with the transformations in the permafrost layer (Strzelecki et al., 2020). When retreating, glaciers rapidly change their surface shape, frequently forming large-area surface lakes, glaciological moulins, rivers, caves and faults on the surface, caused by the glacial drainage which changes over the year. As glaciers retreat, they expose changes in the length and shape of the coastline in polar areas, as well as changes in the shape of fjords

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and bays (Dudek et al., 2023). The above only some of the elements shaping the polar landscape are, appearing and disappearing at different rates, and changing the environment at different time intervals.

The condition of glaciers is most frequently analyzed by determining the movement rate of ice masses, as well as variations in surface height, mass balance, location of the terminus, and equilibrium lines. The location of successive, different ice fractions is measured using glaciological and geodetic methods (Romshoo et al., 2022). Direct all-year measurements of all glaciers in the polar regions are difficult or even impossible and often dangerous to perform. Glacier monitoring today relies heavily on remote sensing techniques, particularly active synthetic aperture radar interferometry (SAR) systems (Bertone et al., 2022).

SAR data plays a key role in image classification and enables the monitoring of changes and the measuring of the ice flow velocity on the surface. The employed techniques include tracking displacements (features) and speckle-tracking – a method of monitoring both amplitude and phase changes, particularly useful for monitoring fast and time-varying surface velocities (Apanowicz, 2022; Lei et al., 2021; Milczarek et al., 2022).

The displacement velocities of the ice cover in the northern part of the globe are analyzed as part of numerous research projects. The most important include MEaSUREs ITS_LIVE (Gardner et al., 2018; Lei et al., 2022; Nagler et al., 2015; Mouginot et al., 2019), in which the information is based on optical images acquired from the Landsat 4-8 satellites. The presented values describe the average annual displacement velocities of the glacier surface in the years 1985 – 2019. On the other hand, the data available in the PROMICE (Monitoring of the Greenland Ice Sheet) project was collected for Greenland at 12-day time intervals from January 2016 to the end of December 2022 (Solgaard et al., 2021). The GFZ (German Research Centre for Geosciences) (Friedl et al., 2021) provides glacier surface velocity data for Svalbard covering the period from January 2015 to November 2020. However, these services do not include up-to-date information on ice flow velocities and the associated landscape changes. Milczarek et al. offer an analysis and explanation of the causes of changes in the movement rates of ice shelf terminuses in Hornsund Bay on Svalbard in 2018-22 (Milczarek et al., 2022).

The aim of the study was to analyze transformations in the polar landscape comprising glaciers as the main and highly dynamic component. Changes in the relief of glacier surface are determined by glacial surface velocities which differ in time and space. The velocity variations were analyzed using the AutoRIFT module (for analyzing the variations) and Geogrid (for geocoding from the ISCE system). The method of data preparation for analyses of glacier surface velocities has been presented by various authors on examples from the polar areas of Greenland and the Hornsund Fjord on Spitsbergen (Gardner et al., 2018; Lei et al., 2022; Milczarek et al., 2022). The correct tracing of changes in the imaging coordinates on the geographic grid required a digital terrain model (DTM) and a digital terrain slope model (DTSM). Two tables were developed that search for matched points in pixel and coordinate grids. The displacements were identified on image pixels and the result was identified in the form of geographical coordinates.

2. STUDY AREA

In the southwestern part of Wedel-Jarlsberg Land, near Nottinghambukta Bay and deeper into the Brateggbeken valley, the University of Wrocław operates the Stanisław Baranowski Research Station, located northeast of the Werenskioldbreen polythermal glacier. Further north of this glacier, there is another polythermal valley glacier – Nannbreen, and not far to the north, the wide Austre Torellbreen ice shelf extends from Skoddebukta Bay. The marginal zone of the Werenskioldbreen glacier is connected with Nannbreen by a wide delta and the Elveflya glacial river plain. The glaciers in this region exhibit horizontal variability, with ice cover increasing progressively from west to east. The valley glaciers are located between mountain ranges starting close to the sea, with the peaks Angellfjellet, Jens Erikfjellet, Wernerknatten, Rundingen, and the highest Solheimfjellet (941 m above sea level). The mountain ranges are free of ice, and small mountain glaciers – Wernerbreen, Tonefjellbreen, Bratthobreen and others without proper names – are located between them. Valley glaciers can be found further in the eastern direction, and Spitsbergen-type glaciers – deeper in land (Jania, 1988). The landscape in this Svalbard region is formed by glaciers located in wide valleys between high mountain peaks and glacial river deltas (Fig. 1).

Regular measurements of glacier surface movement in the study area became feasible with the introduction of Landsat 8 mission imagery, as part of the ITS-LIVE program (Gardner et al., 2018; Lei et al., 2022). Annual data are available for the years 2014–2018. During this time, particularly between 2016 and 2018, most glaciers exhibited an increase in velocity accompanied by the retreat of their terminus. The Austre Torellbreen glacier proved to be the most dynamic: in 2014, its terminal velocity did not exceed 500 m/year (Gardner et al., 2018), but by 2018, velocities in some areas had locally reached 1,000 m/year. The Werenskioldbreen and Nannbreen glaciers did not show such significant displacements in the subsequent years – in this case the velocities oscillate around 25 m/year. This behavior is attributed to their location in glacial valleys (Błaszczyk et al., 2013).

The research results are presented for the period of 2018-2022, for 3 different glaciers having different morphological characteristics, sizes, and ice flow dynamics (Table 1).

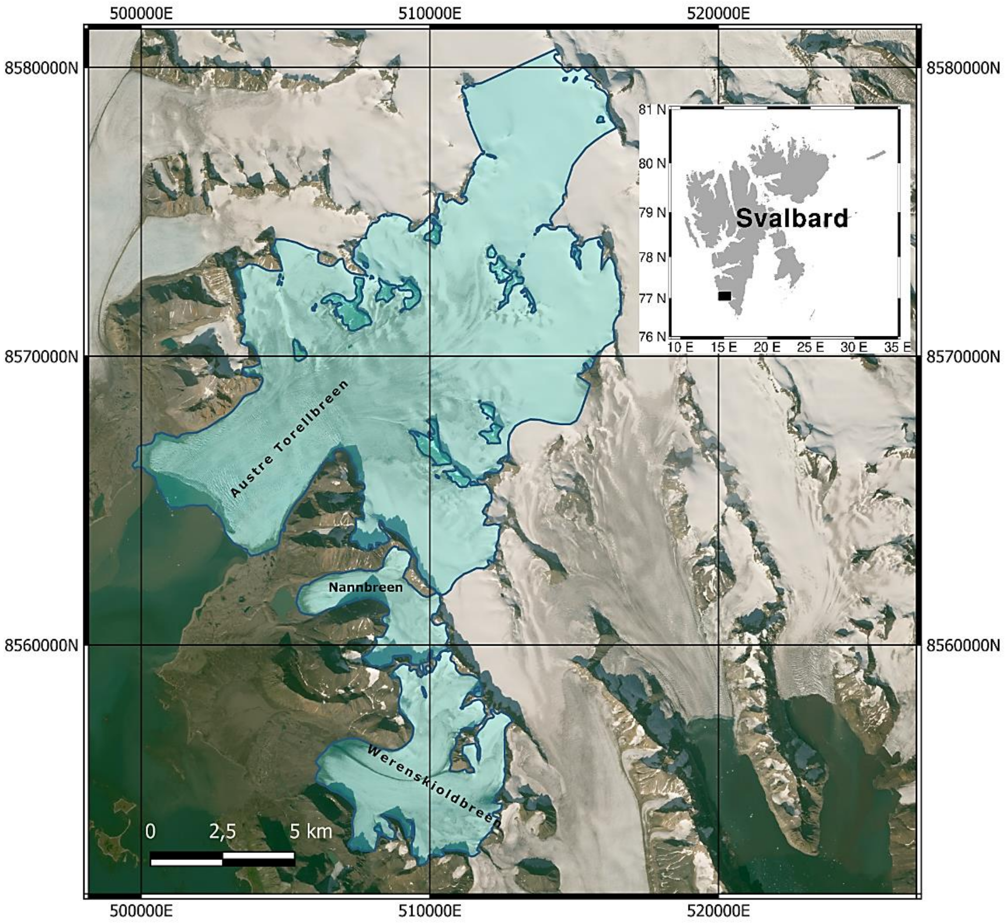

Fig. 1 Svalbard – location of the study area. Base: orthophotomap from the Imaico.de service based on Copernicus Sentinel 2021, glacier outlines based on GLIMS 2015. WGS'84 Coordinate Systém.

Table 1 Glaciological characteristics of the discussed glaciers.

GLIMS No	Name	Type	Area (km^2)	Exposition	Dynamic class	Average inclination (°)
125001	Werenskioldbreen	valley, land-surface	27.4	south-east	surface deformations	3.5
125002	Nannbreen	valley, land-surface	10.0	east	surface deformations	4.8
125003	Austre Torellbreen	complex, partially covered, terminating in the sea	150.0	north-east	basal slide	2.1

Compared to glaciers terminating on land, glaciers terminating directly in the sea have higher ice flow velocities during this period. The displacement of the valley glacier is caused by basal slide, and in the case of the ice shelf, the flow is accelerated by the presence at the glacier bed and the influence of seawater on its terminus (Błaszczyk et al., 2009).

3. METHODS

The analysis of polar landscape transformations focused on determining glacier flow velocity within the study area (Fig. 1), using radar data from Sentinel-1 satellites. These satellites allow surface changes to be monitored under all weather conditions.

3.1. SENTINEL-1 DATA

The radar images analyzed in this study span the period from beginning of January 2018 (18.01.06) to the end of January 2022 (21.01.22)~~.~~

402 images from the ascending orbit 14 were utilized to examine changes in the terrain relief, which contribute to landscape transformations.

The analysis was based on Sentinel-1 Level-1 Single Look Complex (SLC) products acquired in Interferometric Wide (IW) mode. The preprocessing consisted of precise co-registration of SLC image pairs and preparation of the interferometric geometry in the ISCE environment. No conversion from raw (Level-0) data was performed; instead, standard Level-1 SLC products provided by the Sentinel-1 mission were used as input for the subsequent AutoRIFT processing.

Image pairs were then co-registered at an initial interval of 6 days, maintaining temporal continuity through to the end of December 2021. After this point, the interval between images was increased to 12 days to continue the analysis. The result was a continuous time sequence of 236 interferograms. Each of the secondary images in the interferogram was also a reference image for the successive image. The calculations were performed in ISCE software, described in detail by Lei et al. (2021). The study was based on the high-resolution ArcticDEM digital terrain model (32x32 m), from optical data from Maxar imaging satellites (Porter et al., 2018). In 2022, the temporal baseline between consecutive Sentinel-1 image pairs was increased from 6 to 12 days. In the context of the objectives of this study, this change does not significantly affect the reliability or accuracy of the derived glacier surface velocities. Both 6-day and 12-day intervals are commonly used standards in glacier velocity studies based on Sentinel-1 data and the AutoRIFT method. The 12-day interval still provides sufficient temporal sampling to correctly resolve seasonal variability and long-term trends in glacier dynamics. A noticeable loss of coherence and a significant degradation of velocity accuracy would be expected only for substantially longer temporal baselines, on the order of 20–40 days or more, which were not used in this study.

3.2. *METEOROLOGICAL DATA*

A permanent weather station stands on an elevated sea terrace approximately 10 meters above sea level, located about 300 meters from the northern shore of the Hornsund fjord. The station performs point-based measurements. The straight line distance from Werenskioldbreen is 12 km, from Nannbreen – 17 km and from Austre Torellbreen – 23 km. Moreover, several mountain ranges extend between the research station and the study area, obstructing the free flow of air masses and affecting local weather conditions. Therefore, the weather data recorded at the station are not reliable, and the differences in temperature may reach 3 C, in wind speeds – 5 m/s, and in wind directions – 90 degrees (Wawrzyniak and Osuch, 2020). A permanent weather station on the Werenskioldbreen glacier operated until 2016 (Ignatiuk et al., 2022). Unfortunately, because of the climate conditions, the measurements were discontinued and the location was closed. Due to the above limitations, the study was based on meteorological data collected continuously. They utilized the C3S Arctic Regional Reanalysis (CARRA) data and global sea surface temperature (SST) data in NetCDF format, with the CARRA data featuring a horizontal resolution of 2.5 x 2.5 km (source: cds.climate.copernicus.eu). The air and sea temperatures and the precipitation are recorded at a point 2 m above the ground surface, directly in front of the glacier terminus. In order to ensure data repeatability, the study was based on weather values measured every day at 12:00 (UTC).

3.3. *AUTORIFT CALCULATIONS*

The principle of operation of the AutoRIFT module is described in detail by Lei et al. (2021, 2022). In this study, glacier surface velocities were derived using an amplitude-based pixel (feature) tracking technique applied to Sentinel-1 SAR intensity images. The method relies on cross-correlation of image patches between co-registered image pairs to determine horizontal surface displacements. Unlike classical InSAR, the phase information was not used for displacement estimation.

Interferometric processing was limited to precise co-registration of the image pairs within the ISCE framework in order to ensure sub-pixel alignment prior to the AutoRIFT analysis. The displacement search windows were adaptively adjusted depending on expected glacier velocities and surface deformation. Areas of low coherence were automatically excluded, while dense tracking was performed in regions characterized by stable correlation. Additionally, areas with surface slopes exceeding 5° were masked to reduce geometric distortions and tracking errors.

The resulting pixel displacements were geocoded using the Geogrid module and converted to surface velocities using the ArcticDEM digital elevation model. Thus, all velocity estimates presented in this study are based on the feature (pixel) tracking of SAR image amplitudes rather than interferometric phase measurements.

The entire AutoRIFT processing chain, including chip size optimization, search window definition, and accuracy assessment using MAD, follows the methodological framework previously developed and tested by the authors for the Hornsund Fjord glaciers (Milczarek et al., 2022).

3.4. *ACCURACY OF THE STUDY*

The accuracy of the obtained results was determined in accordance with the method described by Lei et al. (2021 and 2022). The method is based on calculating the median of the standard deviation relative to the reference value. The reference values are areas defined as stable, exposed, and ice-free. Additionally, areas with a slope of more than 5 degrees were masked. Account was also made of the coastline, identified on the basis of the Sentinel-2 images in order to analyze changes in the vicinity of Austre Torellbreen, current as of September 27, 2021. The analysis of glacier surface velocity variations is referenced to a specific point in time. The availability of frequent acquisitions (every six days) yields more accurate results in dynamically evolving landscapes, as denser temporal sampling allows for a more precise assessment of glacier motion dynamics. Nevertheless, within the framework of large-scale analyses of glacier surface morphology and its long-term transformations in polar environments, a 12-day

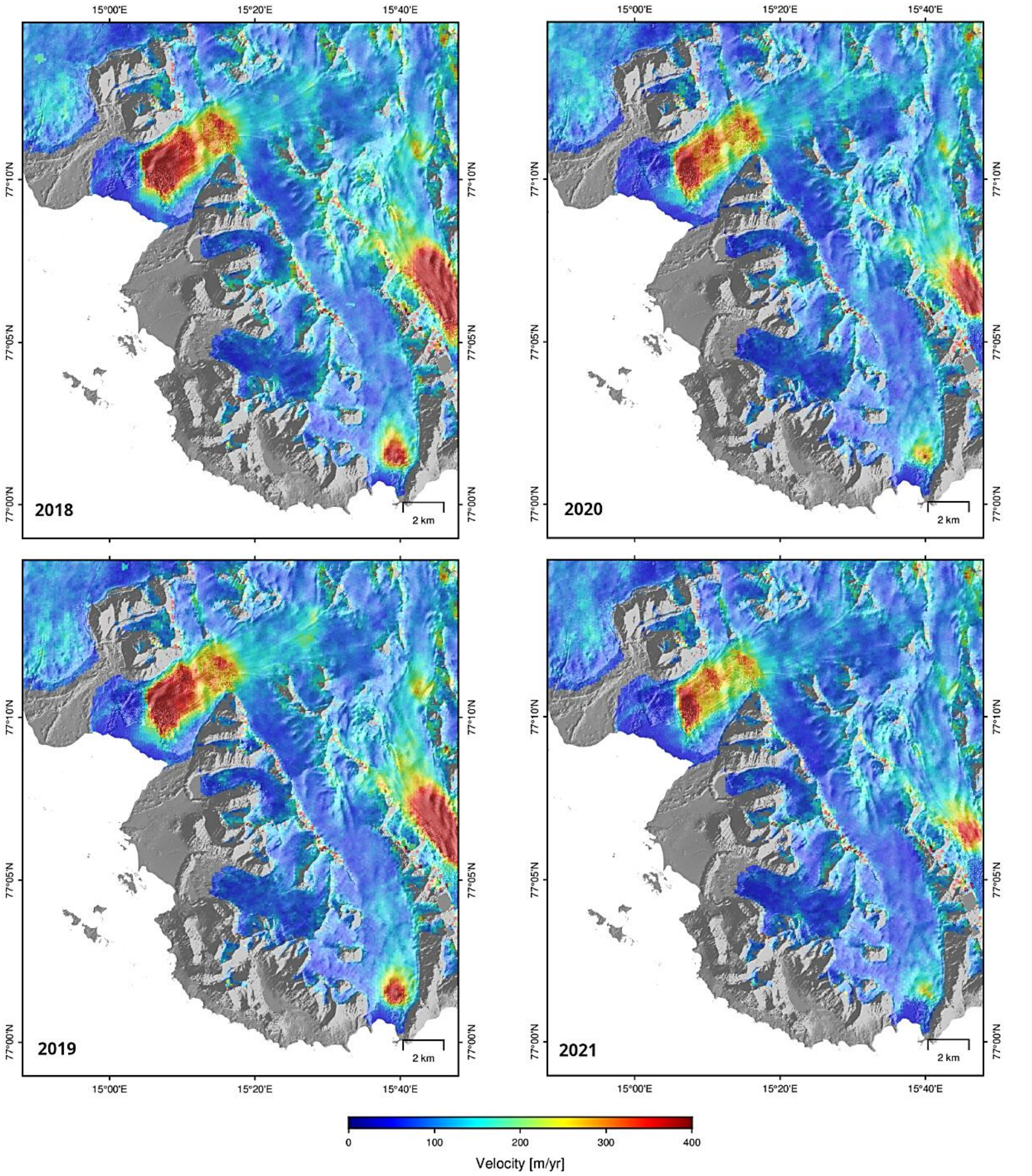

Fig. 2 Average ice cover velocities in 2018-2022.

acquisition interval can be considered sufficiently adequate. Such temporal resolution reliably captures the spatial and temporal evolution of glacier surface morphology.

4. ANALYSIS OF POLAR LANDSCAPE TRANSFORMATIONS

The polar landscape is formed mainly by glaciers. Changes in glacier surface relief result from the flow of masses over the terrain surface. The varied bed causes changes in ice flow velocities, and when exposed, it shows a new landscape of the polar region. The flow velocities of ice masses constantly vary in time and space, and the variations depend on many natural factors, different for individual Svalbard glaciers. This study presents a 4-year period of velocity changes on the Werenskioldbreen, Nannbreen and Austre Torellbreen glaciers. The most significant landscape transformations, and thus in the flow velocities, were observed on Austre Torellbreen, which terminates in the sea (approx. 700 m/year). Werenskiodbreen and Nannbreen showed velocities of approximately 25 m/year. The change in the location of the glacier terminus and its movement inland result in the exposure of the mineral bedrock.

The results indicate that the average ice cover velocity has been decreasing since 2018 (Fig. 2). The trend is especially noticeable on Austre Torellbreen, where the largest velocity decreases were recorded in 2020, as compared to previous years. A decrease in ice flow velocity was also recorded on Werenskioldbreen and Nannbreen, but these variations are not significant and within the error limits of the study.

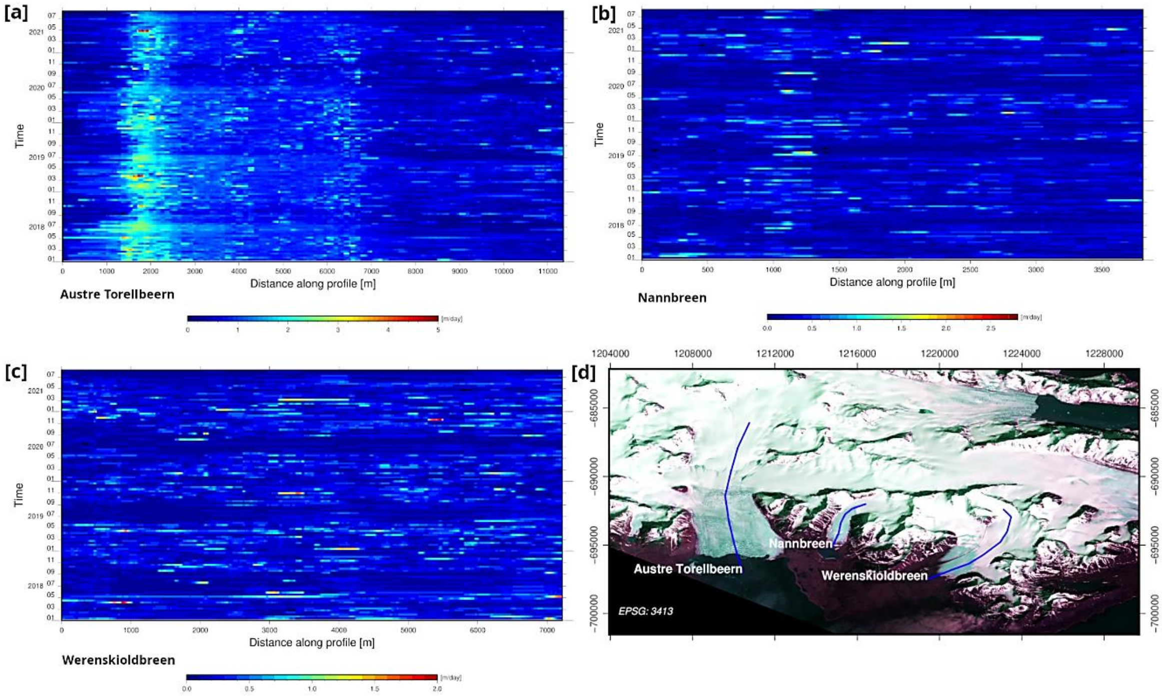

Fig. 3 Variations of glacier surface velocities in time along the profile: a) Austre Torellbreen, b) Nannbreen, c) Werenskioldbreen, d) the profiles location.

The results, presented as a consistent four-year time series with short intervals of 6 or 12 days, enabled the analysis of glacier dynamics and their variability over time and space. Profiles ranging from 5.5 to 18 km in length were defined along each glacier to illustrate velocity changes over time.

Velocity distributions along the Werenskioldbreen profile suggest a relatively steady glacier advance rate over the four-year analysis period. (Fig. 3c). The velocities along the entire profile are similar (0 – 2 m/day). The highest velocities can be observed in the central part of the profile (2000 – 5000 m) – up to 2 m/day. In the entire period, the highest velocities were recorded at a distance of approximately 4 km from the initial point of the profile (Fig. 3d). In the initial and final parts of the profile, the variations are significantly smaller. The profile also indicates a seasonal repeatability of the variations. From June to August, the glacier practically does not move – in the summer season it is stagnated along the entire profile. From September (the end of the ablation season) to May, the glacier displacement is regular. The highest velocities are recorded around January. Changes in weather conditions are presented (Fig. 5) for comparison in the form of a humidity and precipitation graph over the analyzed 4-year period. Reduced precipitation and a change in humidity can be observed in 2020. However, the changes are minor and likely influenced by the glacier's topography (its slope) as well as the transitions between the ablation and accumulation zones. The relatively low velocities can be attributed to the glacier's location in a wide valley, its eastern exposure, and its gentle slope (see Table).

Nannbreen is a small glacier and is slightly more dynamic than Werenskioldbreen. Here, the velocity increase can be clearly observed on the profile (Fig. 3d) around 1000 to 1500 m, up to 2 m/day (Fig. 3b). This is the only location in which the velocity of the glacier increases so noticeably. Velocities during the summer months (June to August) in all years are noticeably lower. A comparison of the data for the subsequent years allows a conclusion that the velocities are similar only at the end of 2021. In the final part of the profile (from 2500 m) the ice flow velocity significantly decreases, to almost zero. Changes in weather conditions are also indicated (Fig. 5) for comparison purposes. As expected, precipitation and humidity values are similar to those recorded on the neighboring Werenskioldbreen glacier. As in the case of Werenskioldbreen, also here such relatively low velocities may be attributed to the location, eastern exposure and inclination. Additionally, the glacier is situated in a valley surrounded by high mountains whose peaks block the sun and limit the flow of air masses, slowing the ice flow velocity.

Austre Torellbreen is an ice shelf with a wide terminus. Velocity distributions along the glacier profile reveal that the values decrease over the analyzed period of time (Fig. 3a). In the first two years (2018, 2019), in the terminal area (1000 – 2,000 m of the profile), exhibited zones of very high flow velocities (up to 4.6 m/day) were observed in the winter period. In the summer, the velocities decreased to 1 m/day. In the terminal area (1500–3,000 m of the profile), the velocity changes also exhibit a distinct seasonal pattern, with velocities decreasing at the end

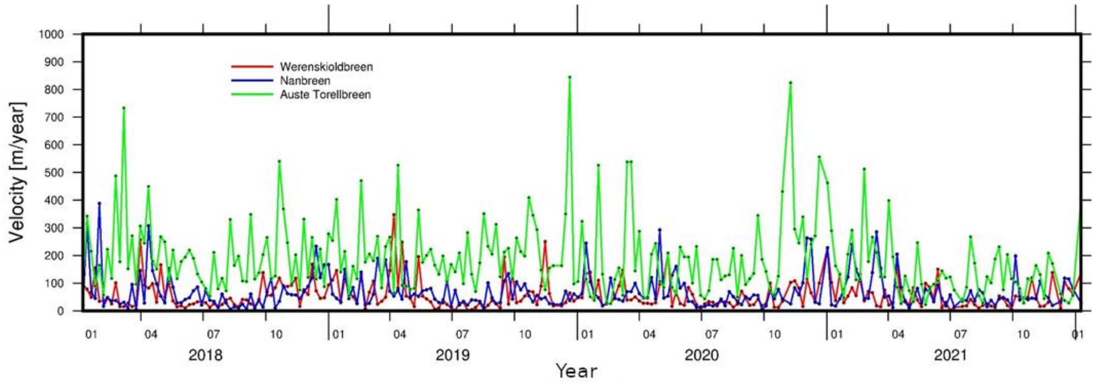

Fig. 4 Variations of glaciers surface velocities.

of each ablation period (around September). In the further part of the profile, the velocities decrease significantly. Two areas can be identified here. The first area, reaching a distance of 6500 m, is where the velocities remain at up to 2.2 m/day. In the second area, until the end of the profile. The velocity values decrease and stabilize at a similar level throughout the observation period. The variations in velocity along the entire profile are influenced by the glacier's topography (its slope) and the transitions between the ablation and accumulation zones. For comparison, a graph of weather conditions (Fig. 5) shows insignificant variability over the 4-year period. Despite the velocity decrease, this glacier has very high dynamics, driven by a relatively steep slope, southeastern exposure and location in a wide but narrowing valley (see Fig. 1). The glacier is exposed and the surrounding low mountain ranges do not cover its surface from sunlight, particularly in the summer. The rate of changes remains consistent across successive recurring periods. At the beginning of summer (April–June), the dynamics are greater, likely due to the outflow of ice from the valley and the glacier's calving activity.

Moreover, detailed graphs of velocity changes were plotted for the most intensively changing areas (at the terminuses) of the studied glaciers (Fig. 4). A systematic velocity decrease observed on Austre Torellbreen confirms the above observations. For points located in the areas of Werenskioldbreen and Nannbreen, seasonal patterns are consistently observed throughout the entire four-year period, also including along the profiles. (Figs. 3a – 3c). The velocities increase significantly during the summer months (June–August) and decline around September and October. Isolated velocity spikes are evident in the time series for all the analyzed glaciers, occurring on Nannbreen in June, Werenskioldbreen in July, and Austre Torellbreen in August.

Regular changes of ice flow velocities throughout the calendar year are a natural phenomenon (Figs. 3a, 3b, 3c). However, after 2019, noticeable velocity decreases are observed for Austre Torellbreen and not for the other two glaciers. In the next stage of the analysis, the calculated velocity changes were compared against meteorological data acquired at points representing each of the described areas in the marginal zones of the glaciers (Fig. 4).

The data show that the highest temperatures were observed in 2018, when the average annual temperature value increased by 0.23 °C each year, to later decrease by even more than 1 °C in the following years. Increased precipitation in the winter and spring months, in combination with low temperature, cause water particles on the surface of the glacier to freeze, the fissures to close, the glacier surface to become smooth and – as a result – the velocity of ice surface movement to decrease. Changes in the glacier surface flow velocity and the transformation of the dynamic landscape of the glacier surface is also caused by humidity and the amount of atmospheric precipitation. In 2019 the precipitation was lower than in the other analyzed years. It was particularly limited in the summer months. The differences in humidity and in temperature changes suggest high variability of meteorological conditions in such a small area. The diversity of meteorological factors in both time and space affects changes in ice flow velocities, which in turn have an impact on the shape of glacier surfaces. This phenomenon is especially evident in large ice shelves.

The accuracy of the results obtained for the entire area of southwestern Svalbard was discussed as part of the study by Milczarek et al. (2022). Errors in velocity calculations against the reference values adopted in the study indicate a significantly higher data accuracy in the summer period (June – September), with mean error of 56.5 m/year than in the winter period (October – May) when mean error was 93 m/year. The inaccuracies are caused by snowfall, which may cover some of the characteristic areas in the winter. In subsequent years, mean errors were also observed to decrease from 89 m/year (2018) to 77-79 m/year (2020, 2021). The decrease was most likely related to a general decrease in ice flow velocities (Lei et al., 2021) and lower precipitation.

5. DISCUSSION OF THE ANALYZED POLAR LANDSCAPE TRANSFORMATIONS

This analysis of polar landscape transformations due to the dynamics of the glacier surface was based on the examination of glacier flow velocities, which

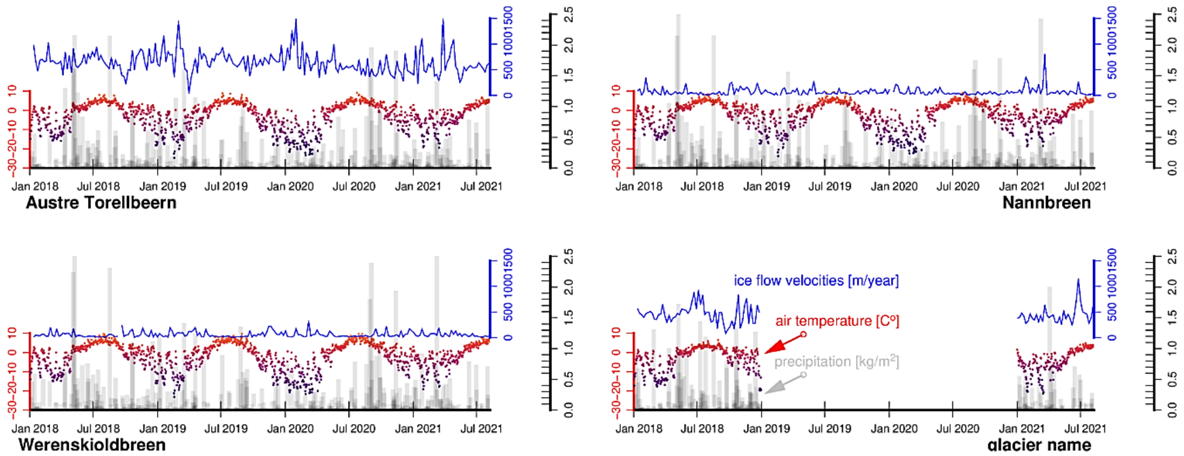

Fig. 5 Comparison of meteorological data and glacier flow velocities.

have a major role in the creation of a diversified polar landscape. Svalbard, Greenland and Antarctica are areas suitable for investigations of global landscape transformations resulting from the constantly warming climate. The analysis of glacier velocities in these areas should be viewed as a contribution to predicting the environmental response to future changes. For such a goal to be accomplished, continued measurements and research must be performed in the polar regions. Photogrammetric measurements have been performed in Svalbard since the beginning of the 20th century and were repeated until the end of the century at intervals of approx. ten years. The first study on the geometry of the Hansbreen glacier dates back to 1938 (Pillewizer, 1939). Over the following years, until the end of the 20th century, the measurements were based on ground and aerial photogrammetry (Jania, 1997). The 21st century marks an increasing use of satellite data, including SAR data.

Glaciological and measurement data from the end of the 20th century provided for an assessment of the dynamics of glaciers in the Hornsund region. In large glaciers (e.g. Hansbreen, Storbreen), changes on the surface are due to ice deformation, glacial drainage and basal slide, and in small glaciers (Lorchbreen, Fuglebreen) the changes are due to ice deformation and glacial drainage (Jania, 1997). The dynamics of glaciers terminating in the sea is higher than that of glaciers terminating on land. In the late 1990s, Hansbreen moved at a speed exceeding 200 m/year (Barzycka et al., 2020). Glacier velocities in Svalbard were discussed by Noel, who demonstrated their constant increase (Noël et al., 2020). Ignatiuk notes that the glacier has had a constant negative mass balance since 2010 (Ignatiuk et al., 2022).

The results presented here for the southwestern part of the Wedel-Jarlsberg Land are based on SAR data. The analysis makes it possible to identify changes in the polar landscape, including ice flow dynamics for the last four years. Two of the described valley glaciers, Werenskioldbreen and Nannbreen, move slower, while the AustreTorellbreen ice shelf moves faster. The factors directly affecting ice flow velocity and glacier retreat include terrain relief, the width of the glacial valley, glacier size, the length of the frontal line, and surface inclination (Jania, 1988). Among the studied glaciers, Austre Torellbreen exhibits the highest annual displacement dynamics (595 m/year). This glacier is situated in a wide valley with a steep incline, it has a long frontal line and it is exposed to the south-west. It is also the largest glacier in the analyzed group. The velocity values recently reported in the literature are 260 m/y for the years 2005 – 2008 (Blaszczyk et al., 2009). The average velocity of the Werenskiold glacier is 25 m/y. It is a medium-size glacier in a wide valley with a low gradient of slope and a relatively long frontal line of approx. 2.5 km. In terms of the glaciological mass balance analyzed until 2020, the glacier is systematically retreating (Ignatiuk et al., 2022). The dynamics are different, albeit comparable over the subsequent years. When compared to the glacier flow velocities, these glaciological values complement the results of the analyses here presented. Nannbreen is a small valley glacier with an average speed of 25 m/y. It has a steep slope, in particular at its terminus. It is situated in a narrow valley, surrounded by towering peaks, with a predominantly eastern exposure. The velocity dynamics of this glacier had not been analyzed previously.

Average annual temperatures are approx. 1 C lower at Wereskioldbreen than at Nannbreen, and precipitation and humidity are similar (Fig. 5), indicating that temperatures alone have no influence on the ice flow rate. A comparison of the subsequently analyzed years demonstrates that the changes are mostly accelerated by air humidity, together with temperature. The increase in temperatures and humidity in subsequent summer seasons resulted in a slight increase in ice flow velocity. Temperature decreases and changes of other weather parameters prevent the retreat and degradation of glaciers inland.

The calculations and analyzes indicate that landscape transformations occur at different rates. All the three study areas share a noticeable decline in glacier surface speed in the years 2020–2021, the lower velocities observed for Austre Torellbreen can be attributed to the glacier terminus approaching the limits of the grounding zone and entering a deeper trough valley. The ice remaining on land slows the retreat velocity, while the portion of the glacier still in the sea causes velocities to increase. This behavior may result from water flowing beneath the terminus and over the bedrock, reducing ice flow velocities. However, as seawater offers less resistance, it accelerates the degradation process. Sea currents further contribute by washing ice away from the bed, intensifying the degradation. This phenomenon, commonly observed in Svalbard glaciers, has been documented by Schuler, Strozzi and Milczarek (Schuler et al., 2020; Strozzi et al., 2022; Milczarek et al., 2022), who note that the sporadically significant velocity variations have a seasonal character. The peaks occur at irregular time intervals, and in the case of Austre Torellbreen they are observed in the winter. The analysis shows that the differences between the ablation seasons reach 3 m/day. This glacier is very large and its changes are consistent with the changes of other glaciers, such as Hornbreen. Seasonal velocity variations may also occur in Werenskioldbreen and Nannbreen, but they are much smaller, reaching 1.5 m/day. Also in this case, higher velocities are recorded in the winter months

6. CONCLUSIONS

The article presents the results of investigations into polar landscape transformations caused by deformations of glacier surfaces which depend on the flow velocity of ice cover in the analyzed part of Spitsbergen. The analysis was established using a set of 402 satellite radar images from the Sentinel-1 constellation compared with weather data. The landscape transformations were determined by analyzing velocity variations for three glaciers in southwestern Spitsbergen. The analysis covered the period from the beginning of 2018 to the end of 2022 with an average interval of 6 days. The calculations employed the feature tracking technique.

The glacier velocity analysis indicates that changes on the surface of the sea-terminating Austre Torellbreen ice shelf are much greater than those in the Werenskioldbreen and Nannbreen valley glaciers, which terminate on land. The highest ice flow velocities were recorded in Austre Torellbreen – they were approximately 700 m/year in 2018. In contrast, valley glaciers move at an average velocity of under 30 m/year. The average ice cover velocity in the described region has been decreasing year-to-year since 2018. The velocities of valley glaciers are low and decrease at a slower rate than the velocity of the described shelf glacier. The lowest glacier velocities were recorded in 2020.

Changes in ice flow velocities during the calendar year are a natural phenomenon. However, in this case the velocities are observed to decrease throughout the year for the Austre Torellbreen glacier after 2019. Such annual changes are not observed for the other two glaciers. In the next stage of this study, the results of velocity variation analyses were compared with meteorological data acquired at points in the forefield of the discussed glaciers. The results indicate that humidity has the greatest influence on the velocity variations, and in combination with variable temperatures, it intensifies changes in the shape of the glacier surface.

The polar landscape, closely related to glaciers, is expected to change. These changes should be further analyzed, leading to the development of mathematical models describing the condition of natural objects. We plan to further utilize the AutoRIFT method in our upcoming studies aimed at analyzing the dynamics of polar landscape change. Currently, we are conducting research focused on glacier displacement and surface transformation in Greenland, Svalbard, and Antarctica. The AutoRIFT algorithm enables high-precision velocity field estimation based on satellite imagery, which is essential for understanding glacier degradation processes and their impact on polar geomorphology. The results of these studies will be progressively published in peer-reviewed scientific journals. Such observations, records and analyses are now possible with the use of satellite images, which can be acquired free of charge and at short intervals. The availability of continuously recorded weather data enables the analysis of transformations in the polar landscape in relation to environmental factors.

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