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Glacier dynamic study of the Terre de Lambert glacier in Greenland based on Landsat 8 and Sentinel-1 data

Jiachen Zhou

School of Resources and Environmental Engineering, Hefei University of Technology, No. 193 Tunxi Road, Hefei City, Anhui Province, China

2021215124@mail.hfut.edu.cn

Abstract. With global temperatures on the rise, the trend of glacial melting is becoming increasingly evident. This study focuses on the northeastern region of Greenland as the research subject, utilizing remote sensing technology and geographic information technology to study glacial dynamics. Initially, the research processes Landsat 8 data using QGIS to classify the widespread snow and ice cover, facilitating the observation and analysis of its temporal variations. The study then narrows its focus to Terre de Lambert for further analysis. Subsequently, using satellite data from Sentinel-1 and employing SNAP, the research conducts an in-depth analysis of glacier flow speed in specific regions. Through intricate computational models and algorithms, precise glacier flow direction and speed maps are generated. By combining historical data, the study compares and analyzes the glacier flow speed between 2018 and from June 20th to July 14th, 2023. Results indicate that the glacier flow speed in 2023 during the same time frame was faster. Throughout the research process, limitations in current data acquisition and processing methods were identified. Thus, the paper suggests improvements to data acquisition and processing tools to enhance the efficiency of glacier flow speed studies. There's a fervent hope for the emergence of more convenient, streamlined, and customizable temporal dimension tools for glacier flow speed data in the future. The research findings aim to draw global citizens' attention to the issue of glacial melting and inspire collective actions to protect our planet.

Keywords: Land Cover Classification, Glacier Flow Speed, Landsat 8, Sentinel-1, Terre de Lambert

1. Introduction

With the rise in global temperatures, the issue of glacier retreat has garnered worldwide attention. Over the past 50 years, the melting of glaciers has shown a continuous expanding trend, with half of the glaciers expected to disappear within this century [1]. The melting and retreat of glaciers have irreversible impacts on global climate change, sea-level rise, water resources, and biodiversity. Greenland, where three-quarters of the area lies within the Arctic Circle and is inhabited, is particularly important for glacier evolution studies. Such research is crucial for predicting future trends in glacier development, formulating strategies to slow glacier retreat, and avoiding disasters caused by glacier shrinkage [2]. Traditional human exploration methods are time-consuming and labor-intensive in polar regions, hence the urgency to adopt remote sensing image analysis for research. Additionally, glacier research can also emphasize the urgency of glacier protection, thereby enhancing public environmental awareness.

Currently, many studies use remote sensing data to track and analyze glacier evolution. Some studies use the Landsat dataset from the United States Geological Survey (USGS) to study the surface characteristics and retreat of glaciers. Peng Jiajia and others used Level 1T Landsat remote sensing images to study the dynamic changes in the glacier landscape pattern in the Yarkant River Basin [3]. Ji Qin and others used Landsat to extract the Himalayan boundary to analyze glacier dynamic changes [4]. Tang Yuanwei analyzed the spatiotemporal changes of glaciers in the Central Asian Altai Mountains through the ratio threshold method and snow cover index method [5]. Other studies use Sentinel-1 SAR data from the European Space Agency (ESA) to study glacier movement and bedrock. Li Lanyu based on SAR data to extract the glacier boundary of the Yigong Zangbu Basin and calculate its surface three-dimensional flow speed [6]. Zhao Jiarui and Ke Changqing used Sentinel-1 data to extract the winter and summer flow speeds of the Matsushima Glacier from 2015 to 2017 using the feature tracking method, analyzing the annual and seasonal changes in glacier flow speed [7]. Guo Weina used SAR data based on the offset tracking method to estimate the monthly flow speed of glaciers in the Pamir Plateau region and then calculate their annual flow speed and seasonal flow speed [8].

Despite many studies on glacier evolution, there are still some gaps in the measurement of glacier evolution speed and direction. In addition, many studies mainly focus on a single data source and use multiple data sources for comprehensive analysis. This may limit a comprehensive understanding of glacier dynamics. For the study of glacier evolution, it is often necessary to obtain specific information at a certain location before further research can be carried out. To improve efficiency, it is necessary to screen data over a large range and a long period, and then select possible areas for further research based on the results.

Therefore, based on previous studies, this study combines Landsat 8 data and Sentinel-1 SAR data to study glacier evolution. Through the analysis of Landsat 8 data, glaciers, and non-glacier areas can be more accurately identified, and the retreat of glaciers can be evaluated. Using Sentinel-1's SAR data, this paper can obtain the direction and speed information of glacier movement, and further compare the changes in glacier flow speed in different years, to deeply understand the mechanism of glacier retreat. In addition, the results of this study are of great guiding significance for predicting future glacier changes, understanding the impact of climate change on glaciers, and formulating related environmental policies. In general, this study will provide a strong scientific basis for glacier research and global change research and has important scientific and practical value for promoting research in related fields.

2. Methods and data

2.1. Study area

This study focuses on the northeastern part of Greenland, as shown in Figure 1 which provides a schematic diagram of the northeastern region of Greenland and the glacier research area. By obtaining Landsat 8 images of this area and after observation and analysis, it was decided to further select the glaciers in the Terre de Lambert region for study.

Terre de Lambert is a large glacier protrusion (or tongue) located in the northeastern part of Greenland, specifically in the region of King Frederick VIII Land. A glacier protrusion refers to parts of plateaus or glaciers that are exposed and not covered by snow or ice, often consisting of rock formations, such as mountain ranges, hills, or peaks. This region is named after the French geographer Raoul Lambert. Its exact location is 79°30'N 22°00'W. The study area in this paper is the glacier nearby - marked by a red box, which is temporarily referred to as the Terre de Lambert Glacier.

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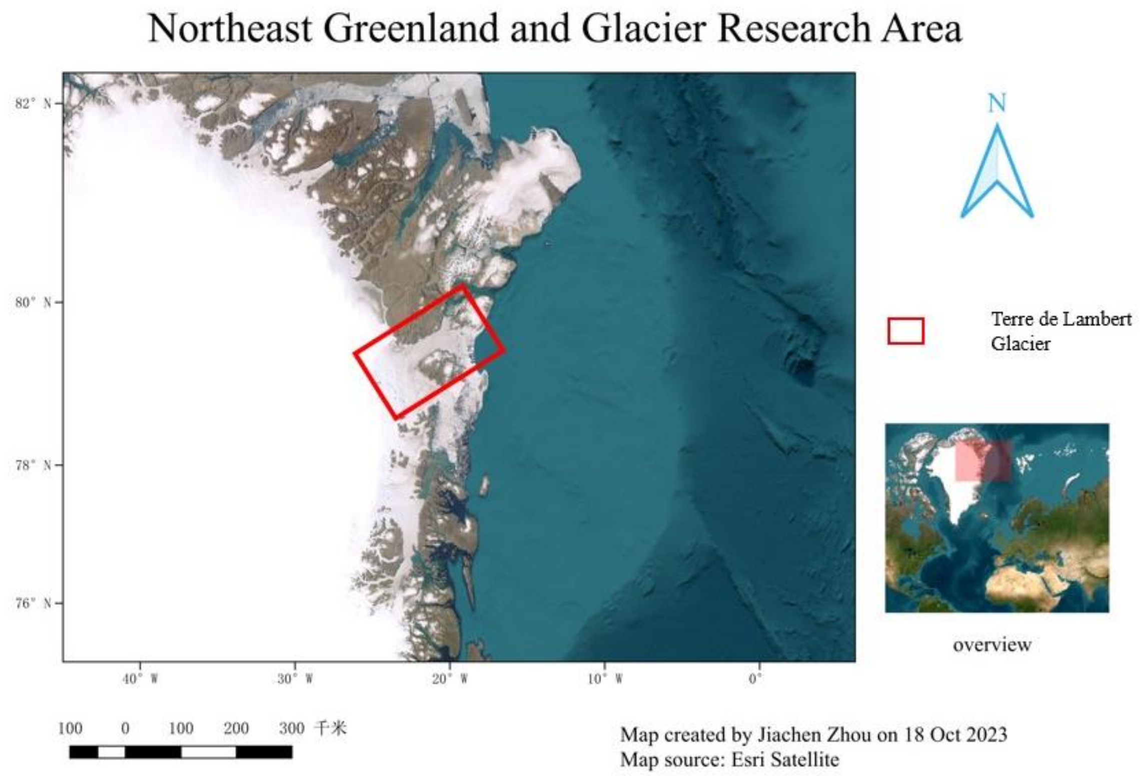

Figure 1. Northeast Greenland and Glacier Research Area.

2.2. *Data sources*

Landsat 8 is an Earth observation satellite developed in collaboration between the National Aeronautics and Space Administration (NASA) and the United States Geological Survey (USGS). Launched in February 2013, it represents the latest generation in the Landsat program [9, 10]. Landsat 8 is equipped with two sensors: the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS)[11]. The OLI sensor can capture surface images in nine different bands, including visible light and near-infrared, with a resolution of 30 meters. The TIRS sensor measures surface thermal radiation with a resolution of 100 meters, aiding in the study of surface temperature variations. Landsat 8 offers global observation capabilities every 16 days. Its data is crucial for monitoring and assessing global changes, including urban expansion, forest cover variations, glacier melting, and shifts in water resources. The thermal infrared data can illustrate variations in glacier surface temperatures, while its high-resolution optical images can reveal details of glacier fractures and crevices. This provides a unique perspective for understanding the processes and mechanisms of polar glacier changes. This paper utilized level 2 data from Landsat 8 to analyze glacier changes in the northeastern part of Greenland from June 20 to July 14, 2023.

Sentinel-1 is a significant satellite mission launched by the European Space Agency. As part of the Sentinel satellite family, its primary goal is to support European environmental and security policies by providing continuous and systematic global remote sensing observations. The mission consists of two identical satellites, with Sentinel-1A launched in 2014 and Sentinel-1B in 2016[12]. Sentinel-1 offers all-weather, year-round imaging capabilities. Through its C-band Synthetic Aperture Radar (SAR), it can overcome challenges posed by cloud cover and lighting conditions, making it particularly suitable for observations under frequent cloud cover or in polar day/night scenarios [13]. This capability is especially vital for polar and glacier observations, which are often affected by harsh weather and extreme lighting conditions. Furthermore, Sentinel-1's C-band SAR data provides abundant information for glacier dynamics research, and its high-resolution observational capabilities allow users to study polar regions and glaciers on a finer spatial scale. This provides this paper with a fresh perspective for understanding the large-scale processes and detailed features of polar regions and glaciers. This paper employed 12 scenes of interferometric wide swath mode in Ground Range Detected (GRD) format to estimate glacier flow speeds from June 20 to July 14, 2023 [14].

2.3. Data pre-processing

This study preliminarily focuses on the primary regions affected by ice and snow melt due to temperature changes, and thus selected the Level 2 product of Landsat 8[15]. Since Level 2 has already undergone radiometric calibration and atmospheric correction, there is no need for complex processing. This enables the research to measure surface conditions more quickly and accurately. On the other hand, the Level 2 product provides surface reflectance rather than reflectance at the top of the atmosphere. Surface reflectance is the pure ground reflectance information unaffected by the atmosphere, which is very important for the quantitative study of glacier changes, aiding in a more detailed assessment of glacier status.

After determining the specific glacier area, this paper selected the descending grid data mode of Sentinel-1, labeled as IW. After undergoing Linear To/From db and Multilook processing, the noise is reduced, resulting in better visual effects that are more suitable for deformation analysis [7]. Although some preliminary processing was conducted, preprocessing still needs to go through the apply orbit file, Thermal Noise Removal, and Calibration processes. The process is illustrated in Figure 2 as Sentinel-1 Data Preprocessing.

Figure 2. Sentinel-1 data preprocessing

(1) Apply Orbit File: The satellite orbit file contains accurate information about the satellite’s position and speed, which is very important for interpreting satellite images and spatial resolution. Users can obtain more accurate glacier flow speed measurement results. Applying the satellite orbit file step allows users to use the precise location and speed information of the satellite when recording data, further enhancing the accuracy of radar measurements, especially when performing operations that require precise geometric corrections such as terrain correction and radar interferometry.

(2) Thermal Noise Removal: During the satellite radar signal reception process, there will be certain thermal noise. This is caused by the heat generated by the satellite receiver’s electronic equipment when it operates. The presence of thermal noise will, to a certain extent, affect the measurement results of radar reflectance intensity and interfere with data interpretation. Therefore, removing the data interference caused by thermal noise generated by the satellite’s radar receiver can make the radar measurement of glacier reflectance intensity more accurate, which is conducive to accurately measuring glacier flow speed.

(3) Calibration: Radar calibration is the process of converting radar measurement signals into physical reflection or backscatter intensity values. This process needs to be corrected based on factors such as radar antenna characteristics and emission power to obtain the true value of the surface’s reflection properties (such as the reflection coefficient). Obtaining the true reflection properties of the surface glacier is crucial for subsequently generating the glacier’s velocity field map through radar interferograms to measure glacier flow speeds.

2.4. Research method

2.4.1. Band fusion.

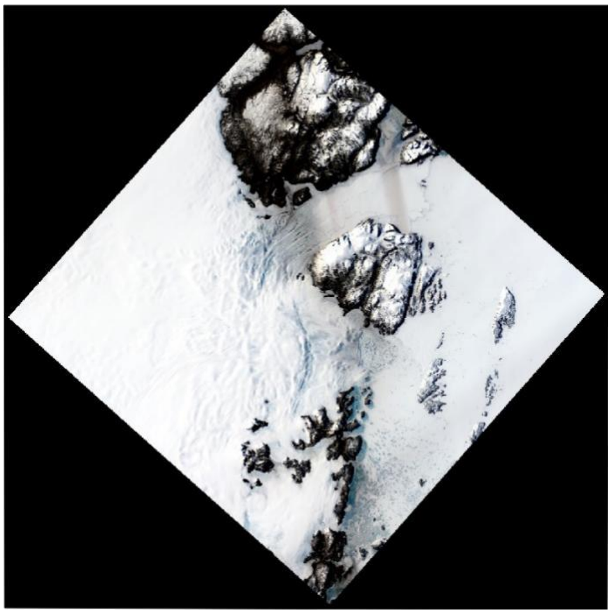

Figure 3. True color view of northeast Greenland

In this study, the image data obtained from Landsat 8 was used to construct a true-color virtual raster, as shown in Figure 3 of the northeastern part of Greenland. It was observed that the differences between snowy and glacial areas are minimal, making them nearly indistinguishable to the naked eye. Therefore, after extensive research, three bands were chosen from numerous spectral bands to construct the virtual raster:

(1) Band 2 (Blue): The blue band is very useful for ice and snow mapping because the reflectance of ice and snow in this band is extremely high. Simultaneously, the blue band can also be effectively used to detect turbid water bodies, which is crucial for mapping the water areas formed during the ice and snow melting and movement processes.

(2) Normalized Difference Snow Index (NDSI) [16]: NDSI is designed to extract and identify snow-covered areas in optical satellite data. This index distinguishes snow-covered pixels from non-snow-covered pixels by calculating the difference in reflectance values of the green and near-infrared bands. Snow-covered areas typically exhibit high positive values in the NDSI, while most non-snow-covered objects (e.g., clouds, water, vegetation, and bare ground) produce negative or values close to zero. This helps to differentiate between snow-covered and exposed glacier areas, especially during the spring snowmelt season. The calculation for this band needs to be done in advance, with the formula being:

$$\mathrm{NDSI} = \frac{(\mathrm{Green} - \mathrm{SWIR})}{(\mathrm{Green} + \mathrm{SWIR})} \tag{1}$$

Where "Green" corresponds to Band 3 of Landsat 8, and "SWIR" corresponds to Band 6.

(3) Normalized Difference Glacier Index (NDGI) [17]: NDGI is designed to detect surface features containing glacier ice. Similar to NDSI, it differentiates between glacier and non-glacier areas by calculating the difference ratio between bands. Applying the NDGI index can help users distinguish glacier and non-glacier areas on the map more clearly. The formula is:

$$\mathrm{NDGI} = \frac{(\mathrm{Green} - \mathrm{NIR})}{(\mathrm{Green} + \mathrm{NIR})} \tag{2}$$

Where "Green" corresponds to Band 3 of Landsat 8, and "NIR" corresponds to Band 5. After calculating the last two bands using the raster calculator and adding Band 2, all three are output through the virtual raster to produce the final remote sensing spectral composite image.

2.4.2. Semi-automatic classification and land cover change. Remote sensing analysis methods can be broadly categorized into two main types: automatic and semi-automatic. The core difference between them lies in how images are processed: one being pixel-based, and the other being object-based. Depending on the specific geographical features being analyzed, each technique has its strengths. Fully automatic methods are praised for their simplicity and cost-effectiveness due to the lack of human intervention.

Specifically, the Semi-automatic Classification Plugin (SCP) for QGIS is designed to combine the advantages of both these methods, aiming to achieve a more refined remote sensing image processing [18]. This plugin can link to various RS satellite products and then complete the downloading and preprocessing steps of the images. By filling in predefined parameters within the user interface, it continues to execute supervised or unsupervised classification tasks. Additionally, the SCP plugin offers several classification algorithms to choose from, including Minimum Distance, Maximum Likelihood, and Spectral Angle Mapping[19]. Practically speaking, this follows a traditional pixel-based image classification scheme. It identifies the most similar pixels around a given pixel by calculating and comparing spectral characteristics. When conducting unsupervised classifications, it further processes the band collection using ISODATA and K-means, two commonly used clustering algorithms. For the "Land cover change" function, the plugin takes advantage of both automatic and semi-automatic methods, achieving more detailed and effective processing of two related remote sensing images of the same area. This approach, which combines both pixel and object analysis, retains the convenience of fully automatic processing and fully leverages the benefits of human intervention in semi-automatic processing, making land cover change analysis more accurate and efficient.

In summary, when users utilize these technologies and methods, they can achieve accuracy and flexibility without investing significant effort or resources.

For band fusion images, users manually delineate areas of interest and divide the areas into rocks, unmelted regions, and melted snow and glaciers. The semi-automatic classification is then applied to the entire image. Subsequently, the remote sensing band fusion images from June 20 and July 14 are selected for "Land cover change" analysis to determine the changes in different types of land cover, which further aids in glacier analysis.

2.4.3. SAR data processing. After preprocessing Sentinel-1 images, they can be subjected to Digital Elevation Model (DEM)-Assisted Coregistration, Subset, Offset-Tracking, and Range-Doppler Terrain Correction, as shown in Figure 4, the SAR Data Processing Workflow.

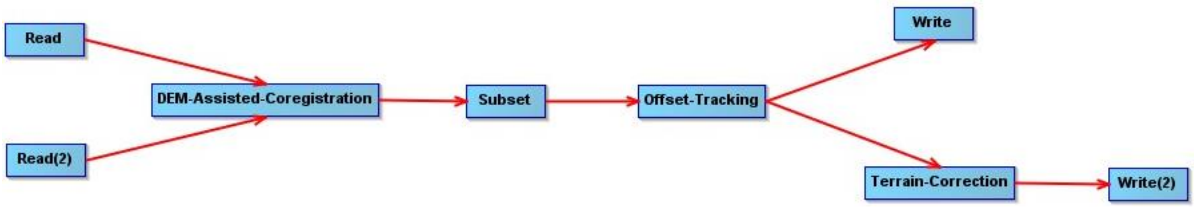

Figure 4. SAR data processing flowchart

(1) DEM-Assisted Coregistration: This is a process that accurately aligns multiple satellite images from a time series. It relies on a Digital Elevation Model (DEM) to lock in shared geographic features, which serve as a reference to enhance the alignment accuracy of the images. This step is crucial in studying glacier movement because precise alignment between images is vital for ensuring the accuracy of the measured glacier flow speed.

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(2) Subset: Setting a subset of the remote sensing image is an effective method to select regions of interest to the user. This can significantly reduce the volume of data processed, enhancing the efficiency of data analysis. This becomes particularly important when dealing with extensive images where the user is only interested in a small section, such as a glacier. In this experiment, the user's focus is placed on the Terre de Lambert glacier.

(3) Offset-Tracking: Offset-Tracking is a process in which the brightness (or intensity, also known as echo power) correlation between overlapping radar images of adjacent areas is used to estimate object movement, resulting in a displacement map. Compared to optical image processing methods, offset-tracking has the advantage of not requiring visible light, meaning that radar measurements can still be conducted under low-light conditions or adverse weather conditions such as fog or snow. Through offset tracking, users can measure the distance that the glacier has moved between two satellite transits, from which the glacier's flow speed can be calculated.

(4) Range-Doppler Terrain Correction: Range-Doppler Terrain Correction adjusts the pixel positions in SAR images by considering the influence of terrain, aligning them more closely with their actual geographical locations. This enhances the spatial accuracy of the images, especially in areas with significant terrain variations, setting the stage for the subsequent exportation of kmz files for Google Earth

3. Results and discussion

3.1. Band fusion result

Before conducting Semi-Automatic Classification, the calculated bands are inputted, allowing different surface reflectance characteristics to be combined [19]. This preprocessing simplifies the subsequent classification process, leveraging the user's expertise to enhance the precision and effectiveness of the classification. It aids in distinguishing glaciers, snowfields, bodies of water, and other surface features in the multi-feature pixel space, providing critical input for subsequent land cover change monitoring. As shown in Figure 5, the band fusion image of northeastern Greenland is an example of a processed image where rocks, un-melted regions, and melted snow and glaciers can be clearly distinguished by the human eye, facilitating the subsequent semi-automatic classification.

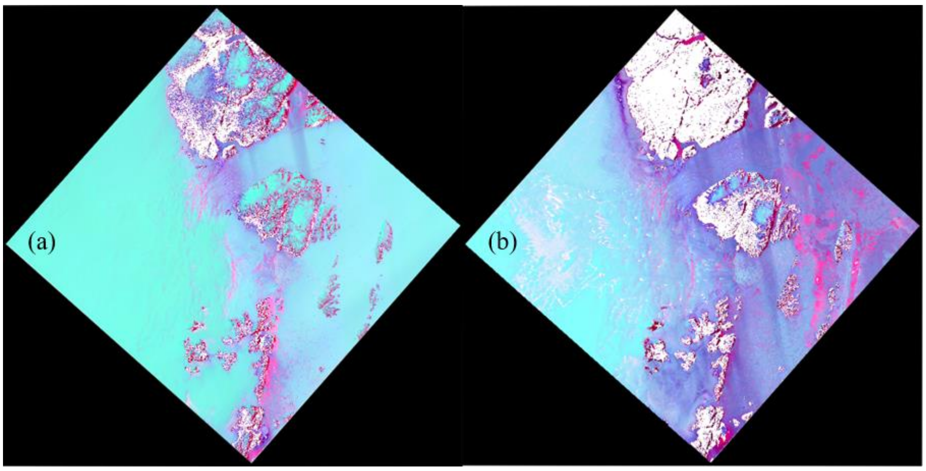

Figure 5. Band fusion image of northeastern Greenland: (a) June 20th ;(b) July 14th.

3.2. Semi-automatic classification result

In the specific operation, the processed remote sensing images are divided into rocks, unmelted regions, and melted snow and glaciers. After semi-automatic processing, this paper obtained semi-automatic processed image of northeastern Greenland, the semi-automatic processed image of northeastern Greenland, respectively for (a) June 20th and (b) July 14th. From part (a) of Figure 6, it can be observed that most of the ice and snow had not melted on June 20th, 2023, and residual snow can still be seen on

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the black rocks, with very few purple areas representing the melted regions. However, in part (b), it can be seen that most areas have melted, and only a little snow remains on the rocks.

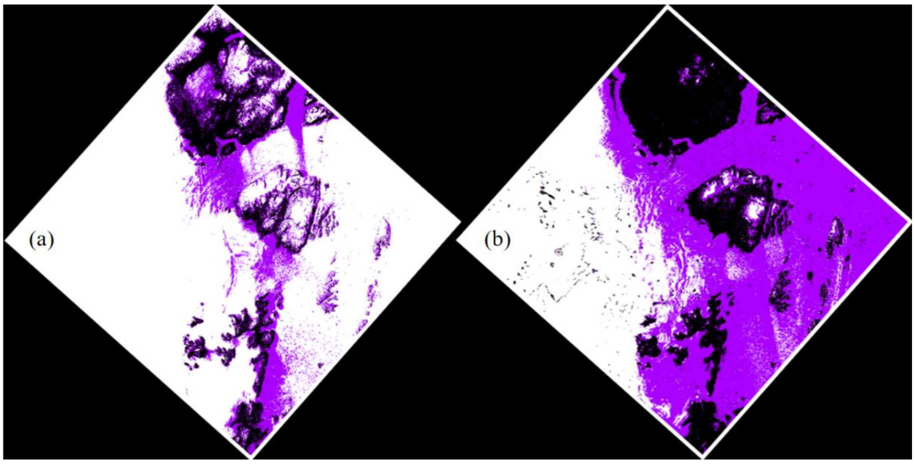

Figure 6. Semi-automatic processed image of northeastern Greenland:(a) June 20th ;(b) July 14th.

After the semi-automatic classification process, the specific analysis of land cover change plays a crucial role in the subsequent analysis of glacier flow speeds and provides decision-making analysis for the selection of glacier flow speed study sites. Based on all land cover changes, Table 1, Land Cover Change Table, was generated to identify areas where glacier melting occurred. Figure 7, Raw Glacier Map, was then generated based on the data with the highest degree of change, without any processing.

Table 1. Land cover change table

Change area(m^2)	Rocks	Un-melted regions	Melted snow and glaciers
Rocks	38168370000	1481636700	2336312700
Un-melted regions	1029600	12303264600	76235400*
Melted snow and glaciers	18261900	13033798200	3098634300*

* denotes that the data selected for display in Figure 7, which also represents the type of geographical features of the glacier

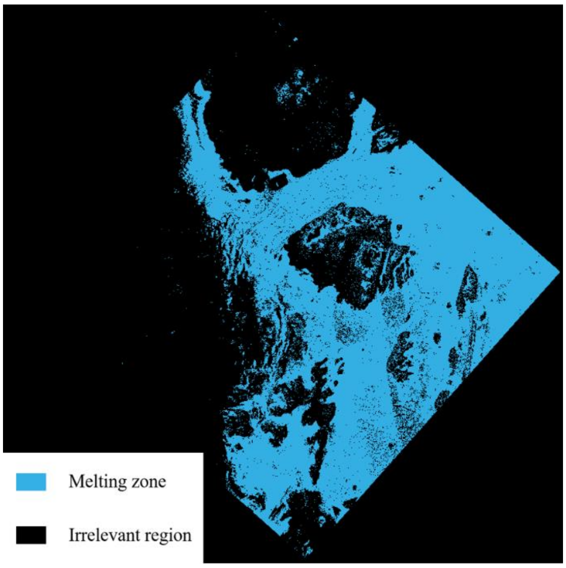

Figure 7. Unprocessed glacier map

By removing the area of sea ice melt, we obtained Figure 8, the glacier distribution map. Through the classification results of Landsat 8 in QGIS, the most suitable area for analyzing glacier flow speed, Terre de Lambert, was identified (highlighted in the red box in the image).

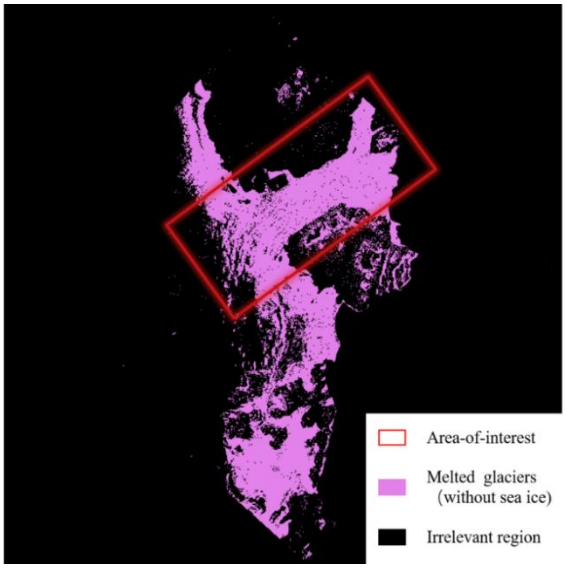

Figure 8. Glacier distribution map

3.3. Result of glacier movement

Upon completing these steps, the direction of glacier displacement and concurrently derive information about the glacier's flow speed can be determined. For a clearer observation, this data can be viewed in Google Earth Pro. As evident from Figure 9, which depicts the direction and speed of glacier movement, the flow speed at the edges is the slowest, less than 0.5 m/day. The upper part of the glacier, as shown in the image, flows faster than the lower part, with speeds reaching up to 2 m/day in the upper (southwest direction). In contrast, the speed in the bottom (east direction) is approximately 1 m/day. Through the analysis of the flow direction, it can be inferred that the movement is from higher to lower altitudes, and from the center outward in all directions.

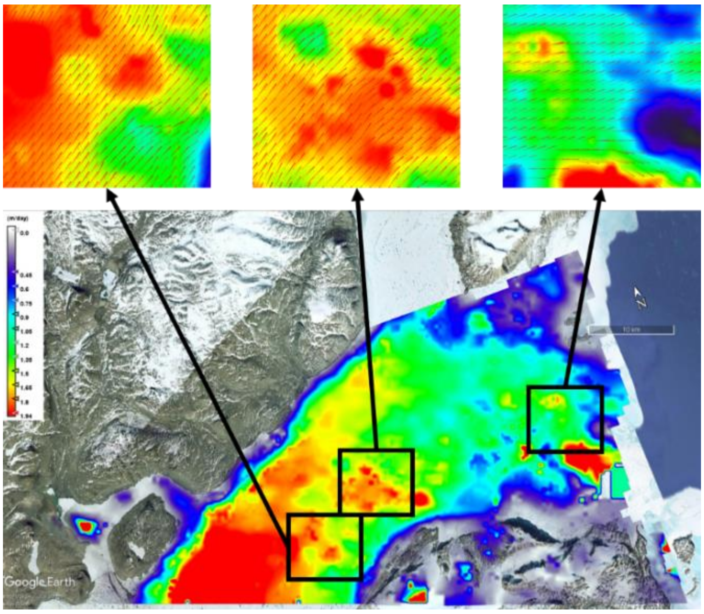

Figure 9. Direction and speed of glacier movement

3.4. Comparison of glacier flow velocities between 2023 and 2018

Observing Figure 10, which contrasts the glacier evolution speeds between June 20th and July 14th for the years 2023 and 2018, it becomes evident that the flow speed from June 20th to July 14th in 2023 was significantly faster. Such an acceleration in speed could suggest an intensifying process of glacier retreat, leading to the instability of the glacier system. Global warming is a primary factor behind this phenomenon. As the Earth warms, meltwater on the glaciers increases, resulting in the lubrication of the glacier base, which further accelerates glacier flow and retreat [20]. Additionally, the rise in temperature leads to increased precipitation in polar regions, with some areas experiencing a shift from snowfall to rainfall, thus augmenting the glacier melting rate. Beyond global warming, tectonic changes may also be a reason for the accelerated glacier flow. Movements of the Earth's crust and tectonic activities can modify the topography at the glacier's base, impacting its flow rate. For instance, crustal uplift might increase the slope at the glacier's base, thereby elevating the flow speed of the glacier. Naturally, there are other contributing factors, but these will not be elaborated upon here.

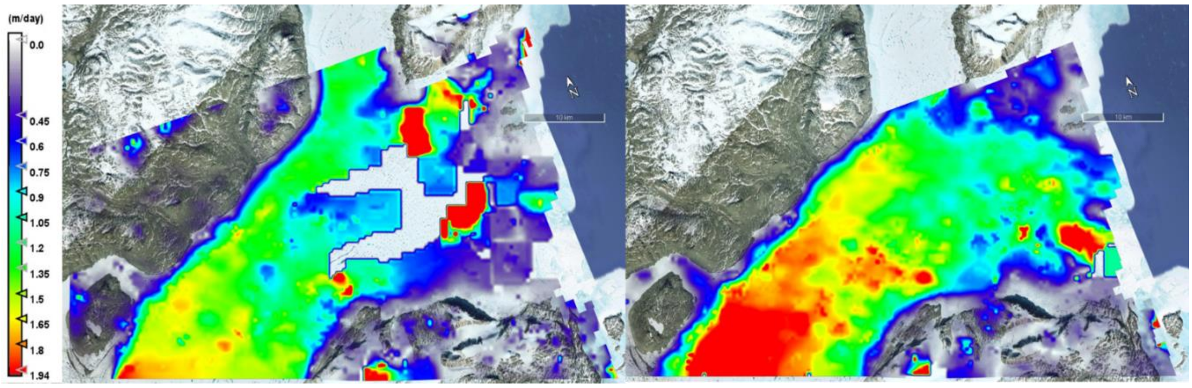

Figure 10. June 20 - July 14 Glacier evolution speeds in 2023 (right) compared with 2018(left)

4. Conclusion

This study utilized QGIS to analyze the Landsat 8 data of northeastern Greenland and identified the Terre de Lambert region as suitable for examining glacier evolution. Subsequently, using Sentinel-1 data in combination with SNAP software, the study analyzed the changes in land cover types, glacier movement speed, and direction in this area from June 20th to July 14th, 2023. The research revealed that the glacier flows slower in the marginal areas, and its upper parts flow faster than its lower sections. By analyzing the flow direction, a movement trend from higher latitudes to lower ones and from the center outward was discerned. When compared to the data from 2018, it was observed that the melting rate of glaciers in 2023 significantly surpassed that of five years prior, potentially due to global warming or tectonic shifts.

For a more in-depth study of glacier flow speeds, it is recommended that researchers initially employ Landsat 8 data to perform land cover classification and temporal change analyses over extensive snow-covered areas. This will provide a comprehensive understanding of the entire research region, taking into account all the factors within. Subsequently, NASA's ITS_LIVE can be used to discern global real-time glacier flow speeds and changes over several years, with SNAP software assisting in the processing, despite the issues related to data stitching discrepancies. In the future, we hope to offer more convenient, streamlined, and customizable time-scale continuous glacier flow data to bolster more precise studies.

Additionally, this study emphasizes the phenomenon of glacier melting, suggesting that both natural and anthropogenic factors, especially global warming, drive this process. The melting of glaciers symbolizes the tears of Mother Earth. Through this research, we aspire to draw global citizens' attention to the changes in glaciers, hoping to inspire collective efforts to mitigate the greenhouse effect and contribute towards safeguarding our planet.

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