MONITORING OF GLACIERS ON HORSESHOE ISLAND, ANTARCTICA BASED ON A DEEP LEARNING APPROACH FROM HIGH-RESOLUTION ORTHOPHOTOS (TAE-6 & TAE-7)

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KEY WORDS: Antarctica, Glaciers, Orthophoto, Deep learning, Change detection

ABSTRACT:

Global climate change is a phenomenon that seriously affects the balance of a wide variety of ecosystems and is the intense focus of climate scientists and environmental researchers. In this context, periodic monitoring of glacier areas in terms of a better understanding of atmosphere-ocean interactions; thus, predicting the effects of climate change and planning against future threats by evaluating environmental impacts is an important research area. Especially the polar regions, where the melting of glaciers and the rise of sea levels are visibly observed, are important for climate scientists in providing crucial observations to understand and predict global climate change. In this study, within the scope of the international bilateral cooperation project carried out in cooperation with Istanbul Technical University (ITU) and the Bulgarian Academy of Sciences (BAS) (Project No: 121N033), the spatial changes in snow/glacier areas obtained from UAV Photogrammetry products generated during the 6th and 7th Antarctic National Science Expeditions. Snow/glacier areas were segmented with the K-Net deep learning approach which has been previously tested for accuracy and provides glacier mapping with accuracy metrics over 99%, on the high spatial resolution orthophotos produced during the two periods. The snow/glacier areas difference between the two periods were calculated and compared and water bodies which are critical areas, were specifically examined. The result of this comparison shows that the glacier area decreased by approximately 11% in just 1 year. However, to better understand these changes in snow/glacier areas, the region needs to be observed closely for longer time periods. It is thought that future studies will contribute to efforts to manage global environmental impacts and cope with climate change by focusing on monitoring and better understanding changes in these critical regions.

1. INTRODUCTION

Glaciers are a critical component of the climate system and changes in these areas have an important role in the interactions between the atmosphere and oceans. Monitoring glacier changes, especially in Antarctica, one of the regions with the world's largest glaciers (Windnagel et al., 2023), is of great importance for better understanding the effects of climate change and for predicting future changes. In this regard, satellite imagery, which could be the main data source, is advantageous in many monitoring applications with its wide coverage area, however, it also has some limitations such as weather conditions, resolution etc. On the other hand, UAV technologies have the potential to provide high resolution data for research and interest in using these technologies in Antarctica appears to have increased significantly in recent years. In the literature, several studies on UAV-based applications in this unique region have been used by different disciplines for different purposes (Pina & Vieira, 2022). Studies carried out in snow and glacier areas, which are one of the most current issues, are important in terms of understanding the effects of global climate change and global warming.

In the study conducted by Westoby et al. (2015) in the Patriot Hills glacier area in West Antarctica has showcased the capability of Structure from Motion (SfM) methods in classify the distribution of particle size of loose glacial surface sediments. These data were compared with results obtained by established methods such as manual dry sieving and terrestrial laser scanning (TLS) (Westoby et al., 2015). In the study conducted on Demay Point Peninsula on King George Island, spatial analysis of periglacial landforms was carried out founded on a digital elevation model (DEM) and high-resolution orthophoto data produced by the UAV photogrammetry method (Dąbski et al., 2017). A study using UAV Photogrammetry to create the surface micro-topography model around China's Zhongshan Station in East Antarctica, the features such as ice dolin, blue ice and crevices were extracted and investigated. It has been observed that the features of surface micro-topographic can be observed in UAV-based models but are challenging to be revealed in satellite imagery (Yuan et al., 2020). In another study conducted on Signy Island, located in the northwest of the Antarctic Peninsula, UAV Photogrammetry was used to monitor snow thickness and spatial changes. Orthophoto and DEM were generated by UAV Photogrammetry, and they were used to extract topographic and land cover features in a region where snow depth was monitored. While the study results indicate that there is a strong relationship between the average annual air temperature and the average annual snow depth, it also supports the view that potential warming in the future may reduce the snow depth in the region (Tarca et al., 2022). In a study involving the investigation of the movements of the Dålk Glacier in East Antarctica, digital surface models (DSMs) and orthophotos created in different studies with UAV Photogrammetry were used. A modified pseudo parallax method was employed to calculate the movement of glaciers. Using transverse and longitudinal profile analysis, stretching of the glacier body due to the decrease in glacier elevation and the formation of new crevasse zones was observed (Skrypitsyna et al., 2023). According to the results of these studies, it appears that UAV-photogrammetry has been used successfully in determining snow/glacier change.

Nowadays, with the developing technology, artificial intelligence and deep learning methods come to the fore in change detection studies. In studies revealing glacier changes using these approaches, images obtained from remote sensing satellite systems have been commonly used. For instance, in a study using Sentinel-2 and Landsat 8 images were used to classify images into glaciers, non-glacier, and debris-covered glacier classes using three machine learning algorithms. The supervised classification methods examined in the study carried out in the Hunza basin are Support Vector Machine (SVM), Random Forest (RF), and Artificial Neural Network (ANN), respectively (Khan et al., 2020). In another study carried out in two different regions, La Laguna basin (Chile) and Poiqu basin (Central Himalaya), which contain rock glaciers of various sizes and activities, Sentinel-2 and Sentinel-1 imagery were used. Using 2018 and 2019 Tri-stereo Pléiades satellite images, DEMs were created across the two research areas. A semi-automated approach was proposed using a combination of CNNs (Convolutional Neural Network) and OBIA (Object-Based Image Analysis) from Sentinel data and a high-resolution DEM in the study (Robson et al., 2020). In a study conducted by Kumar et al. (2021), one of the supervised classification approaches, Maximum Likelihood Classification (MLC), was used to detect and monitor Bhutan's glacier cover changes over approximately 40 years through Landsat images (Kumar et al., 2021). In the study of Xie et al., (2021), Landsat-8 data was used in a selected test area in the Himalayan region (the Karakoram range and its surroundings) in the process of DCG (Debris-Covered Glacier) mapping, that is, determining the boundaries of debris-covered glaciers and mapping these glaciers. The study evaluated the GlacierNet model's performance against a number of CNN segmentation models, including DeepLabV3+, FCDenseNet, Res-UNet, Mobile-UNet, and R2UNet. (Xie et al., 2021). In addition to research topics in snow/glacier areas, photogrammetric outputs obtained from the UAV Photogrammetry method are also used in various research areas such as investigations about the vegetation (Lucieer et al., 2014; Turner et al, 2018), fauna (Pfeifer et al., 2019; Fudala and Bialik, 2022), atmosphere (Cassano et al., 2021) and technology (Rodzewicz et al., 2018; Inoue et al., 2022).

Despite significant advancements in monitoring regional ice masses, a critical component in global climate change investigations, there exists substantial uncertainty and a dearth of comprehensive information about glaciers. In this context, advanced artificial intelligence and deep learning methods have the potential to provide a solution for optimized glacier monitoring from UAV Photogrammetry, which provides high spatial resolution. The main objective of this study is to reveal the changes in glacier areas by utilizing the photogrammetric products produced by UAV Photogrammetry method in two different periods on Horseshoe Island, Antarctica. The photogrammetric data used in this study are the products produced after flight missions performed at a test site on Horseshoe Island within the scope of the TÜBİTAK international bilateral cooperation project (Project No: 121N033). K-Net architecture, a deep learning approach that has been previously tested in the same study area and achieved high performance (Selbesoğlu et al., 2023), was used to monitor the temporal changes of snow and glacier areas quickly and effectively.

2. MATERIALS AND METHODS

2.1 Study Area

Horseshoe Island, where the Turkish Scientific Research Station is located (-67°49'46.21", -67°14'12.61"), is one of the islands in Marguerite Bay located in the south-central region of the Antarctic Peninsula. Horseshoe Island has a total surface area of 60 km^2 and 66% of this area is covered by snow/glacier (Yıldırım, 2020). The region, which has a rich snow/glacier cover, is an ideal environment to observe changes in snow/glacier cover because of how the world's climate is changing in these regions. UAV Photogrammetry method is used for snow/glacier investigations in the study area, which covers an area of approximately 2.6 km^2 and is roughly defined in the center of the island (Figure 1). This region, which is located close to the location of the camp, is the most optimum region for the safe completion of UAV flight missions.

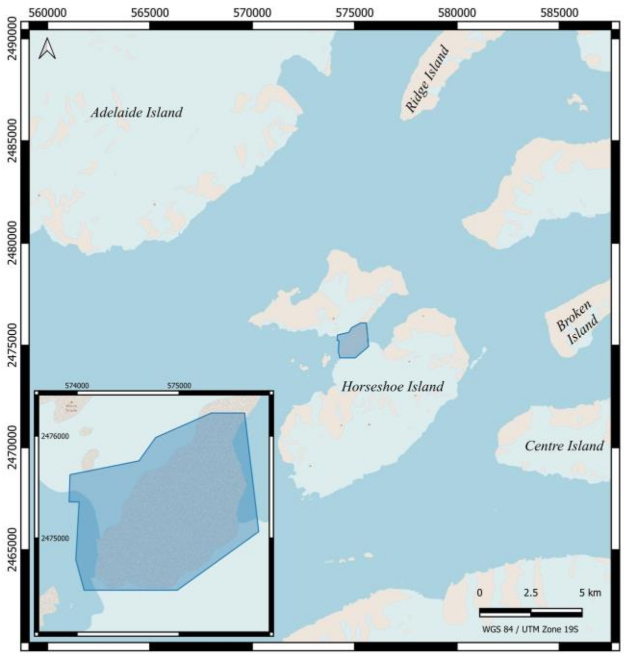

Figure 1. Study area in Horseshoe Island.

The southern part is the richest part of the Horseshoe Island in terms of glaciers, and the largest glacier of the island, Shoesmith Glacier, located in this region, is very important (Smith 1973, Yıldırım 2020). The south of our study region corresponds to a significant part of this glacier.

2.2 Materials

Ground control points (GCPs) are necessary to rectify images and investigate the position. The 14 GCPs distributed from the west coast to the east coast of the island, were placed and their positions were surveyed precisely with the classical RTK (Real-Time Kinematic) method. For safe and efficient flight missions, features such as the UAV's weight, maximum wind speed resistance, maximum flight time and ability to operate at low temperatures are very important, considering the climate and environmental conditions of Antarctica. Flight plans were prepared for two different periods, taking into account the physical characteristics and weather conditions of the study area. Front and side overlap rates were determined to be approximately 70% and 80%, respectively, and flight missions were completed at a constant height relative to the take-off point. Additionally, while performing UAV missions in the region, the possibility of the UAV falling due to system errors and the dangers of disturbing wildlife should be taken into consideration. In this regard, the flight altitude was constantly controlled during the flight, care was taken not to disturb wildlife and precautions were taken to ensure that the pilot was very close to the flight area. All flights were successfully completed in TAE 6 (Turkish Antarctic Expedition, February 2022) and TAE7 (February 2023).

The orthophotos (Figure 2) were created from two different periodic image data in the Pix4Dmapper software environment with the SfM approach, which is an image-based modeling technique that enables 3D models to be obtained from 2D overlapped photographs taken from different angles.

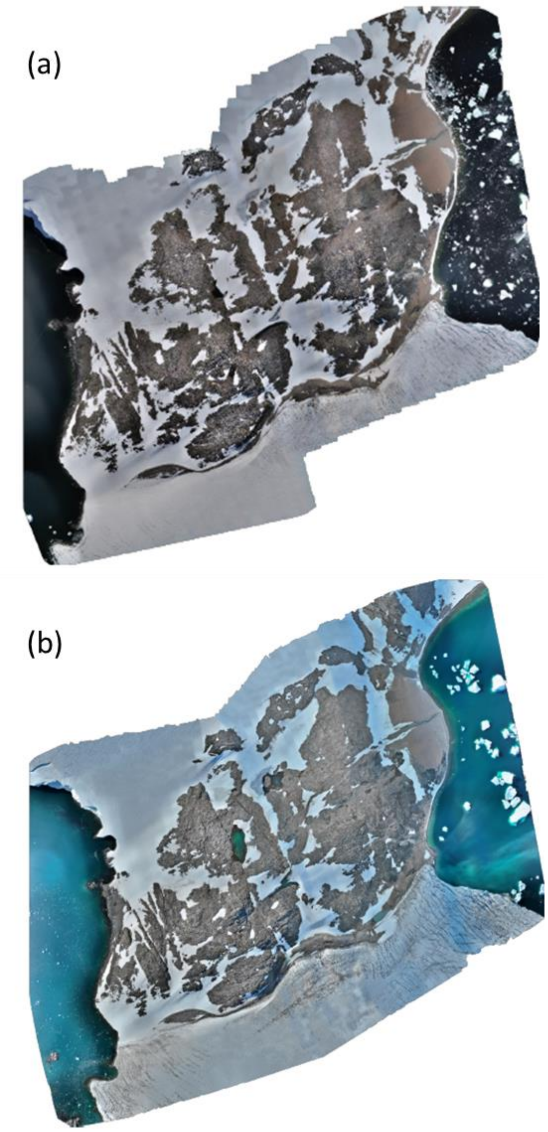

Figure 2. (a) Orthophoto generated in 2022 (TAE-6), (**b)** Orthophoto generated in 2023 (TAE-7).

The flight missions were carried out during the same season of the year, however various sudden changes in the glaciers were visible on orthophotos. The average ground sampling distance (GSD) value of the orthophoto generated from UAV data is 2.95 cm and in 3.55 cm in 2022 and 2023, respectively. In the orthophoto generated in 2023, there were new puddles, glacier crevasses and glacier calving that were not present in the orthophoto generated in 2022.

2.3 Implementation of K-Net

K-Net architecture employs a group of kernels to assign each pixel to either a semantic class or a potential instance (Zhang et al., 2021). It iteratively refines the static kernels and image segments based on features collected from the segmented groups. K-Net can perform successfully in glacier segmentation from high-resolution orthophotos obtained from UAV-Photogrammetry and in general, it can outperform approaches such as Deeplabv3+ and Segformer in terms of preserving glacier boundaries and segmenting small-sized glaciers (Selbesoğlu et al., 2023).

In order to monitor the temporal change of glacier areas quickly and effectively, the K-Net architecture was exploited, and snow/glacier areas were segmented over two periods of orthophotos in 2022 and 2023 (Figure 3 and Figure 4). The segmentation process was performed in the overlapping flight region and was limited to the coastal regions.

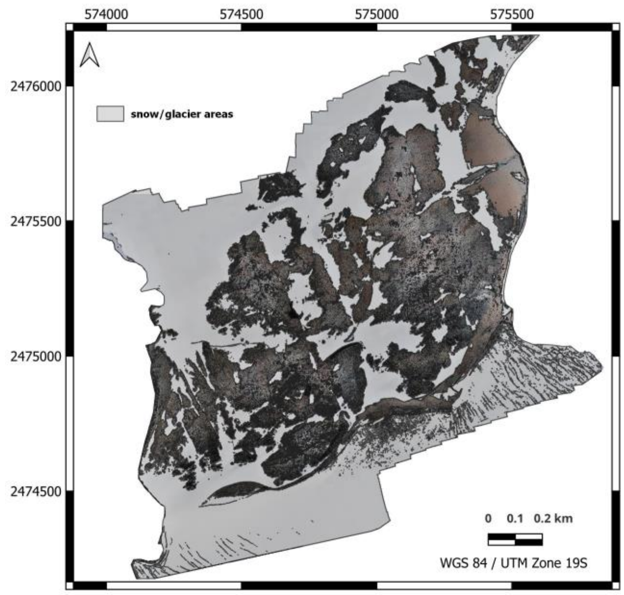

Figure 3. Snow/glacier area obtained with K-Net deep learning approach from orthophoto in 2022.

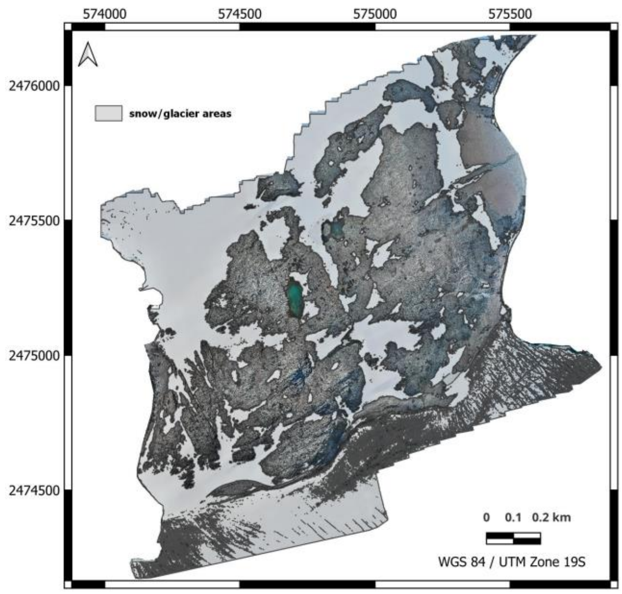

Figure 4. Snow/glacier area obtained with K-Net deep learning approach from orthophoto in 2023.

3. RESULTS

The accuracy assessment results of the classification of snow/glacier areas with the K-Net model for the orthophoto created in the TAE-6 process. The relevant assessment results according to different metrics is presented in Table 1.

Metrics	Assessment result
Accuracy	99.62%
Precision	99.82%
F1-Score	99.79%
IoU	99.58%
Recall	99.76%

Table 1. Accuracy assessment of K-Net from orthophoto generated in 2022 (Selbesoglu et al. 2023).

Segmentation Method	Snow/Glacier Area 2022 (ha)	Snow/Glacier Area 2023 (ha)
K-Net	119.72	106.38

Table 2. Snow/glacier areas detected with K-Net approach on Horseshoe Island.

After classification of the two-period orthophoto, the total areas corresponding to the snow/glacier class were calculated for the relevant periods. According to the segmentation with the deep learning approach, 119.72 hectares of glacier area (Figure 3) was detected in the TAE-6 period and 106.38 hectares (Figure 4) in the TAE-7 period (Table 2). As a result, it was observed that the glacier area decreased by approximately 13.34 hectares in total, and this value shows that the glacier area decreased by approximately 11.14% in just 1 year. Furthermore, a difference map was created to visually analyse the changes in glacier areas (Figure 5). When the changes are examined in general, it is seen that the glacier areas have decreased from the border parts, but it has been determined that there are intense changes in three sub-regions.

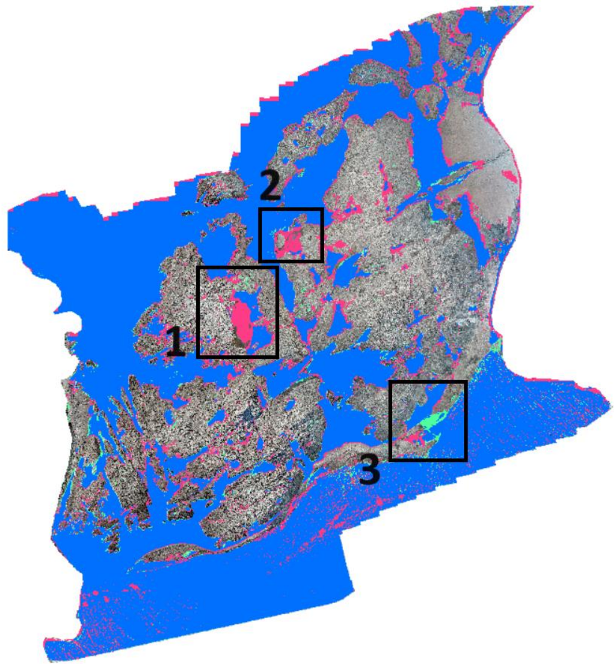

Figure 5. Glacier change map between TAE-6 and TAE-7. Blue region: protected glacier, red region: decreased glacier, green region: increasing glacier, black boxes: regions where changes are continuous and significant.

When the region number 1 given in the difference map (Figure 5) and orthophotos (Figure 6a and Figure 6b) is examined in detail, it is observed that the lake surface, most of which was covered with glaciers during the TAE-6; it appears to have melted almost completely during the TAE-7. A similar situation was observed in region number 2, and it is clear that there is intense melting in the wide area, especially on the right side of the lake surface (Figure 6c and Figure 6d). If the melting continues in this way, it can be predicted that the left part of the lake in this region will also melt in the next measurements. In region number 3, it was observed that the glacier area increased (Figure 5, Figure 6d and Figure 6f). In this region, the lake water level rises as a result of melting; it is thought that the surface of the rising lake water level may have frozen and this region was determined as a glacier area as a result of segmentation. Moreover, such a regular and continuous increase has not been observed anywhere outside this region.

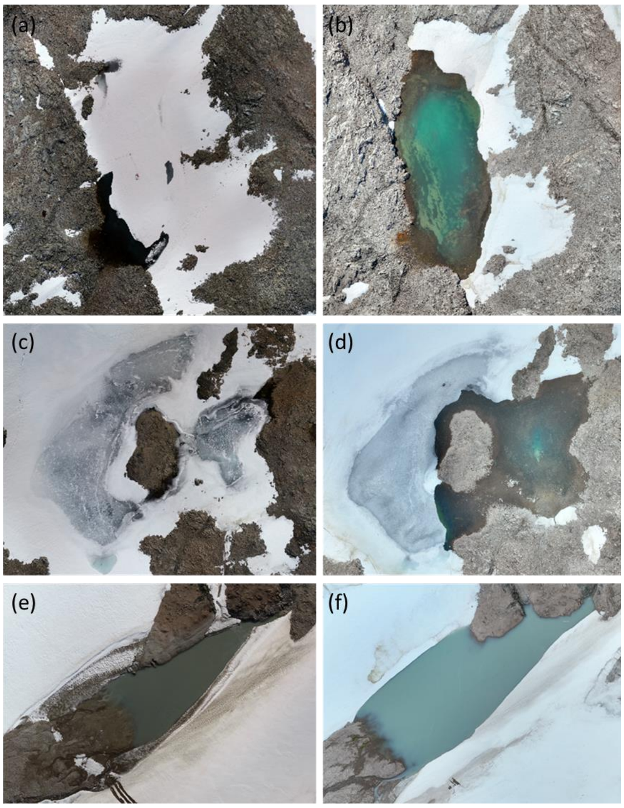

Figure 6. Regions where snow/glacier areas change intensely, **(a)** Region 1 in TAE-6, **(b)** Region 1 in TAE-7, **(c)** Region 2 in TAE-6, **(d)** Region 2 in TAE-7, **(e)** Region 3 in TAE-6, **(f)** Region 3 in TAE-7.

4. DISCUSSION&CONCLUSION

Antarctica offers a unique laboratory for understanding the world's climate system and making plans against the negative effects of climate change on various ecosystems. Scientific research conducted in this critically important region has the potential to reconstruct the effects of climate change and provide important clues about future changes. Studies on climate change effects provide valuable information about the global climate system by analyzing the melting of glaciers, changes in sea levels, and atmospheric interactions in this region. The literature focuses on the use of innovative techniques such as satellite imagery and UAV photogrammetry, which are one of the possibilities offered by modern technology, to better understand the effects of climate change on this huge continent and for various purposes in glacier areas.

Studies carried out in glacier areas in Antarctica with UAV Photogrammetry generally focus on the production of high spatial resolution orthophotos and DEM for topographic mapping purposes or for comparison with other methods when used for different purposes. For instance, in the study by Westoby et al. (2015), UAV-Photogrammetry achieved accuracies of 0.17 and 5 cm for patch and site scale modeling compared to equivalent datasets obtained using the terrestrial laser scanning method. Dąbski et al. (2017), investigated the usability of high-resolution aerial photographs obtained with a fixed-wing UAV, together with GIS data processing, to detect periglacial landforms; In this study, orthophotos could be produced with a 5 cm spatial resolution method (Dąbski et al., 2017). In the study of Yuan et al. (2020), on modeling the surface micro-topography by the application of UAV in the polar environment, it was concluded that the UAV used achieves a relative mapping accuracy at the centimeter level. The study suggests that UAV-derived micro-topographic features offer insights into interactions between surface and beneath processes in regional polar glaciers, which are difficult to visualize from satellites. Three potential applications for UAVs in polar environments were highlighted: the need for more durable UAV platforms, improved positioning for better surface modeling, and the use of various sensors such as LiDAR (Light Detection and Ranging) or multispectral sensors for enhanced data collection in Antarctica (Yuan et al., 2020). In the study of Tarca et al. (2022), the DEM generated with an accuracy of 0.048 m was used to obtain topographic parameters such as elevation, slope, aspect, and topographic position index (TPI). Land cover and vegetation were classified with 82% overall accuracy using maximum likelihood classification, a supervised classification method from orthophoto produced at the same resolution as the DEM (Tarca et al., 2022). The study, which investigates the changes in the surface topography of Dålk Glacier and the movement speed of different parts of the glacier, comes to the fore with the use of various types of UAVs in glacier areas and the application of a direct georeferencing approach. DSMs and orthomosaics were generated for the two test areas at resolutions of 0.5 m and 0.2 m, respectively. The mean velocity of the glacier actively moving was 1.3 meters per day while the average displacement of the central region over two years amounted to 423 meters, equivalent to around 0.6 meters per day. (Skrypitsyna et al., 2023). Such studies support the usability of the UAV photogrammetry method we used in our study in glacial areas under the harsh environmental conditions of Antarctica.

On the other hand, artificial intelligence and deep learning methods come to the forefront in change detection studies with the developing technology. In studies focusing on the changes in snow/glacier regions using these methods, satellite imaging data are more prominent. The study of Khan et al. (2020), constitute an example of using machine learning approaches in the glacier field, and out of the 3 approaches they used, random forest performed the best accuracy result (f-measure: 95.06% and Kappa: 0.95) for distinguishing debris-covered glaciers Khan et al. (2020). Another example is Robson et al. (2020)'s classification with CNN_OBIA, user accuracy varies between 63.9% and 68.9%, according to the classification accuracy analysis of rock glaciers in two different periglacial environments. Producer accuracies for the La Laguna and Poiqu basins were 75.4% and 75.0%, respectively; this is in most cases an overestimation of individual rock glacier polygons (Robson et al., 2020). In another classification study based on Landsat satellite imagery, Kumar et al. 2021 monitored glacier cover changes. The overall accuracy of the classification performed with MLC in three different years was found as 80%, 67.28% and 71.42%, respectively. After examination of satellite image data between 1978 and 2017, it was revealed that there was a 2.54% decrease in the total glacier area (Kumar et al., 2021). In the study conducted by Xie et al. (2021), among different networks for DCG mapping, DeepLabV3+ has the highest Intersection-over-Union with 86.23% and is the leader CNN segmentation model in overall performance (Xie et al., 2021).

Although these classification studies are successful for their own purposes, the resolution of satellite imagery is a limitation for monitoring changes in snow/ice fields in topography such as Antarctica, where similar features are generally dominant. The presence of similar objects or features in the environment could make it difficult for image-matching algorithms to accurately distinguish which features belong to which object. In this context, as can be seen from the orthophotos used in our study, deep snow/ice cracks and water/ice separation are challenging for feature extraction, so it would be advantageous to utilize deep learning methods that can work effectively. Considering the studies in the literature conducted for similar purposes, it could be inferred that there is a lack of studies on revealing the changes in glacier areas by utilizing deep learning methods over high spatial resolution orthophotos.

In the study area located on Horseshoe Island in the Antarctic Peninsula, orthophotos generated by UAV Photogrammetry during the TAE-6 and TAE-7 periods were compared to reveal the one-year change in snow/glacier areas. For these purposes, spatial differences were analyzed by performing snow/glacier segmentation with a deep learning approach on the orthophoto produced by UAV Photogrammetry for two periods. For the segmentation of snow/glacier areas, the K-Net model, which has been previously tested for accuracy and provides over 99% glacier mapping, was used. With the K-Net deep learning network, maps of snow/glacier covered areas for two periods were generated. According to the spatial comparison of snow/glacier covered areas from two different years, it was concluded that there is a significant melting in snow/glacier areas, especially towards the coastline. The amount of melting calculated as surface area in a year is approximately 13.34 ha and the critical areas were examined through orthophotos, and the changes were interpreted. As it is known, the melting of glaciers caused by global climate change increases sea and ocean levels. The decrease in glacier coverage we observed in our study area over a year is an example of this and should be constantly monitored.

In the future, the classification method can be improved by separating snow and glaciers, and changes in glacial crevasses can also be examined. Monitoring structural changes in glaciers over time is crucial for future studies aimed at observing the effects of global climate change.

ACKNOWLEDGEMENTS

This study was carried out within the scope of the international bilateral cooperation project titled " Glacier Monitoring and 3D Modelling in Horseshoe Island Antarctica Based on UAV-GPR Observations" (Project No: 121N033) and the project was funded by The Scientific and Technological Research Council of Turkey (TÜBİTAK).

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