Kadurin, S., & Andrieieva, K. (2021).
Ice sheet velocity tracking by Sentinel-1
satellite images at Graham Coast Kyiv Peninsula.
Ukrainian Antarctic Journal, 1, 24—31.
https://doi.org/10.33275/1727-7485.1.2021.663

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Ice sheet velocity tracking by Sentinel-1 satellite images at Graham Coast Kyiv Peninsula

Abstract. The study of Antarctic glaciers and ice sheets velocity is one of the most discussed topics. Such high interest in this topic is primarily because the ice from the Antarctic glaciers, which gets to the ocean, significantly affects the ocean level and the global climate. Development of modern satellite technologies for Earth remote sensing made it possible to elaborate a number of methods for ice sheets' displacements estimation and calculation of such displacements velocities. This work uses remote sensing data from the satellite system Copernicus Sentinel-1 to estimate the ice cover velocities in the Kyiv Peninsula in the time interval from December 2020 to March 2021. To this end, 10 radar images of the study area from early December to the end of March were used with an interval of 12—14 days. All selected images were analyzed in pairs to establish changes on the surface for the selected time interval. GRD-format images from Copernicus Sentinel-1 satellite, corrected for Earth's ellipsoid shape, were used. Based on the offset tracking operation, we calculated the speeds of ice cover movements within the Kyiv Peninsula for each pair of images with approximately two weeks' time difference. As a result, the speed of ice movements varies considerably and at the glacier mouth can reach 3.5—4 meters per day. Also, the rate of ice displacement in the glacier body changed over time. Thus, the highest ice velocities were in the glacier's mouth. However, short-term time intervals of intensification were recorded for the rear and even the marginal parts of the glaciers in contact with the ice sheet. Thus, the lowest part of the glacier activating sequence leads to the upper part shifting. Notably, this increase in the displacement of ice cover was recorded in February, one of the warmest months in this part of Antarctica.

Keywords: Kyiv Peninsula, Sentinel-1, glacier velocity, remote sensing

1 Introduction

The science of Antarctic glaciers' displacement velocities is lately a topic of a most active discussion (Baumhoer et al., 2018; Wearing et al., 2015; Wesche et al., 2013). Such attention to this question is not accidental: the Antarctic holds the largest ice reserves in the world (Fox et al., 1994), yet they are destroyed so fast, losing ice and meltwater at such pace, that their effect on changing ocean levels and global climate is quite significant (Vaughan et al., 2013). Field monitoring of ice sheets' state is complicated by matters both technical and climatic. Therefore, remote sounding is employed to record the glaciers' state and position progressively more often (Savchin & Shylo, 2020; Baumhoer et al., 2018; Liang et al., 2021). Typically, studies track displacements and changes of the glaciers' edge margins (Baumhoer et al., 2019; Wearing et al., 2015; Wesche et al., 2013). Practically all the cited researchers use Earth remote sounding methods to some extent. Usually, they rely on satellite radar systems like RADARSAT-1, MODIS (Moderate Resolution Imaging Spectroradiometer), Cryo Sat-2, or Copernicus Sentinel-1 (Wuite et al., 2019). Using multispectral satellite systems like Landsat 7, 8, or Copernicus Sentinel-2 imposes some limitations and strongly depends on the cloud coverage over the studied area (Huber et al., 2017).

Current developments in satellite observation and especially data treatment gave rise to techniques to evaluate dynamic changes in ice sheets. This paper aims to estimate the rate of ice sheets' and glaciers' displacement rates within the Kyiv Peninsula of the Graham Coast based on satellite data of Copernicus-Sentinel-1.

The object of our research is the ice cover of the Kyiv Peninsula. The area includes both ice sheets and glaciers. Thus, practically the whole coast area is occupied by large glaciers' outcrops, with glacier troughs divided by rock edges and crystalline rocks often piercing the ice through to the surface as separate peaks and ridges. The central part of the peninsula lies under an ice sheet that thins down coastwards. Glaciers nest in broad valleys, backed steeply behind by the plateau ice sheet and fanning out in front to the shore itself. They bear meltwater's tracks, splits, and crevasses; it is precisely within glaciers that the highest displacement velocities are to be expected. Therefore, our research focussed mainly on establishing the field of ice movement velocities in different parts of the Kyiv Peninsula. The time range was December 2020 to March 2021.

2 Data and methods

Our study used Sentinel-1 data for the Graham Coast. The satellite bears the C-SAR equipment to record observations in any weather, nighttime or daytime. The apparatus's active antenna has radiation frequency of 5.405 GHz and receives reflected waves of this range. In this way, the ground is mapped along with the coastal strip and the ice sheet cover, and the reflection intensity of the chosen wave range is established for different kinds of surfaces. For our study, we selected Level-1 pictures which have precise spatial and temporal tags.Moreover, they include information on the height markings corrected for the Earth's ellipsoid shape (Ground Range Detected data). The data have 10-meter resolution per image pixel.

The pictures are available at the Copernicus Open-Access Hub. The data of Sentinel-1 sounding are updated once a fortnight. Thus, the images we used for the chosen time range were taken on 02.12.2020; 14.12.2020; 26.12.2020; 07.01.2021; 19.01.2021; 31.01.2021; 12.02.2021; 24.02.2021; 08.03.2021; 20.03.2021.

To treat the data, we used the Sentinel Application Platform (SNAP), freely available on the European Space Agency website (https://step.esa.int/main/download/snap-download/).

The procedure consists of the following steps:

1. Matching coordinates and co-registering pictures of the same area taken on different days. To match two images, one is chosen as the dependent one, and all its pixels are corrected in space by the coordinates of the other chosen as the main one. For this to be possible, all pictures must be accurately tagged. The pairs of pictures we selected were taken the minimal time interval apart, i.e. 02.12—14.12.2020; 14.12—26.12.2020; 26.12.2020—07.01.2021; 07.01—19.01.2021; 19.01—31.01.2021; 31.01—12.02.2021; 12.02—24.02.2021; 24.02—08.03.2021; 08.03—20.03.2021. This way, we identified nine time intervals for which we determined changes in ice sheet covers and calculated ice displacement velocities.

2. Delineating the study area. The step directly allows determining the study area. A full picture by Sentinel-1 encompasses 250 by 170 km of the Earth's surface, together with a big patch of the water area near the Graham Coast. So to optimize the work and precisely determine the work area, we would take only a part of an image 61 by 82 km in size to analyze only the shoreline part of the Graham Coast and the Kyiv Peninsula in particular (Fig. 1a).

3. Determining the glaciers' displacement velocities based on tracking of the differences at a later date. This is done with a software procedure of Offset-Tracking Operation for a pair of related images with precise geo-positioning. The function was developed directly for glacier movement monitoring. It requires a specific sequence of actions starting with choosing two related images having reference points. These reference points should be present on both pictures and have precisely identified spatial coordinates. The points are selected automatically without human input. Secondly, the program computes spatial displacement for every chosen reference point. Since every image

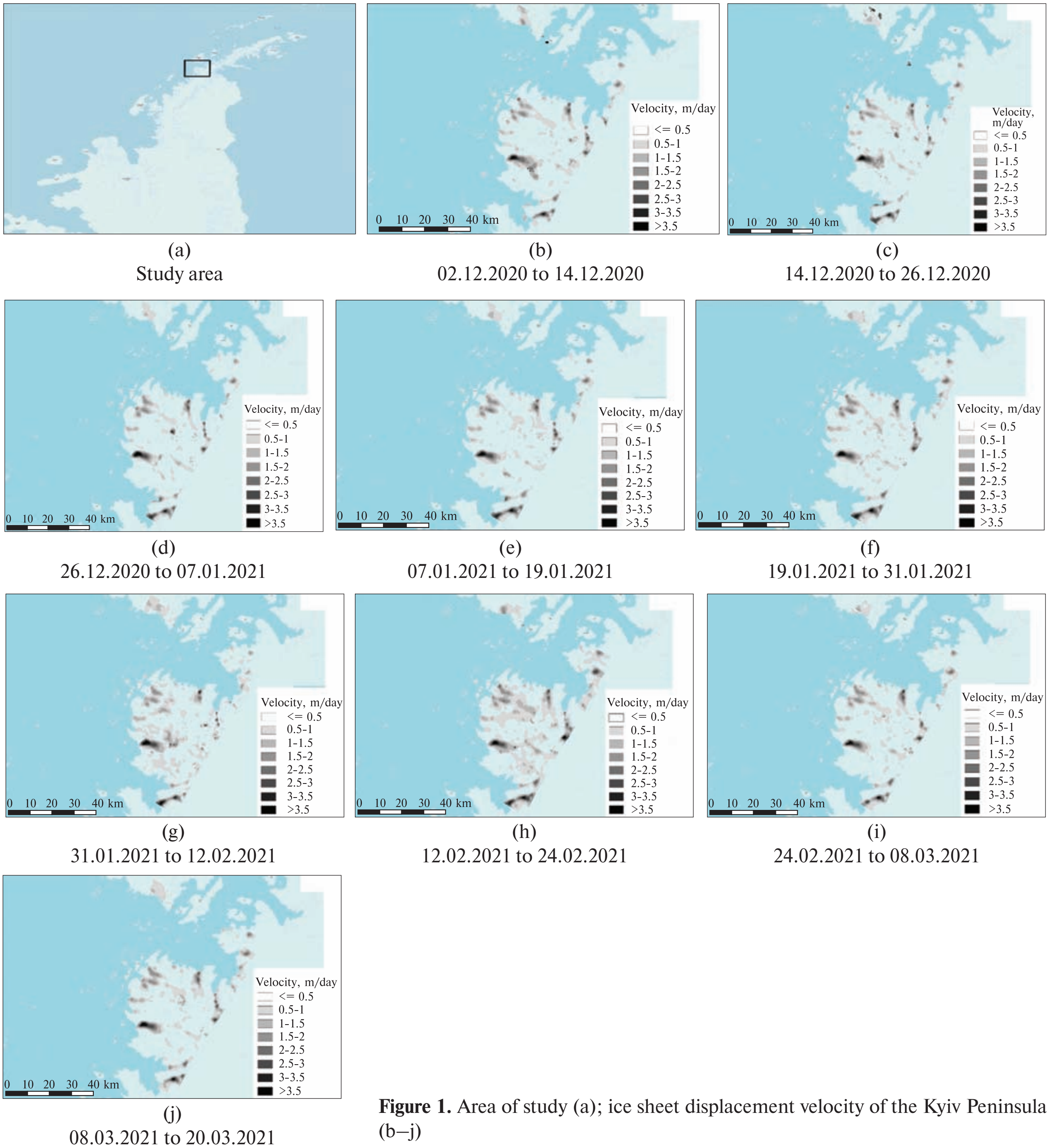

Figure 1. Area of study (a); ice sheet displacement velocity of the Kyiv Peninsula (b–j)

has precise coordinates in space and time, it is possible to calculate the displacement velocities for every reference point. Thirdly, the digital surface of ice sheet velocity is calculated on reference points' numbers averaging procedure.We chose positions of reference points for all pairs of images so that a plot of 400 by 400 m included one such point. The total number of reference points was 31930. This allowed us to draw a

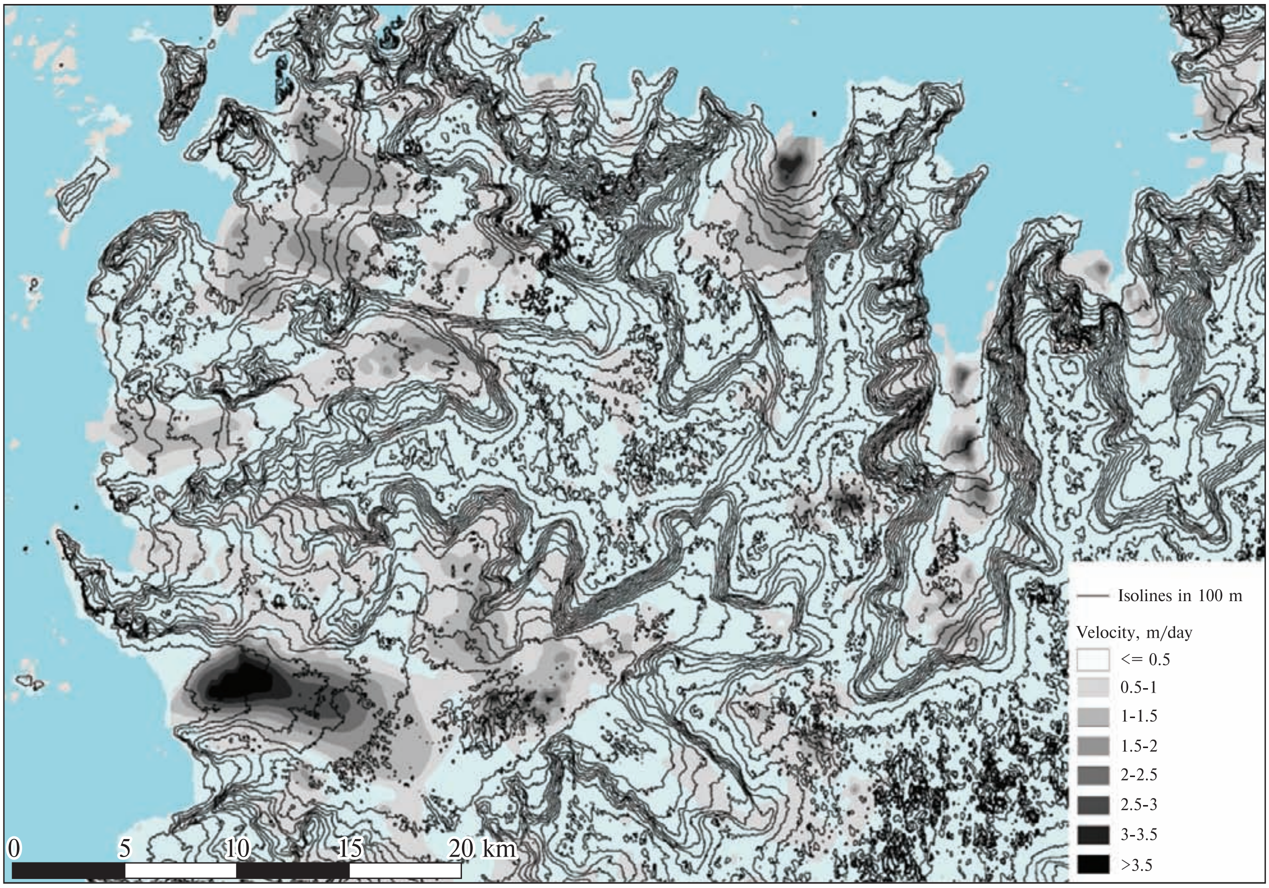

Figure 2. Kyiv Peninsula glaciers ice displacement velocity from 31.01.2021 to 12.02.2021

sufficiently detailed and accurate velocity field for ice sheet displacements within the Kyiv Peninsula.

4. Geo-positioning of the ice sheet displacement velocities and fitting the field to the landscape's digital surface. This includes precise geographical localization of every reference point and correction of its height markings. Because of the incline of the satellite's sensor and the landscape specifics, the computed heights can somewhat mischaracterize the actual landscape. These deviations are compensated for by the orthorectify method of Range-Doppler Terrain Correction (Small & Schubert, 2008). It incorporates information about the orbit state, radiosounding chronometry, and the sensor's angle relative to the planet surface taken from the metadata accompanying every satellite image used. Also, the height markings are checked against the preexisting digital landscape model. For the study area, the height correction was done based on the digital surface ACE30 GDEM.

The described procedure yielded nine maps of ice sheet displacement velocities for the Kyiv Peninsula of the Graham Coast (Figs. 1, b–j).

3 Results

The maps of ice sheet displacement velocity on the Kyiv Peninsula show it is quite variable in time and space. By remote observations, the ice sheet displacement velocity reaches 3.5—4 m/day for the glaciers, with an average of 1.5 to 2.5 m/day. The highest recorded velocities were observed for the Funk Glacier, Trooz Glacier, Daguerre Glacier, and Talbot Glacier. (Figs. 2, 3)

Most of the ice sheet remained practically stationary. However, one should note that the glaciers are in

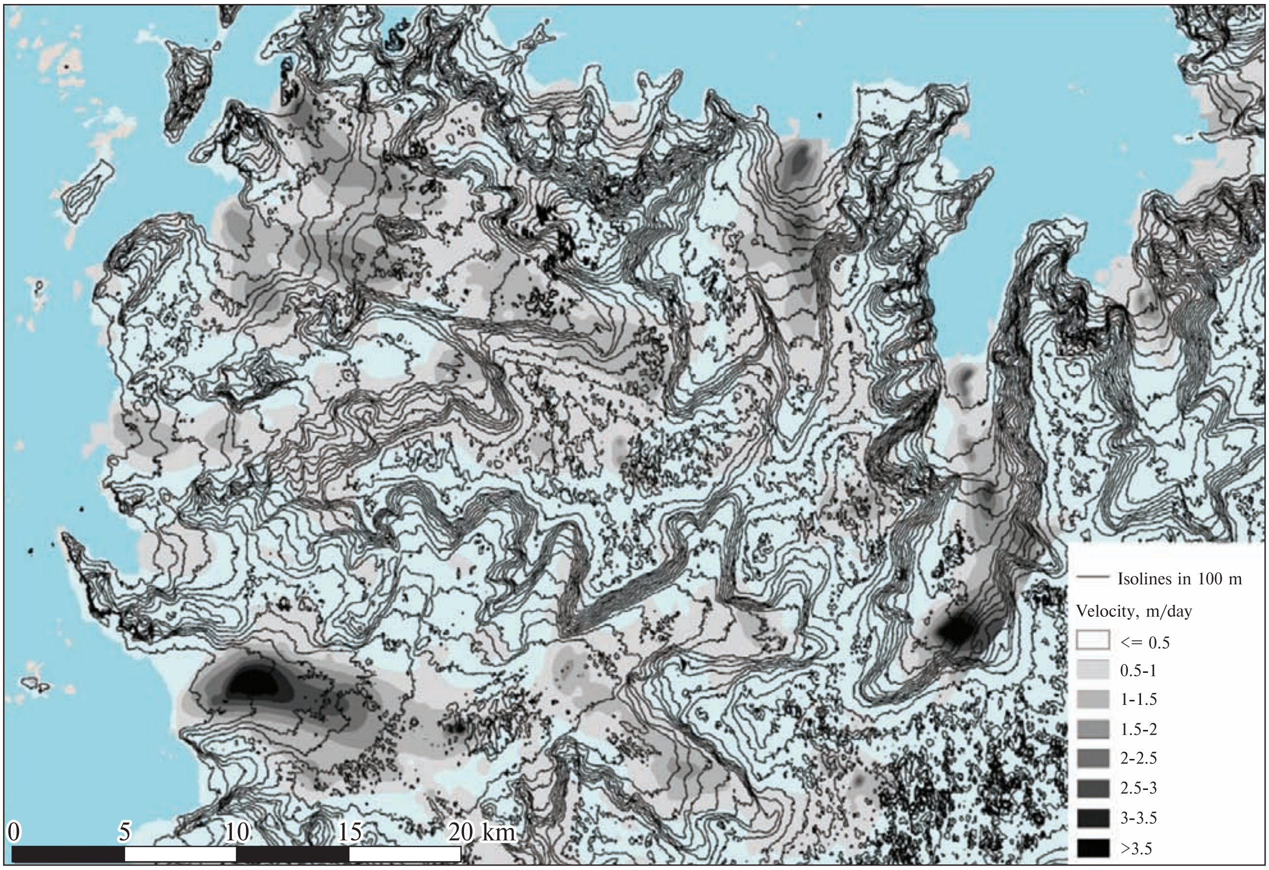

Figure 3. Kyiv Peninsula glaciers ice displacement velocity from 12.02.2021 to 24.02.2021

any case fed by the ice input from the sheets. Thus, at the ice sheet and the glacier border, there occasionally break off ice masses that begin to move more swiftly to the seashore. Our study revealed a particular order of these events. From early December to the end of January 2021, the main displacements were in the glaciers' mouths. Then, over the rather short period from January 31 to February 12, 2021, there moved ice masses in the inland parts of the glaciers (Fig. 2). This, in its turn, led to the displacement of the hindmost glacier parts (Fig. 3). All of this shows that glaciers move gradually, and ice input occurs not only due to new ice added on by precipitation but also due to the mobilization of sheet ice.

4 Discussion

Studies on the evaluation of Antarctic glaciers' displacement using radar satellite systems are a much-discussed topic lately (Zhou et al., 2011; Wearing et al., 2015; Mengzhen et al., 2020).The velocity of glacier movement depends on a whole complex of causes, of which the most powerful are the climate's influence (Cook et al., 2005), the ocean's influence on the glacier's outer margin (Cook et al., 2016), and the glacier's internal dynamics (Lovell et al., 2017). As a result, for different glaciers, velocities vary within a fairly wide range from practically zero to 660 m per year (Jawak et al., 2019; Jawak et al., 2018) in different parts of a glacier depending on the season. Thus, practically every study pointed out that the velocity of ice displacement in the ice flow grows from the glacier's head to the mouth, reaching the highest values exactly at the edge of the sea. Besides that, within the ice sheet on the plateau, the displacements are practically absent. Thus, the ice flow somewhat accelerates from the glacier's inland border towards

 ISSN 1727-7485. Ukrainian Antarctic Journal, 1, 2021, https://doi.org/10.33275/1727-7485.1.2021.663

its mouth. Such a "gain in momentum" should be accommodated by an incoming ice volume and lead to disjunctions in ice flow. As the lower part of the glacier accelerates, a system of crevasses crisscrossing the glacier's body is readily observable at all near-mouth parts of glaciers.

The research of ice displacement within the Kyiv Peninsula is uncommon among similar studies in Antarctica in that it uses small time intervals. Due to such observations, it became possible to pinpoint the changes in ice velocity in different glacier parts at different times. The displacements occur as a sequence. At first, the most actively moving parts are the lower ones. This, in all probability, causes shear stress between the boundary of the faster-moving lower part and the slower upper one. The stress is relieved by ice from the upper parts accelerating for a short while. This latest displacement activates movement at the boundary between the ice trough and the plateau within the bergschrund. This displacement stage is also relatively short, but it allows for upper parts of the glaciers to stabilize and, most probably, some more ice to be added from the plateau.

5 Conclusion

As a result of the research, we found that ice sheet at the Kyiv Peninsula from December 2020 to March 2021 demonstrates different patterns of displacement velocity in different parts. Velocity varies from practically zero within the ice sheet to 3.5 m/day in the mouths. Glacier displacement velocities vary from the mouth to the head. Ice moves the fastest at the mouth in contact with the ocean. However, periodically displacement of the head ice accelerates for a short while, leading to a corresponding displacement of the bergschrund. Such sequential displacements of ice masses were recorded for the Kyiv Peninsula during February 2021, that is, during the summer season. Remote observations of the changes and dynamics of ice sheet displacement of the Kyiv Peninsula allow us to obtain timely, relevant, and objective information but do require verifying the data by *in situ* surveys.

Author contributions. SK: Conceptualization, Methodology, Investigation, Writing — Original & Draft. KA: Investigation, Writing — Review, Editing.

*Acknowledgments.*The paper is a part of training program "The use of remote sensing to solve geological problems of Antarctic coast" which took place in the State Institution National Antarctic Scientific Center of Ministry of Education and Science of Ukraine.

Conflict of Interest. The authors declare that they have no conflict of interest.

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Received: 14 May 2021
Accepted: 22 June 2021

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Відстеження швидкості рухів льодового покрову на півострові Київ берег Грейама за допомогою супутникових знімків Sentinel-1

Реферат. Дослідження швидкості рухів льодовиків в прибережній зоні Антарктиди є однією з найбільш активно обговорюваних тем. Такий значний інтерес до цієї теми пов'язаний, в першу чергу, з тим, що крига, яка потрапляє до Світового океану з антарктичних льодовиків, істотно впливає на рівень океану та на глобальний клімат. Розвиток сучасних супутникових технологій дистанційного спостереження Землі дозволив розробити певну кількість методик оцінки зміщень льодовикових покровів та розрахунку швидкостей таких зміщень. Метою цієї роботи є застосування даних дистанційного зондування Землі з супутникової системи Copernicus Sentinel-1 для оцінки швидкостей рухів льодовикового покрову в межах півострова Київ у часовому інтервалі з грудня 2020 по березень 2021 року. Для досягнення встановленої мети були застосовані 10 радарних знімків території, що вивчалася з початку грудня до кінця березня з інтервалом у часі зйомки у 12–14 діб. Обрані знімки аналізувалися попарно так, щоб встановити зміни, які виникли на поверхні за обраний інтервал часу. Застосовані знімки супутникової системи Copernicus Sentinel-1, які мають корекцію за формою еліпсоїду Землі у GRD форматі. На основі методики офсетного трекінгу (Offset Tracking) для кожної пари знімків з різницею у часі приблизно у дві неділі були розраховані швидкості рухів льодового покрову в межах півострова Київ. Встановлено, що швидкість рухів коливається у значних межах та у пригирлових частинах льодовиків може досягати 3,5–4 метрів на добу. Також встановлено, що швидкість зміщення криги у тілі льодовика змінюється у часі. Так, найбільші значення фіксуються у пригирловій частині, але були зафіксовані короткострокові інтервали часу, коли слідом за нижньою частиною льодовиків активізувалися і тилові та навіть крайові частини льодовиків, які розташовані на контакті з льодовим покровом плато. Таким чином, виникає послідовність рухів, коли активізація нижньої частини льодовика призводить до зрушень більш високо розташованих частин. Слід зазначити, що така активізація зміщення льодового покрову була зафіксована у лютому 2021 року, що співпадає з одним з найбільш теплих місяців у цій частині Антарктики.

Ключові слова: півострів Київ, Sentinel-1, швидкість льодовиків, дистанційне зондування Землі