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Monitoring of glacier frontal parts on Galindez and Winter islands (the Argentine Islands) in 2018—2019

Abstract. The work presents an analysis of climate variability and glaciological changes of the Antarctic Peninsula and the results of glacier monitoring on Galindez Island and Winter Island (the Argentine Islands in the Wilhelm Archipelago, Antarctic Peninsula) in 2018—2019. The **main objective** of research was to determine how the volumes of glaciers changed in 2018—2019 in the course of a complex study. **Methods**. The material of the Ukrainian seasonal expedition of 2018—2019 was used: terrestrial laser scanning data of 2018, terrestrial digital photography of 2018 and 2019 and an unmanned aerial vehicle survey of 2019. The technique used to determine changes in the volumes of glaciers can significantly improve both the speed and accuracy of the measurements. It included complementary processing of scanning data and digital photography of 2018, and digital photography and aerial survey of 2019. **Results**. Changes in the volumes of glaciers were 36 000 m^3 for the western part of the glacier on Galindez Island, 1 100 m^3 for the southern part of the glacier on Galindez Island, and 9 800 m^3 for the southern part of the glacier on Winter Island. **Conclusions**. The results demonstrate significant changes since 2002. This is confirmed quantitatively by independent studies of the West of the peninsula. Monitoring of the dynamics of glacier volumes enables detection of climatic and glaciological changes in the Antarctic region.

Keywords: glacier, terrestrial laser scanning, stereophotogrammetry.

INTRODUCTION

The Antarctic ice cover is a complex natural system whose internal dynamics is sensitive to both atmospheric and oceanic influences. A deeper understanding of the underlying processes may have a profound impact on the development of prognostic models.

The volume of the Antarctic ice translates into the equivalent of 57.2 m of sea level. Annual snowfall contributes 2100 Gt, except for shelf glaciers, which is equivalent to a 5.8 mm fluctuation of sea level (van Wessem et al., 2018). In a mass equilibrium state, snowfall accumulation should balance surface ablation and ice loss off the periphery into the Southern Ocean. However, the overall loss of the Antarctic glacier cover has increased from 40 ± 9 Gt/yr in 1979–1990 to 50 ± 14 Gt/yr in 1989–2000 to 166 ± 18 Gt/yr in 1999–2009 and then to 252 ± 26 Gt/yr in 2009–2017 (Rignot et al., 2019). The average contribution of the Antarctic to sea level rise has been 3.6 ± 0.5 mm per decade with accumulation of 14.0 ± 2.0 mm since 1979, including 6.9 ± 0.6 mm from West Antarctica, 4.4 ± 0.9 mm from East Antarctica and 2.5 ± 0.4 mm from the Antarctic Peninsula (AP).

The reason for such a global loss of the ice cover has been climate change. A significant change, or to be precise, significant warming, has been registered in the AP region. The late XX century was characte-

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rized by elevations in surface temperatures, melting of glaciers and increased snowfall (Thomas, Tetzner, 2018). The strongest trends toward climate warming are observed in the west and north of the Peninsula; the region exhibits the most drastic year-to-year variation on the entire continent (Turner et al., 2014). Notably, the highest statistically significant trend of +0.54 °C per decade has been recorded at Akademik Vernadsky station (1951–2011).

The progressive rise in air temperature is connected with a sequence of glacial events on the AP in the 1990s (Silva et al., 2014), such as iceberg calving, fragmentation of shelf glaciers (Kunz et al., 2012), alterations in the height of the snow line, collapse and melting of shelf glaciers (Cook et al., 2005; Cook et al., 2014). The observed changes indicate that the AP rapidly reacts to climate change. Yet the changes are not uniform across the region (Shepherd et al., 2012).

The tendency towards the largest change is characteristic of the north of the AP, then the west and the islands. In terms of area reduction, the most loss is seen in shelf glaciers. According to observations (Silva et al., 2020), 60% of the AP glaciers are shrinking, 25% are growing in size, and 7% are fluctuating. The melting of most glaciers confirms that the peninsula loses more ice mass than it receives, so the process is unbalanced (Cook et al., 2014).

The North-West region of the AP has undergone the most pronounced changes; 74% of glaciers there reduced in size in 2000—2015. Of the 94 glaciers, 69 lose frontal area and 80 are outlet glaciers, meaning that 85% are more sensitive to frontal change.

Due to the gradual rise in air temperature, western AP underwent the most dramatic change in the height of dry snow line between 1995 and 2005. Studies analyzing 244 glaciers on the western coast of the AP showed that between 1945 and 2004, approximately 87% reduced in size (Cook et al., 2005). In general, the model is consistent with melting due to gradual warming of the atmosphere, but its speed suggests the process is not the only factor of the deglaciation.

Despite the tendencies toward regional warming in the west of the AP at the end of the XX century, the mean annual temperature decreased during 1999–2014 at a statistically significant rate (<5%) (Turner et al., 2016).

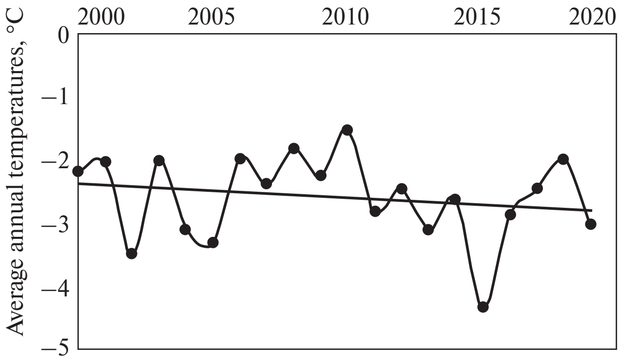

Fig. 1. Average annual temperatures on Akademik Vernadsky station for 2000—2019

The trend toward smaller increases in temperature (Fig. 1) has also been recorded at Akademik Vernadsky station (2000–2019) (according to Antarctic Meteorology Online from the British Antarctic Survey).

One hypothesis is that the rapid warming after the 1950s and further reduction in temperature increases after late 1990s are not connected with global changes in temperature but reflect a large-scale natural variation in the regional atmosphere circulation. This underscores the need for longer observations of temperatures and other meteorological parameters in order to evaluate regional climate variability (Sobota et al., 2015).

Climate change might cause loss of ice mass leading to a rise in sea level. In order to isolate this factor, short-scale fluctuations in snow accumulation are taken into account while measuring the thickness of ice cover (Shepherd et al., 2019). Researchers note that the strongest trend toward accumulation of the snow cover is seen at the AP (Thomas et al., 2017). Increased snow cover complicates remote sensing studies.

Therefore, field measurements are required to verify the results (Wang et al., 2017).

So, as it can be seen, monitoring of glaciers is very important and reveals the need for long-term observations to establish patterns of changes in the volume of glaciers for assessing the variability of the regional climate.

MATERIALS AND METHODS

Terrestrial digital photography (TDP) and terrestrial laser scanning (TLS) are used for monitoring of is-

DETERMINATION OF SURFACE VOLUME CHANGE

Creation of a Technical Project

• Determination of TLS parameters • Planning the placement of scanner and reference targets (spheres) • A prior estimate of TLS accuracy	• Determination of TDP parameters • Planning the placement of bases and ground control points • A prior estimate of TDP accuracy

Field measurements

• Measurement of coordinates of the scanner and reference targets (spheres) • Terrestrial laser scanning	• Measurement of coordinates of bases and ground control points • Terrestrial digital photography

Data analysis and post-processing

• Determination of coordinates of the scanner and reference targets (spheres) • Scan registration • Scan filtration and edition • Creation point models	• Determination of coordinates of bases and ground control points • Distortion correction • Image orientation • Creation digital elevation models

Determination of surface volumes change

- Co-alignment of TLS and TDP models
- Creation of TIN models
- Calculation of volumes relative to the reference plane
- Calculation of the differences between observation cycles
- Graphical representation of changes in surface volumes

Fig. 2. Technological scheme of the complex method

land glaciers and their frontal parts. A technique based on the use of digital stereophotogrammetric photography and terrestrial laser scanning is proposed. The use of a complementary methodology can significantly increase the speed of measurements of glacier surfaces and the accuracy of quantitative parameters of the objects of study. The general layout is given in Fig. 2.

Another approach to observation of melting glaciers is to apply current means of remote surveys, such as images taken by unmanned aerial vehicles (UAV). In view of this, the complex method has been modified for the use of terrestrial digital stereophotogrammetric and UAV survey.

The data were collected by season expeditions of 2018—2019; TLS was done in 2018, TDP in 2018 and

Fig. 3.1. Overall view of the western side of the glacier on Galindez Island in April, 2018

Fig. 3.2. Overall view of the western side of the glacier on Galindez Island in April, 2019

Fig. 3.3. Overall view of the southern side of the glacier on Galindez Island in April, 2018

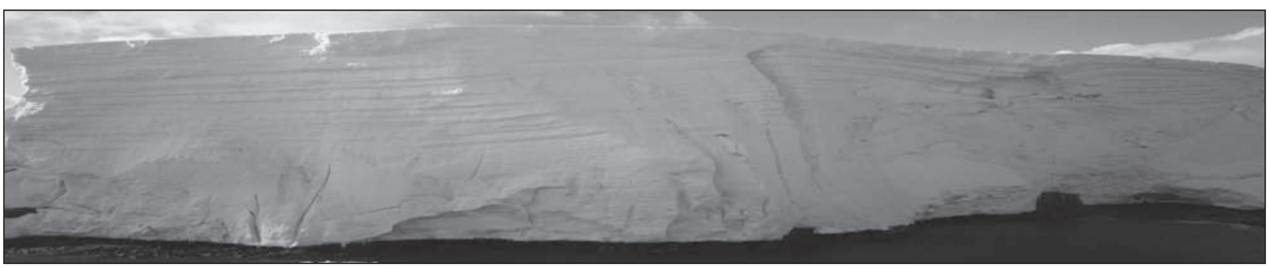

Fig. 3.4. Overall view of the southern side of the glacier on Galindez Island in April, 2019

Fig. 3.5. Overall view of the southern side of the glacier on Winter Island in April, 2018

Fig. 3.6. Overall view of the southern side of the glacier on Winter Island in April, 2019

2019 (Fig. 3) and UAV survey in 2019. For terrestrial laser scanning we used Faro Focus 3D S 120 scanner (FARO Laser Scanner Focus 3D, 2010). Terrestrial digital photography was done using digital cameras Canon EOS 450D and Canon EOS Mark III D. The focal distances used to take the images were 16 mm, 18 mm, 35 mm and 55 mm. Cases of surveying: normal and convergent. For the UAV survey, we used Trimble UX5 (Trimble UX5 HP Unmanned Aircraft System) with Canon EOS Mark III D camera.

Digital terrestrial photography data processing. The images are processed using digital photogrammetric stations (DPS). Preference should be given to DPS in which the mathematical solution of photogrammetric problems allows the researcher to realize the accuracy potential of a digital image, regardless of the projection, focal distance, and exterior orientation elements. The software should allow maximum automation of the image orientation, creation of the photogrammetric model and recovery of the digital information about the territory. The cameral processing of the obtained digital survey materials was performed at the Delta-2 digital photogrammetric station using the Digitals software (Delta/Digitals, GeoSystem). The procedure includes preparatory steps, preliminary processing of the input data, image orientation and creation of a digital elevation model (DEM).

GML C++ Camera Calibration Toolbox (GML C++ Camera Calibration Toolbox, Graphics and Media Lab) software was used to account for distortions in the images.

The images obtained after removal of distortions at known coordinates of the projection centers of the images are oriented with the application Models.exe in “Ground photography” and “Two single images” modes.

In order to create the DEM, regular grid interval and grid node density have been calculated (Tretyak et al., 2016).

The UAV pictures were treated using Pix4Dmapper (Pix4Dmapper, Pix4D).

Terrestrial laser scanning data. The preparation included data processing, estimation of the accuracy of the exterior scan orientation and 3D modeling.

Fig. 4.1. Point model of the western part of the glacier on Galindez Island in 2018

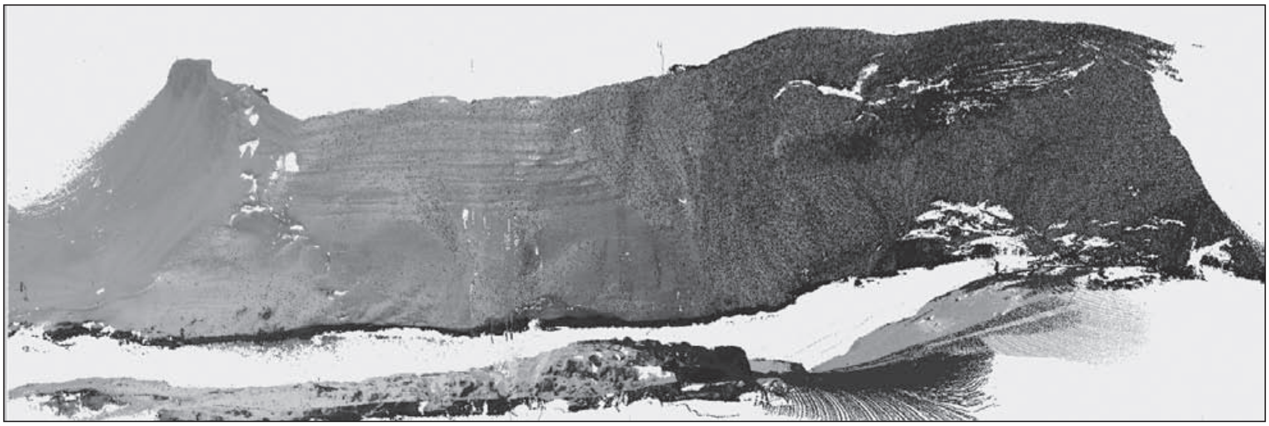

Fig. 4.2. Point model of the southern part of the glacier on Galindez Island in 2018

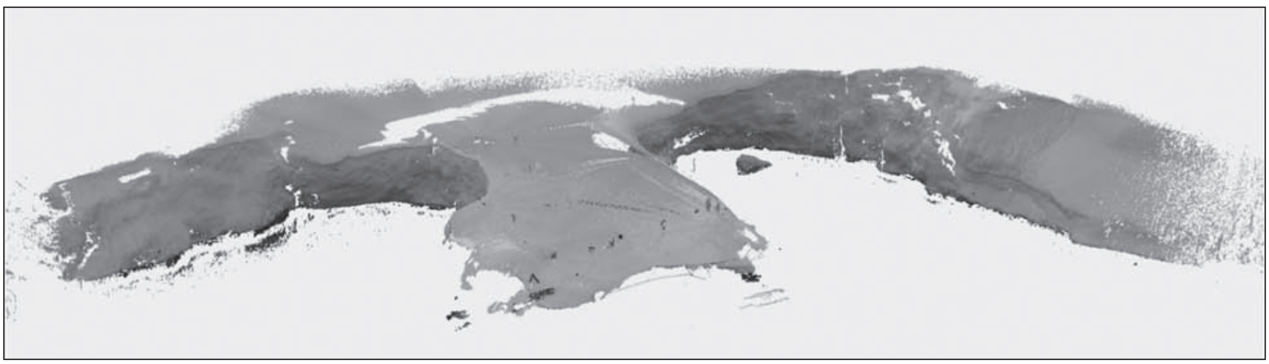

Fig. 4.3. Point model of the southern part of the glacier on Winter Island in 2018

Preliminary data processing was done using software developed for the company's laser scanner Faro Scene (Faro Scene Software, Faro).

Low reflectance surfaces can be a source of high noise, and their surface points may contain incorrect coordinates. Such points are therefore recommended for removal. The FARO SCENE software has several types of filters to delete the most dubious data depending on the choice of settings.

After filtering, glacier scans were combined into a

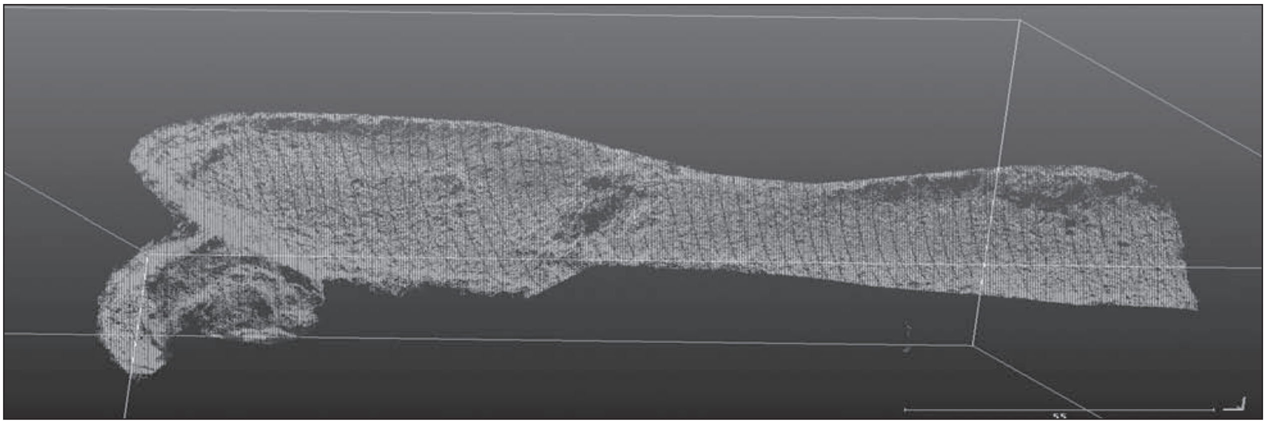

Fig. 5.1. Point model of the western part of the glacier on Galindez Island in 2019

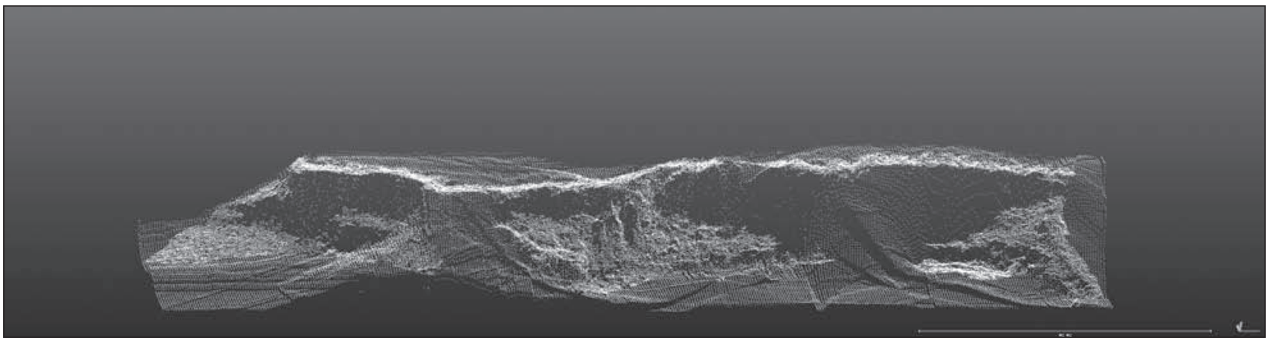

Fig. 5.2. Point model of the southern part of the glacier on Galindez Island in 2019

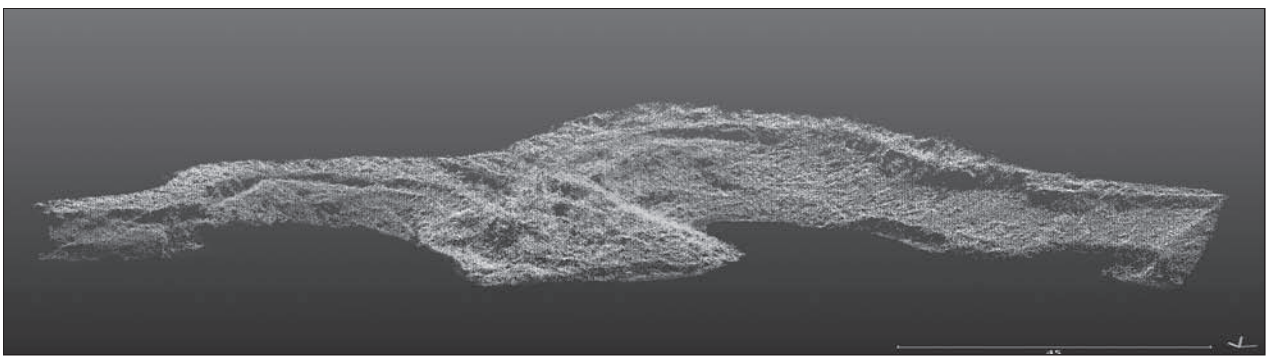

Fig. 5.3. Point model of the southern part of the glacier on Winter Island in 2019

single point model (Seredovych et al., 2009) using automatic recognition of reference targets with subsequent editing and verification of the accuracy of the models. As a result, the minimum error for scan alignment for the glacier on Galindez Island was 0.46 mm and the maximum one was 10.13 mm; for the glacier on Winter Island, the range was 0.75 to 6.48 mm.

In order to correlate point models with the World Geodetic System (WGS84), it is necessary to mark the reference targets on the models in accordance with the field sketch and to set their coordinates obtained from satellite observations.

Creation of point models. After filtering out dubious measurements and noise, points not belonging to the glacier's surface were also removed from the point cloud. The resulting 3D model was assigned textures obtained by laser scanning.

Based on the combined processing of TLS and TDP material in April, 2018 point models of glacier frontal parts on Winter and Galindez islands were created (Fig. 4). Based on TDP and UAV imaging in April, 2019, DEM of glaciers' frontal parts were created (Fig. 5).

Calculations of changes in surface volumes. The changes in glacier surface volumes were calculated using the Cyclone software (Leica Cyclone, Leica Geosystems).

Triangulated irregular network (TIN) models were created based on the combined models of 2018—2019. They were visually verified and edited when necessary.

In order to determine volume changes, a rectangular prism method is proposed. This choice is explained by the fact that it allows to calculate the volume of an object relative to a certain reference plane (hereinafter – the plane). The method is included in many software packages allowing volume computation. The rectangular prism method calculates the total volume as a sum of separate prism volumes (Yanalak, 2005):

$$V = F * h_m - h_0 , \tag{1}$$

where

$$h_m = \frac{\sum_{i=1}^{n} (g_i * h_i)}{4 * n} , \tag{2}$$

i – quadrangle's number; h_m – mean height; F – area of the whole object; g_i – number of vertices of the adjacent triangles; h_i – vertex height; n – number of all quadrangles; h_0 – height of the reference plane.

In order to compute the changes in surface volumes, we built a precisely vertical reference plane, which was constant for all observation cycles. The changes in volumes relative to the plane were first calculated, and then the differences between the sequential cycles, i.e. the changes in glaciers' volumes, were found.

RESULTS AND DISCUSSION

The changes on surface volumes were determined based on the data obtained by TLS (2018), TDP (2018 and 2019) and UAV imaging (2019) of the western and southern frontal parts of the Galindez glacier and the southern outlet of the Winter glacier (Table). In order to compare the changes in surface volumes

Table. **Changes (reduction) in surface volumes of island glaciers**

Glacier on Galindez Island, western part		Glacier on Galindez Island, southern part		Glacier on Winter Island, southern part	
Time period	Volume change (m^3)	Time period	Volume change (m^3)	Time period	Volume change (m^3)
2002—2003	23 000	2002—2003	1 500	2002—2003	—
2003—2004	28 000	2003—2004	350	2003—2004	1 250
2004—2005	17 000	2004—2005	4 800	2004—2005	4 800
2005—2013	64 000	2005—2013	94 000	2005—2013	82 000
2013—2014	16 000	2013—2014	500	2013—2014	1 400
2014—2018	1 200	2014—2018	600	2014—2018	800
2018—2019	36 000	2018—2019	1 100	2018—2019	9 800

we provide the results of previous studies of the glaciers (Tretyak et al., 2016) started in 2002. All observations were made in March or April. However, all the relevant seasonal Antarctic observations were interrupted from 2005 to 2013, and then from 2014 to 2018, which is why the observation cycles are not constant.

According to Cisak et al. (2008), in 2000—2005 the glacier on the Galindez Island lost overall 2—3% of its volume, which is 20 000 m^3/year, on average. According to Tretyak et al. (2016), on average, the Galindez glacier shrinks at 12 000 m^3/year (western part) and 9 150 m^3/year (southern part), and the southern part of the glacier on the Winter Island shrinks at 8 800 m^3/year.

By the data for 2014—2019, the volumes of glaciers have decreased, but not uniformly. As already mentioned, the thickness of the snow layer can have an impact on the apparent volume, obscuring the actual change. The 2018 survey was held after a snowfall, which might have resulted in minor changes in the surface volumes relative to the period of 2014—2018, and changes in 2018—2019 could have been underestimated. A negative factor complicating the interpretation of the results is the non-regularity of monitoring (long intervals between observation cycles).

Comparison of the changes in frontal parts of glaciers on Galindez and Winter islands with the calculations for ice volumes on the overall glacier surface (Karušs et al., 2019) leads to the conclusion that in 2014—2019, the glacier on Galindez Island lost overall approximately 2.5% of volume, and the one on Winter Island – approximately 1.5%.

The general trend to melting of the Antarctic Peninsula glaciers can be observed in other contemporary publications. Confirmation that AP responds quickly to climate change is presented in (Silva et al., 2020), whereby the authors characterize glaciers on the islands of the Antarctic Peninsula as melting, with the reported loss of 279 km^2 during 2001—2015. For example, the glaciers on King George Island were reduced by 9.41 km^2 (Rosa et al., 2015); on the Shetland Islands, 61% of glaciers are shrinking (Osmanoğlu et al., 2014). The studies of 1956—2004 (Hlotov et al., 2004) suggest that the Galindez glacier is also much reduced. According to (Chernov et al., 2018), the maximum ice thickness found at the ice dome of the Galindez glacier is 35 m, compared to 59 m measured by radiolocation in 1998 (Bakhmutov et al., 2006) and 45—48 m in 2004 (Levashov et al., 2004).

Analyzing temperature changes (Fig. 1) and volumes of the glaciers (Table) on Galindez and Winter islands one should note the correlation between the two parameters. The warming at the Antarctic Peninsula influences the decrease in albedo (Turner et al., 2016). Therefore it is necessary to factor in not only the temperature but also the precipitation, sea ice, change in sea level and other parameters.

In order to record the changes in glacier volumes in a timely manner and to establish the regularities governing the regional climate variation, it is important to continue annual monitoring. Additionally, one should take into account the thickness of the snow cover.

CONCLUSIONS

According to the literature review, glaciological parameters of the Antarctic Peninsula are spatially highly diverse and changing in a variety of ways. The largest changes are observed in the northern and western parts of the peninsula and islands. For the western region of the Antarctic Peninsula, after the warming seen in the late XX century there is seen a reduction in incremental temperature increase. A similar trend is recorded at the Akademik Vernadsky station. Most probably, the changes reflect internal natural variability. However, longer observations of temperature and other meteorological parameters are necessary.

To monitor the frontal parts of the glaciers on the Galindez and Winter islands in 2018—2019 we employed a method based on digital stereophotogrammetrical photography and terrestrial laser scanning. Modified and tested for the first time a method for determining the surface volumes of island glaciers by co-aligning digital stereophotogrammetric imaging and UAV photography. Using complex methods allows to significantly increase the speed of measurement of the glacier surface and the accuracy of the quantitative parameters of the research.

Based on the results of terrestrial laser scanning in 2018, digital photography in 2018 and 2019 and UAV photography in 2019, we estimated the loss of surface volumes, totaling 36 000 m^3 for the frontal part of the western side of the Galindez glacier, 1 100 m^3 for the frontal part of the southern side of the Galindez glacier, and 9 800 m^3 for the frontal part of the southern side of the Winter glacier. Overall, in 2014—2019 the glacier on Galindez lost about 2.5% of its volume, and the one on Winter — about 1.5%

The presented results of monitoring suggest a non-uniform character of changes in the glaciers, since the western part of the glacier on Galindez shrinks faster than southern parts of both glaciers. Two negative factors complicating evaluation of the results are the thickness of snow cover and non-regularity of monitoring (and long time periods between observations).

Analyzing changes in the temperature and the volumes of glaciers on Galindez and Winter islands, one should note the correlation of the parameters. The warming in the region of the Antarctic Peninsula influences the shrinking of the glacier through the feedback between ice/snow cover and albedo.

Melting of glaciers on Galindez and Winter islands has been reported in other contemporary studies that addressed the Antarctic coastline.

Further monitoring of Antarctic coastal glaciers is important for timely detection of changes in them and in order to establish patterns for assessing the regional climate variability. It is planned, additionally, to factor in the thickness of snow cover and to study not only the impact of temperature, but also precipitation, sea ice, change in sea level and other parameters.

The study was conducted as part of the research project "A study of changes in the surface volumes of island and continental glaciers based on the results of digital images, laser scanning and geodetic measurements made during the season works of the 24th Ukrainian Antarctic Expedition of 2019—2020" under a contract with the State Institution National Antarctic Scientific Center of Ministry of Education and Science of Ukraine.

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Моніторинг виходів льодовиків островів Галіндез та Вінтер (Аргентинські острови) у 2018—2019 роках

Реферат. У статті представлено аналіз кліматичних та гляціологічних змін Антарктичного півострова та результати моніторингу льодовиків на островах Галіндез та Вінтер (Аргентинські острови Архіпелагу Вільгельма, Антарктичний півострів) за період 2018—2019 рр. **Метою** роботи було визначення змін поверхневих об'ємів льодовиків на островах Галіндез та Вінтер за результатами комплексних досліджень за період 2018—2019 рр. **Методи**. Для дослідження використано матеріали українських сезонних антарктичних експедицій 2018—2019 років: дані наземного лазерного сканування за 2018 р., наземного цифрового знімання 2018 та 2019 р. та знімання з безпілотного літального апарату 2019 р. Зміни поверхневих об'ємів виходів льодовиків на островах Галіндез та Вінтер визначено з застосуванням методики комплексних досліджень, що дає змогу істотно підвищити швидкість виконання вимірювань поверхонь льодовиків та точність отриманих результатів. Методика базується на сумісному опрацюванні матеріалів наземного лазерного сканування та наземного цифрового знімання у 2018 році, наземного цифрового знімання та знімання з безпілотного літального апарату у 2019 році. **Результати**. Визначено зміни поверхневих об'ємів виходів льодовиків за період 2018—2019 рр., що становлять: 36000 $м^3$ – для західної частини льодовика на о. Галіндез, 1100 $м^3$ – для південної частини льодовика на о. Галіндез та 9800 $м^3$ – для південної частини льодовика на о. Вінтер. **Висновки**. Аналіз отриманих результатів показує кардинальні зміни, які спостерігаються з 2002 року. Це підтверджується кількісними параметрами, визначеними незалежними методами, та сучасними дослідженнями західної частини Антарктичного півострова. Спостереження за динамікою змін поверхневих об'ємів острівних льодовиків дасть змогу виявляти кліматичні та гляціологічні зміни, що відбуваються у Антарктичному регіоні.

Ключові слова: льодовик, наземне лазерне сканування, цифрове стереофотограмметричне знімання.