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GEODETIC MASS BALANCE OF VÖRING GLACIER, WESTERN SPITSBERGEN, IN 2013–2019

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Geodetic mass balance of Vöring glacier, located on Nordenskiöld Land of Western Spitsbergen island (Svalbard archipelago) in 2013–2019, is reported. The glacier is located 4 km away from Barentsburg, and feeds Stemme Lake, where a water-supply of the town starts. Mass balance is computed based on ground-based topographic survey, UAV imagery and ArcticDEM. To eliminate vertical error of ArcticDEM, its strip was co-registered to GCPs on stable ground measured with GNSS methods in 2019. To adjust vertical georeference of used DEMs, ground control points, measured in 2019, were used. Our results reveal that the mean geodetic mass balance value in 2013–2019 was (–1.30 ± 0.17) m w.e. per year, which equals mass loss of (5.9 ± 0.4) Mt total, which is more negative value than earlier reported. Spatial pattern of SMB distribution over the Vöring surface and its relation with elevation above sea level are presented, surface lowering vertical gradient was 0.85 m w.e. for 100 m. Furthermore, based on orthoimage and DEM, we provide accurate areas of elevation zones, used in calculations of glaciological mass balance from ablation stakes. In 2019 the Vöring glacier, lying in elevation interval of 180–400 m (with a mean altitude of 280 m) is found to have an area of 0.75 km^2. Since 1911, the glacier area reduced by 4.5 times, as we found from old topographic map, aerial photographs and Landsat images. Results of this study could be used in further studies of mass balance computations and for reanalysis of glaciological data series.

Glacier mass balance, unmanned aerial vehicle, glaciology, remote sensing, Svalbard, ArcticDEM

INTRODUCTION

Since the beginning of the last century, the area of glaciation in the Svalbard archipelago has been decreasing, and in the 21st century that reduction has accelerated [*Kohler et al., 2007*], which coincides with the global trend [*Zemp et al., 2015*]. Despite the very small contribution of the current degradation of the glaciation in Svalbard to the rise in global sea level (the first mm in a hundred years according to [*Nuth et al., 2010*]), the monitoring observations of mass balance of the glaciers occupying about 60 % of the archipelago's surface [*Kotlyakov, 1997*] and reacting differently to climate change, remains to be an urgent task. The most informative in that regard are the glaciers for which long-term observation series exist, the Vöring glacier in particular.

The small Vöring glacier of the cirque-valley type is located on the western coast of Grønfjord Bay opposite of Barentsburg settlement. It stretches from west to east for about 1.5 km, has a width of less than 700 m and descends to an altitude of about 180 m above sea level (a.s.l.) (Fig. 1). Glaciological studies on the glacier had been carrying out by the Institute of Geography of the Russian Academy of Sciences from the mid-1960s to the end of the 1980s [*Guskov, 1983; Troitsky, 1988*], then they were resumed in 2005, but had an episodic character [*Solovyanova, Mavlyudov, 2007*]. The melt water of the glacier feeds Stemme Lake, from which the Barentsburg water supply originates. According to the research results of 2017–2018, the share of glacial runoff in the total runoff of Vasstak River flowing out of Stemme Lake has reached 30 %, and the main area of glaciation in the lake basin falls precisely on the Vöring glacier [*Romashova et al., 2019*]. Therefore the monitoring of mass balance of the glacier is also of practical interest.

The study aimed to: 1) create a detailed digital elevation model (DEM) that will serve as the basis for future mass-balance observations of the Vöring glacier; 2) to calculate the mass balance of the glacier for a certain period of time in the past based on the obtained DEM; 3) to reveal the dynamics of the glacier area over the past hundred years.

Further, for brevity, under the "glacier balance", "mass balance" or simply "balance" we will mean the average for the period under consideration, and the glacier average specific mass balance of the glacier expressed in meters of water equivalent per year.

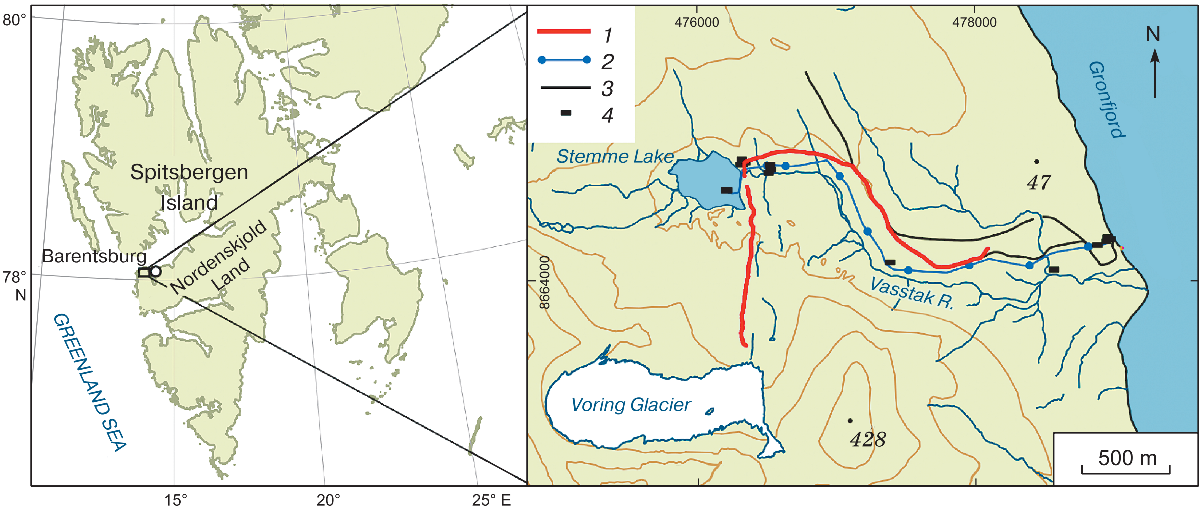

Fig. 1. Location of the Vöring Glacier:

1 – profile for the ArcticDEM georeferencing; *2* – water supply pipeline; *3* – roads; *4* – buildings.

MATERIALS AND METHODS

Topographic survey. A ground-based topographic survey of the glacier surface had been carried out on August 19, 2019, at the end of the ablation season, after the temperature had become lower than 0 °C and the first snowfalls. On the day of the survey, the surface of the glacier was covered with freshly fallen snow first cm thick, which we neglected in our calculations due to the insignificance of the error introduced into the result. The survey was carried out by using the kinematics method with post-processing and by means of the Sokkia GRX1 and GRX2 satellite receivers relative to the base stations, the first of which was located near Stemme Lake (less than 1 km away from the glacier) and the second was situated at a distance of about 4 km, on a hill above Barentsburg. The survey routes associated with slope breaks and other characteristic landforms are shown in Fig. 2.

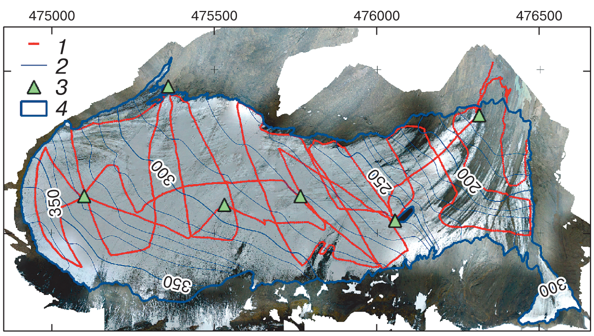

Fig. 2. Relief of the glacier surface in August 2019:

1 – topographic survey routes; *2* – contour lines of the height above sea level; *3* – ground control points of the aerial photography; *4* – glacier outline. Figures are made in the UTM (Universal Transverse Mercator) coordinate system, zone 33N.

In addition to the topographic works on the glacier surface, an altitude profile has been laid along the road from the coast of Grønfjord Bay to the water intake station on Stemme Lake, and further to the glacier (Fig. 1). This profile is required for the ArcticDEM elevation reference. The vertical accuracy of the coordinates obtained by satellite observations is 0.05 m.

Aerial photography. The aerial photography has been taken on August 20, 2019 using a DJI Phantom 3 Advanced drone with an uncalibrated camera. The images were taken with the longitudinal and transverse overlap of 60–70 % from a height of no more than 120 m above the glacier surface in accordance with the requirements of local legislation. The DEM and orthomosaic construction has been performed in Agisoft Photoscan software. For the absolute reference, six ground-control points on the glacier surface have been used (Fig. 2). Their coordinates were determined with an accuracy of no more than 0.02 m in plan and 0.03 m in height. To assess the accuracy of the resulting terrain model, we have compared its heights with those of the corresponding topographic survey points: the standard deviation is 0.30 m.

Determining of the glacier boundaries. To establish the boundaries of the Vöring glacier in the past, the Landsat satellite images have been used, a 1936 oblique aerial photograph taken from a height of about 3000 m in the westward direction, and a Norwegian topographic map at a scale of 1:100 000, dated 1911 [*Anmeldelse..., 1912*], which made it possible to trace the dynamics of glaciation for a little more than a hundred years.

Landsat satellite imagery used to define the boundary of the Vöring glacier in the past: 2008 –

LE07_L1GT_213004_20080731_20161228_01_T2; 2002 – LE07_L1GT_217004_20020711_20170129_01_T2; 1985 – LT05_L1GS_216004_19850830_20170218_01_T2; 1976 – LM02_L1GS_230004_19760718_20180423_01_T2.

The images required mutual referencing and, and those of 1976 and 1985 needed orthorectification. These procedures have been performed using ScanEX ImageProcessor software. The visible contour of the glacier as of 2019 has been determined on the basis of an orthophotomap obtained from the results of aerial photography. Determination of the real boundaries of the ice strike is difficult: the northeast edge of the glacial tongue is armored with moraine and is exposed only partially, and the southern edge it is covered with colluvial deposits.

ArcticDEM. The spatial resolution of ArcticDEM [*Porter et al., 2018*] is 2 m, and the internal (relative) accuracy of ArcticDEM (estimated by [*Noh, Howat, 2015*]) is 0.20 m. However, the absolute height referencing of fragments may contain an error in the first meters; therefore, in order to avoid gross errors in calculating the volume of the melted layer it is necessary to perform the height correction of the model.

The metadata file for the ArcticDEM fragment used by the authors contains a linear transfer vector calculated on the basis of the ICES at altimetry observations which allows us to refine the referencing initially based on satellite ephemeris. We used the values of the *dx* and *dy* components and shifted the DEM in plan, since in the absence of the original high-resolution images which were used to build the DEM it is impossible to identify any control points with acceptable accuracy and to calculate the horizontal shift based on them.

Further, the differences in the heights of the ArcticDEM and the points of the profile laid along the road leading to Stemme Lake were calculated (Fig. 1). The median of differences has amounted to −1.226 m (i.e., the ArcticDEM heights are overestimated), and the corresponding value of the component $dz = -0.857$ in the metadata file is underestimated by almost half a meter. That can be explained by the fact that the ICESat measurements used to calculate *dz* are not simultaneous with the survey which were used to construct the DEM, but precede it by a month and do not take into account the size of the ice layer melted during that month. Therefore, for the vertical shift of ArcticDEM, we will use the value obtained by the authors. The normalized value of the median absolute deviation of the residuals (NMAD) used to assess the quality of the DEM elevation reference [*Nuth, Kääb, 2011*] was 0.64 m.

Mass balance calculation. We determined the mass balance of the Vöring glacier using the geodetic method, i.e. the comparing of the glacier surface heights in 2013 and 2019. Despite the fact that the values of heights obtained by ground-based geodesy are an order of magnitude more accurate than those obtained using the results of aerial photography, their use for balance calculations would require the interpolation to cover the entire surface of the glacier, which inevitably introduces its share of the error, which in that case is difficult to estimate. Therefore, for the entire surface of the glacier, we used the DEM obtained based on aerial photography, taking for its accuracy the RMS value relative to the points of ground measurements, namely 0.34 m.

The average annual decrease in the volume of the glacier over a certain period will have the following formula according to [*Zemp et al., 2013*]:

$$V = \frac{\Delta V}{\Delta t \cdot \overline{S}}, \tag{1}$$

where ΔV is the change in the volume of the glacier over the time period Δt (6 years), $\overline{S}$ is the average glacier area between the beginning and ending of the period.

Thus, the function (1) depends on two variables, and its standard deviation σ_V can be found by the formula:

$$\sigma_V^2 = \left(\frac{\partial V}{\partial \Delta V}\right)^2 \sigma_{\Delta V}^2 + \left(\frac{\partial V}{\partial \overline{S}}\right)^2 \sigma_{\overline{S}}^2 = $$

$$= V^2\left[\left(\frac{\sigma_{\Delta V}}{\Delta V}\right)^2 + \left(\frac{\sigma_{\overline{S}}}{\overline{S}}\right)^2\right], \tag{2}$$

where $\sigma_{\Delta V}$ and $\sigma_{\overline{S}}$ are the errors in determining of change in the glacier volume and the average glacier area between the beginning and end of the period, respectively. We will find these two values further.

Since the change in the volume of the glacier found by subtracting two DEMs is equal to [*Zemp et al., 2013*]:

$$\Delta V = r^2 \sum_1^k \left(h_{k2019} - h_{k2013}\right),$$

where r^2 is the area of the DEM pixel, h_{k2019} and h_{k2013} are the heights of the *k*-pixel in 2019 and 2013, respectively. Then the error of the ΔV value can be calculated by the formula:

$$\sigma_{\Delta V}^2 = r^4 k\left(\sigma_{2019}^2 + \sigma_{2013}^2\right), \tag{3}$$

where *k* is the number of the DEM pixels involved in the volume calculation, σ_{2019}^2 and σ_{2013}^2 are the quality indicators of the DEM in 2019 and 2013, respectively.

The error in determining of the average glacier area $(S_{2019} - S_{2013})/2$ between the beginning and end of the period is calculated by the formula:

$$\sigma_{\overline{S}}^2 = \frac{\sigma_{S2019}^2}{4} + \frac{\sigma_{S2013}^2}{4}. \tag{4}$$

Substituting the values found by the equations (3) and (4) into the equation (2), we determine the error in the value of the average annual decrease in the volume of the Vöring glacier for the period under consideration. Further, for the transition from the units of volume to those of mass, we multiply the equation (1) by the coefficient ρ, which is equal to the ratio of the average density of the material making up the glacier to the density of water. We will use the coefficient value of 0.850 ± 0.060 proposed by M. Huss [*Huss, 2013*]. The resulting value will be the average annual mass balance of the Vöring glacier for the period under consideration:

$$B\text{geod} = \rho V. \tag{5}$$

The final error is calculated using the formula:

$$\sigma_{B\text{geod}} = B_{\text{geod}}\sqrt{\left(\frac{\sigma_\rho}{\rho}\right)^2 + \left(\frac{\sigma_V}{V}\right)^2}. \tag{6}$$

Substituting the necessary values, we determine the error in the value of the average annual balance of the glacier mass as ±0.17 m water equivalent (w.e.) in a year.

Meteorological data. The data on the air temperature of the Vöring glacier area are presented by the records of the weather station in Barentsburg, and have been obtained through the web service of the All-Russian Research Institute of Hydrometeorological Information – World Data Center [meteo.ru/data]. Based on the average daily air temperatures, we have calculated the annual sums of positive air temperatures.

The data on mass balance of glaciers in the world. The World Glacier Monitoring Service (WGMS) data on reference glaciers, which include the glaciers with more than thirty-year observation series [wgms.ch/global-glacier-state/], have been taken as data on the global trend of changes in the mass balance of glaciers. The data represent the annual average mass balance of mountain glaciers from 19 regions. The calculation methodology is described in detail in [*WGMS, 2020*]. Observations data from the Austre Brøggerbreen glacier have also been taken from this source, with the exception of the last two balance years (2017/18 and 2018/19), which have been found on the WGMS web page [wgms.ch/latest-glacier-mass-balance- data /].

RESULTS AND DISCUSSION

The edge retreat and the graph of the Vöring glacier area reduction are shown in Fig. 3. Since 1911, when the Vöring glacier overflowed the northern wall of the cirque, connecting with the small, currently disappeared glaciers located on the slopes with exposure to the east, the area of glaciation has decreased by about four times and has amounted to 0.75 km^2 in August 2019 (determined based on orthomosaic). That value exceeds the size of the glaciated area in the basin of Stemme Lake used for calculating the runoff in [*Romashova et al., 2019*]; therefore, the share of glacial recharge in the water balance of the lake may be higher.

The relief of the Vöring glacier as of 2019 is demonstrated in Fig. 2. The contours have been drawn using a ground-based topographic survey, except for areas near the southern side of the glacier, where the relief characteristics have been taken from the DEM obtained based on aerial photography and superimposed on the orthomosaic.

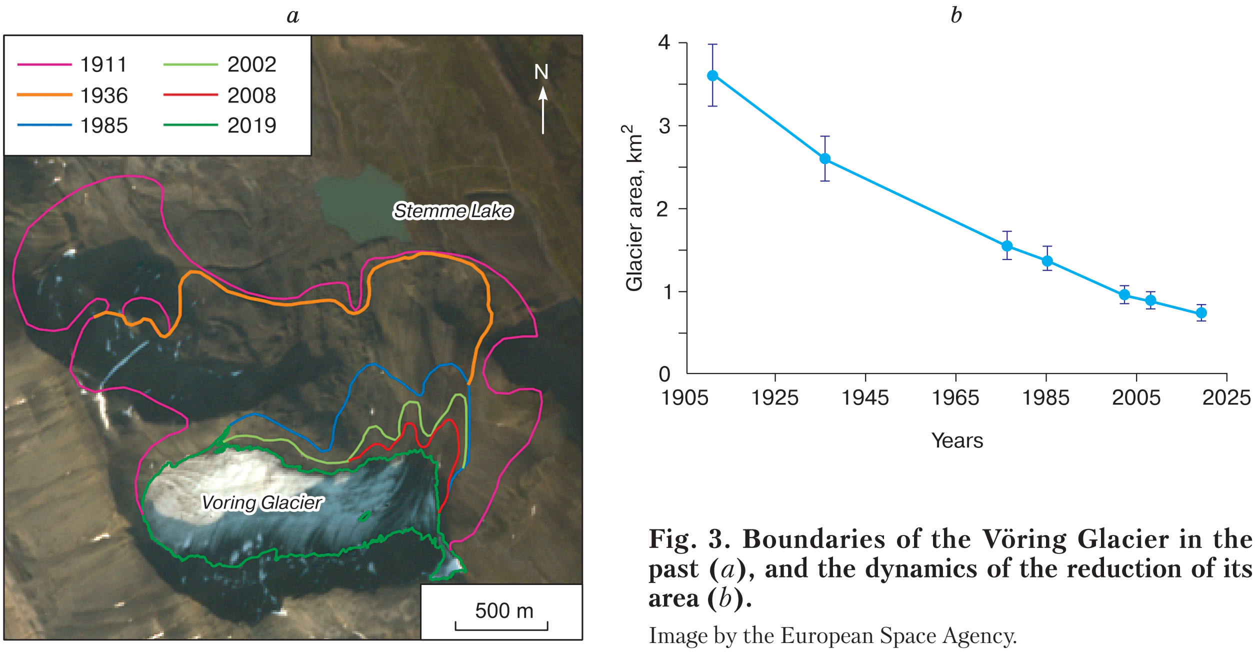

Fig. 3. Boundaries of the Vöring Glacier in the past (*a*), and the dynamics of the reduction of its area (*b*).

Image by the European Space Agency.

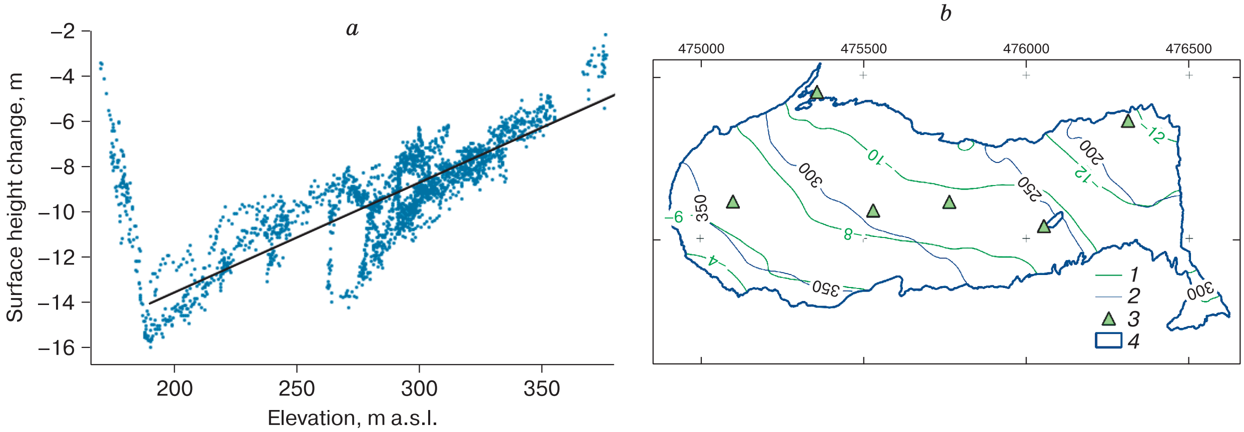

Fig. 4. The distribution of the surface height changes values of the Vöring Glacier in 2013–2019 by height (*a*) and by area (*b*):

1 – contour lines of changes in the surface height; *2* – contour lines of height above sea level; *3* – ground control points of the aerial photography; *4* – outline of the glacier. The glacier outline and contour lines are given as of August 19, 2019.

The dependence of the calculated values of glacier surface reduction in 2013–2019 on the height a.s.l. is demonstrated in Fig. 4. The graph shows only actually obtained values, not interpolated ones; the measurement points on the longitudinal moraines emerging on the surface in the lower reaches of the glacier has been excluded. The altitudinal gradient of the surface lowering has amounted to 0.85 m per 100 m.

The values of the surface lowering below 180 meters, sharply contrast by their ‘inverse’ gradient with the rest of the glacier (Fig. 4). At that area the Vöring Glacier tongue has been retreating since 2013: the balance is less negative here, since the ice thickness was less than that which could melt out for the period under consideration.

The widest dispersion of the surface lowering values observed in the altitudinal interval from 270 to 320 m a.s.l. in the central, flattest part of the glacier can be explained by uneven conditions of insolation in that part, as for the southern side of the cirque is shaded by the ridge. The influence of the rocky framing is most clearly traced by the contour of the change in the surface height with a value of −10 m, which runs in the northern part of the glacier along the 300 m contour line, and in the southern (shaded) part it turns sharply to the east with a drop to the 250 m contour lines (Fig. 4). That result is consistent with the assumption [*Sidorova et al., 2019*] about a noticeable influence of the exposure and the nature of the rock framing on the ablation parameters of mountain glaciers in the study area.

The average surface balance of the Vöring glacier for the period of 2013–2019 is equal to (−1.30 ± 0.17) m w.e. per year, which gives the total amount of weight loss by the glacier of 5.9 ± 0.4 million tons (on average (1.0 ± 0.1) Mt annually). The glacier surface has decreased throughout its entire territory. According to the authors, in the absence of intense ice movement that may indicate the absence of an accumulation area on the glacier in the period under consideration. That is also confirmed by visual observations of the snow line elevation. However, it should be noted that the spatial distribution of surface lowering (shown in Fig. 4) obtained by the geodetic method is not identical to the distribution of the mass balance over the glacier surface, since in addition to surface ablation and accumulation, it also depends on the movement of the glacier, on the compaction of its material, and other factors [*Klug et al., 2018*].

From the published data on the mass balance of the Vöring glacier (Fig. 5) [*Solovyanova, Mavlyudov, 2007; WGMS, 2019*] it follows that none of the previously measured values of the annual balance individually reached such a negative value as the average one obtained by the authors for the period of 2013–2019. That can be explained by the fact that during the period under consideration the annual sums of positive temperatures in the glacier area has become one of the highest for the entire observation period (Fig. 5).

The results of the topographic survey can be used not only to estimate the mass balance of the glacier using the geodetic method, but also for the calculations using the ablation rods. Therefore, we also present a table with the areas of fifty-meter altitudinal zones as of the end of the 2019 ablation season (Table 1). The glacier height interval and average surface height are 280 m and 180–390 m, respectively.

In the study of J. Hagen and O. Liestøl [*1990*] the long-term (from 13 to 21 years) continuous series of mass-balance observations carried out on several glaciers of Spitsbergen had been considered. It is dis-

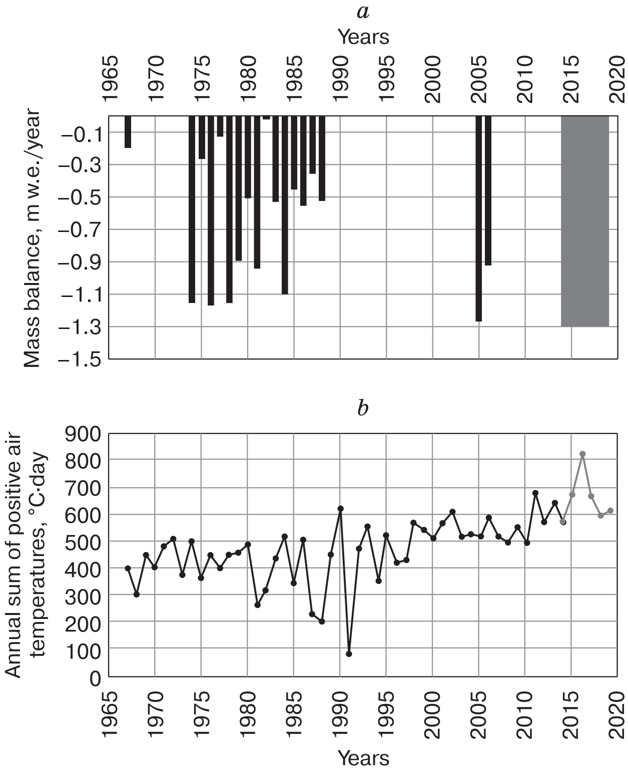

Fig. 5. Values of the annual mass balance of the Vöring Glacier (*a*) and the annual sums of positive air temperatures (*b*).

The values for the period under review (2013–2019) are shown in gray.

Table 1. **Areas of altitudinal zones of the Vöring Glacier in August 2019**

Altitudinal interval, m a.s.l.	Area		Altitudinal interval, m a.s.l.	Area	
	ha	%		*ha*	%
Below 200	0.065	9	300–350	0.213	28
200–250	0.110	15	Above 350	0.063	8
250–300	0.301	40			

played that the annual mass balance indicators of the Vöring glacier has a high correlation (R = 0.81) with those for the Austre Brøggerbreen glacier, which is located in the north of the island in the vicinity of Ny-Ålesund. Assuming that a good correlation persists at the present time, let us consider whether there was a decrease in the mass balance of the Austre Brøggerbreen glacier similar to that calculated by the authors for the Vöring Glacier in the period from 2013 to 2019. To do that, we will smooth the series of annual observations from the Austre Brøggerbreen glacier with a moving average with a period of 6 years; we'll refer the average value to the end of the period (that is, for example, the abscissa of 2019 will correspond to the average annual value for the six-year period from 2013 to 2019).We restrict ourselves to only a qualitative comparison. Since firstly, quantitative ones would require the considering of the error intervals of the used values. However, the errors of the annual balance values remain to be unknown, since they have not been estimated. Secondly, the se-

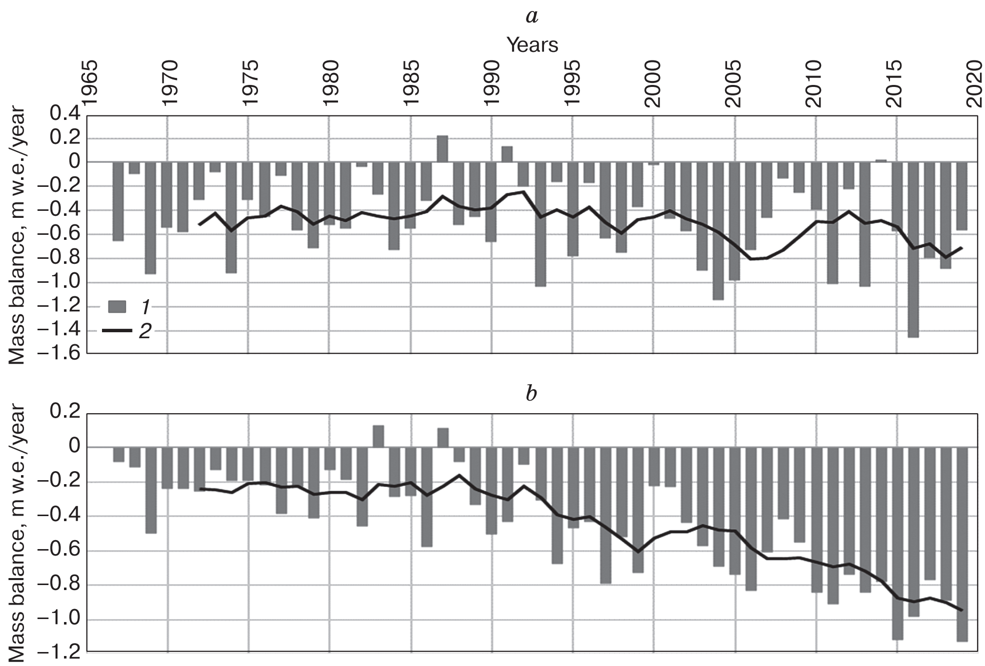

Fig. 6. Значения годового баланса массы ледников (*1*) и их скользящее среднее с периодом 6 лет (*2*).

а – ледник Восточный Брёггер; *б* – опорные ледники WGMS (среднее значение).

ries of observations from the Vöring glacier have long breaks. The graph for the Austre Brøggerbreen glacier is displayed in Fig. 6, *a*. It can be seen that the periods 2013–2019 and 2012–2018 had some of the most negative indicators of the mass balance. In the entire history of observations, only the periods of 2000–2006 and 2001–2007 had the same negative balance. A similar picture is demonstrated by the results of observations from the Vöring Glacier: of all the available balance values, it reached the most negative value in 2005, approaching the average measured by the authors for 2013–2019. In addition, a recent study [*van Pelt et al., 2019*] summarizing the data on the mass balance of glaciers in the Svalbard archipelago over the past six decades, has revealed a negative mass balance trend at –0.06 m w.e. for the archipelago as a whole.

Similarly, we compared the global data on the mass balance of glaciers obtained by WGMS (for a detailed description, see *Materials and methods*). In the 2017/18 mass-balance year, the reference glaciers experienced a weight loss of 0.89 m w.e. The preliminary estimate of the mass balance for the 2018/19 balance year is even more negative and exceeds 1.0 m w.e. in absolute value. Thus, eight out of ten years with the most negative balance in the entire history of observations are years after 2010. Consequently, the acceleration of the mass loss by the Vöring glacier is in full agreement with the general trend of changes in the mass balance of glaciers in the Svalbard archipelago, and with the worldwide ones.

CONCLUSIONS

Based on the results of topographic and aerial photography in August 2019, the authors have obtained a DEM for the entire surface of the Vöring glacier which will become the basis for further monitoring observations of the glacier mass balance using a geodetic method. The glacier area has amounted to 0.75 km^2, which is 4.5 times less than that in 1911, being decreased over the following years. By comparing with the ArcticDEM fragment, the authors has calculated the loss of mass by the Vöring glacier over 6 years: from 2013 to 2019, amounting to (5.9 ± 0.4) million tons, which gives an average annual balance for the period of (–1.30 ± 0.17) m w.e.

None of the previously measured values of the annual balance (from 1975 to the end of the 1980s) reached individually as a negative value as the average one obtained by the authors for the period 2013–2019. A similar picture of the acceleration of mass loss in recent years is also demonstrated by the Austre Brøggerbreen glacier located to the north on Spitsbergen. The acceleration of mass loss by the Vöring glacier fits into the general trend for Svalbard and the global glacier mass balance trend.

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