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By

Anton Viktorovich Terekhov

GLACIER MASS BALANCE VARIABILITY IN THE AREA OF BARENTSBURG (SVALBARD ARCHIPELAGO) IN THE EARLY 21ST CENTURY

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Doctor of Science Sergei Verkulich

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Introduction

The cryosphere is one of the Earth's systems, closely interacting with the hydrological cycle and global climate. A significant part of the cryosphere is made up of terrestrial ice: according to recent estimates, glaciers outside the Antarctic and Greenland ice sheets occupy an area of 706 thousand km^2, with a volume of 170 thousand km^3 [Zemp et al., 2019]. The steady trend towards climate warming and thinning of snow cover has been observed over the past decades. It has led to the fact that the vast majority of regional glaciation centers are experiencing a decrease in ice mass [IPCC, 2019]. Recent estimates indicate that the rate of global ice loss has increased since the 1990s by half — from 800 to 1200 billion tons per year [Slater et al., 2021]. The decrease in the volumes and areas of modern glaciation has several important consequences for the entire geosystem, manifested at its different scale levels [Braithwaite, Hughes, 2020]. At the regional level, the most pressing aspect of such changes is the decrease in fresh water and hydropower resources. Examples of impacts on a global scale are a change in the thermal balance of the planet's surface due to a decrease in its albedo [Marcianesi, Aulicino, Wadhams, 2021] and a rise in the level of the World Ocean [Edwards et al., 2021].

Even though the predominant mass of glacial ice on Earth is concentrated in the Antarctic and Greenland shields, the total contribution of the melting of the remaining glaciers (213 ± 29 billion tons per year) is responsible for approximately one-third of the eustatic sea level rise [IPCC, 2019], and according to newer estimates for almost 45% of it [Slater et al., 2021]. Modeling shows that this contribution will remain significant throughout the 21st century [Schuler et al., 2020]: according to a review by the Intergovernmental Panel on Climate Change (IPCC), mountain and polar glaciers will continue to grow in the current century deviation "with a high degree of confidence" [IPCC, 2021]. This will lead to the complete disappearance of glaciation in many mountainous countries in the coming decades [Zemp et al., 2019].

However, estimates of glacial mass loss for specific regions of the planet still vary widely depending on the methods and data sets used by study authors [Slater et al., 2021]. For obvious reasons, humanity is not able to directly observe every single glacier in the world. Therefore, any assessments of both the future and current state of the cryosphere involve, to one degree or another, methods of mathematical modeling, even if they are represented by the most primitive procedures of spatial interpolation. Consequently, to clarify our understanding of the dynamics of modern glaciation and forecast its changes, there are two main ways: 1) improving modeling methods and 2) improving the quality of field data used for calibration and verification of models, expanding their geography.

Svalbard archipelago possesses up to 10% of the total glaciation area outside Greenland and Antarctica, which is the highest percentage among the polar regions [Nuth et al., 2013]. The unique geographical location of Svalbard, between the Atlantic and the Arctic Ocean, in recent decades, has predetermined a significant increase in air temperature in the archipelago, several times higher than the global average [Isaksen et al., 2022]. This phenomenon is known as “Arctic amplification” and is due to the influence of climate feedback caused by changes in ice and snow cover at high latitudes [Nordli et al., 2014]. Therefore, the glaciation of Svalbard is no exception to the observed global trend for mass loss and is of increased scientific interest from the point of view of observing connections in the ocean-atmosphere-cryosphere system [Schuler et al., 2020]. Here, in Barentsburg, the Russian Scientific Center on the Spitsbergen Archipelago is located, which was established for a comprehensive study of the natural environment and climate of the archipelago [Concept of creation…, 2014]. Employees of the Federal State Budgetary Institution “AARI”, including the author, have accumulated a significant amount of factual material on the mass balance characteristics of glaciers in the Barentsburg region. Purposeful processing of the entire volume of data was not carried out until recently: the results of glaciological monitoring remained largely unpublished until 2023.

The object of study is the terrestrial glaciation of the Spitsbergen archipelago in the area of the Barentsburg settlement, and **the research subject** is the spatial and temporal variability of the mass-balance characteristics of this glaciation. The main results are both long-term series of glacier mass balance and scientific and practical conclusions on improving the organization of glaciological monitoring carried out by Russian researchers.

The state of the art. As of 2021, twelve programs for long-term monitoring of glacier mass balance are known within Svalbard, which may seem considerable in comparison with the area of the archipelago. However, these glaciers are distributed unevenly across the territory, grouping into two main clusters associated with international research centers: Ny-Ålesund in the northwest and Hornsund in the south [Schuler et al., 2020]. As a result, the central part of the island of Western Spitsbergen, where the village of Barentsburg is located, is poorly provided with mass balance data. The only observational series from the Austre Grønfjordbreen glacier does not have seasonal mass balance values and has not been subjected to a comprehensive assessment of random and systematic errors (e.g., Chernov et al., 2019).

Glaciological monitoring programs conducted by Russian researchers are few even outside Svalbard. For the recent report of the World Glacier Monitoring Service (WGMS) on the topic of current problems of glaciological observations, an overview of the current state of monitoring in Russia was presented by V.V. Popovnin, who has been heading research at the Caucasian glacier Dzhankuat [125 years of internationally coordinated glacier monitoring: achievements and future challenges, 2020]. The main thesis of this report was that on the territory of such an extended country as Russia, the monitoring network consists of only three objects: the Aktru glacier in Altai and the Dzhankuat and Garabashi glaciers in the Caucasus. Mass balance measurements on another glacier, not mentioned in the report, have been carried out on the Severnaya Zemlya archipelago by the AARI since 2013 (Mushketov glacier, Bolshiyanov et al., 2016).

All other monitoring programs, including within other centers of modern glaciation, of which there were nineteen in the territory of the former USSR [Grosval'd, Kotlyakov, 1969], were curtailed at the end of the 20th century. Currently, expanding the geography of observations is impossible due to a lack of funding for such projects [Popovnin, 2020]. Thus, the processing of mass balance observation data on Spitsbergen, carried out using the modern generally accepted method of glaciological reanalysis, will help to put another point on the map of domestic glacier monitoring, although located outside the territory of Russia, but which is the result of many years of work by domestic researchers.

The aforementioned evidences **the relevance of the research topic**, aimed at studying the Arctic region, which is one of the priority areas of Russian science [Concept of creation…, 2014].

The main goal is to identify the main spatial and temporal patterns in the variability of the mass balance values of glaciers in the area of Barentsburg (Svalbard) in the 21st century in connection with climate changes. To achieve the stated goal, it was necessary to solve the following **tasks**:

– carry out the necessary *field and analytical work* to calculate the geodetic mass balance of glaciers in the Barentsburg region, including those that are currently being monitored by the glaciological method;

– quantify the *random errors* that arise during calculations using the glaciological and geodetic methods;

– conduct a joint reanalysis of series obtained by glaciological and geodetic methods of measuring mass balance to identify and assess *the systematic error* of monitoring;

– identify the main patterns of *spatial distribution* of mass-balance values over the surface of the studied glaciers;

– analyze *the interannual variability* of the mass-balance characteristics of glaciers for connections with fluctuations in climatic values measured in the area under consideration;

– assess whether *long-term variability* in the mass balance of glaciers in the Barentsburg area is consistent with the general archipelago patterns associated with climatic factor;

– show *the representativeness* of the obtained mass balance data for the entire glaciation of the Spitsbergen archipelago as a whole;

– justify the significance and advantages of parallel application of glaciological and geodetic methods for long-term mass-balance monitoring of glaciers.

The scientific novelty of the study is that for the first time in Russian practice, a long-term series of glacier mass balances have been subjected to glaciological homogenization and reanalysis, as well as a comprehensive uncertainty assessment. As a result, the most reliable new data on the mass balance of glaciers in the central part of the island of Western Spitsbergen, where there had previously been a shortage of such series, was obtained.

The practical application of the work is to fill the lack of mass balance data in the considered area of the Spitsbergen archipelago: homogenized long-term monitoring series were obtained as the main result. The study also has **a theoretical output**, consisting of the conclusions formulated by the author on ways to improve the organization and conduct of glaciological monitoring of Svalbard glaciers.

Personal contribution. The author participated in summer fieldwork on mass balance measurement at two glaciers of the Grønfjorden Bay basin (2018–2019); carried out GNSS ground-based survey of glaciers Aldegondabreen (2018), Vestre Grønfjordbreen, Austre Dahlfonna (2019), performed a drone aerial survey of Vøringbreen (2019). The author computed the geodetic mass balance of the aforementioned glaciers, reanalyzed the available glaciological mass-balance series, and estimated the relationships between the mass balance, climatic and morphometric variables.

Validity of the work results and approbation. All the conclusions are based on factual material of mass balance monitoring collected by the team of the Arctic and Antarctic Research Institute during field expeditionary research, including with the participation of the author. The study is based on well-known and currently generally accepted methods for measuring and calculating the mass balance of glaciers, called “glaciological” and “geodetic”, as well as on a framework for comparison of the results of these two methods, called glaciological reanalysis. Reanalysis of the glacier mass balance series consists of periodically revising the mass balance values based on an intercomparison of the results obtained by two different monitoring methods and is intended to clarify the indicators by, firstly, using the most relevant auxiliary data, and, secondly, by identifying, quantitative assessment and elimination of systematic errors in observation series [Zemp et al., 2013]. The technique was first proposed in 2013 and over the past decade has been successfully tested for many of the world's glaciers (e.g. [Andreassen et al., 2016; Galos et al., 2017; Klug et al., 2018; Wagnon et al., 2020]). The factual material, as well as the results of mathematical, geoinformation, and statistical processing, are presented by the author in tables and depicted in figures.

The thesis results are published in peer-reviewed journals, indexed by Scopus and/or Web of Science, including the Q1 journals, and by the RSCI index:

1. *Terekhov A.*, Tarasov G., Sidorova O., Demidov V., Anisimov M., Verkulich S. Estimation of mass balance of Aldegondabreen (Spitsbergen) in 2015–2018 based on ArcticDEM, geodetic and glaciological measurements. Ice and Snow (*Led i Sneg*). 2020. Vol. 60. №2. P. 192–200 (In Russian);

2. *Terekhov A.*, Demidov V., Kazakov E., Anisimov M., Verkulich S. Geodetic mass balance of Vøringbreen glacier, Western Spitsbergen, in 2013-2019. Earth’s Cryosphere (*Kriosfera Zemli*). 2020. Vol. 24. №5. P. 55–63. DOI: 10.21782/KZ1560-7496-2020-5(55-63) (In Russian)*;*

3. Prokhorova U., *Terekhov A.*, Ivanov B., Verkulich S. Calculation of the heat balance components of the Aldegonda glacier (Western Spitsbergen) during the ablation period according to the observations of 2019. Earth's Cryosphere (*Kriosfera Zemli*). 2021. Vol. 25. №3. P. 50–60. (In Russian)

4. *Terekhov A.*, Verkulich S., Borisik A., Demidov V., Prokhorova U., Romashova K., Anisimov M., Sidorova O., Tarasov G. Mass balance, ice volume and flow velocity of the Vestre Grønfjordbreen (Svalbard) from 2013/14 to 2019/20. Arctic, Antarctic, and Alpine Research. Vol. 54. №1. C. 584–602, 2022. DOI: 10.1080/15230430.2022.2150122;

5. Prokhorova U., *Terekhov A.*, Ivanov B., Demidov V. Heat balance of a low-elevated Svalbard glacier during the ablation season: A case study of Aldegondabreen. Arctic, Antarctic, and Alpine Research. 2023. T. 55. №1. 2190057. DOI: 10.1080/15230430.2023.2190057;

6. *Terekhov A.*, Prokhorova U., Verkulich S., Demidov V., Sidorova O., Anisimov M., Romashova K. Two decades of mass-balance observations on Aldegondabreen, Spitsbergen: Interannual variability and sensitivity to climate change. Annals of Glaciology. 2023. C. 1–11. DOI: 10.1017/aog.2023.40;

7. Prokhorova U., *Terekhov A.*, Demidov V., Verkulich S., Ivanov B. Intra-Annual Variability of the Surface Ablation of the Aldegondabreen Glacier (Spitsbergen). Ice and Snow (*Led I Sneg*). 2023. Vol. 63. № 2. P. 214–224 (In Russian);

8. *Terekhov A.*, Vasilevich I., Prokhorova U. Uncertainty Assessment for Mean Snow Cover Depth Derived from Direct Measurements on Aldegondabreen Glacier (Svalbard). Ice and Snow (*Led I Sneg*). 2023. Vol. 63. №3. P. 357–368 (In Russian);

Some of the results were included in the scientific reports carried out by FSBU «AARI» on the projects of Roshydromet, and registered in the Rospatent service as a database (Certificate of state registration of the database №2021621585 from 22 July 2021 [Verkulich et al., 2021]). Some findings were presented at several international and Russian-wide conferences:

- International Symposium on Atmospheric Radiation and Dynamics «MSARD–2023», Saint Petersburg, Russia;
- International conference of the IAP RAS "Turbulence, dynamics of the atmosphere and climate 2021", Moscow, Russia [Ivanov et al., 2022];
- Glaciological Symposium 2020, Saint Petersburg, Russia;
- Svalbard Science Conference 2019 г., Oslo, Norway [Terekhov et al., 2019].

The contents. The main text of the research consists of four chapters. Chapter 1 substantiates the relevance of monitoring the mass balance of glaciers and gives an overview of the history of the development of methods and principles of mass balance monitoring. Chapter 2 presents a summary of the current state of glaciation of the Svalbard archipelago, as well as a physical-geographical characteristic of the study area and, in particular, the studied glaciers in the area of Barentsburg. In Chapter 3, the source data are described in detail, the essence of the methods used in the work is revealed, and the methodology for quantitative assessment of random and systematic errors in the obtained results is outlined. Chapter 4 presents and discusses the outcome of applying the glaciological reanalysis methodology to a mass balance series of glaciers in the area of Barentsburg. The results include spatial, inter-annual, and decadal variability and the evidence of the glacier representativeness of the whole archipelago. This translated version of the dissertation comprises 114 pages, 29 figures, and 14 tables.

Main scientific findings:

1. In the considered area of the Spitsbergen archipelago, the longest mass balance series was obtained, including seasonal values, a comprehensive assessment of random errors and a proven absence of systematic error [Terekhov et al., 2023, p. 5, table 2]. The degree of personal participation of the author in obtaining/achieving this result: homogenization of mass balance series, calculation of the error of mass balance values, conducting ground topographic survey on the Aldegondabreen glacier and subsequent calculation of the geodetic mass balance and comparing it with the glaciological one;
2. It was shown that, despite a stable trend towards warming of surface air temperature within the entire Spitsbergen archipelago, there was no statistically significant trend for the mass balance series of the glaciers under consideration [Terekhov et al., 2023, p. 9, paragraph 6.4, paragraph 1]. The degree of personal participation of the author in obtaining/achieving this result: statistical analysis of mass balance series of the studied glaciers;
3. It was shown that the alternation of periods of relatively high and low glacier mass balance in the Barentsburg area coincides with changes in atmospheric circulation regimes [Terekhov et al., 2023, p. 10, paragraph 4]. The degree of personal participation of the author in obtaining/achieving this result: statistical analysis of mass balance series of glaciers in the Barentsburg area;
4. The relationship between the mass balance values of the Vestre Grønfjordbreen glacier and the main meteorological variables measured at the weather station in Barentsburg was quantified [Terekhov et al., 2022, p. 597, Figure 8]. The degree of personal participation of the author in obtaining/achieving this result: computation of statistical values that quantify the relationship between glacier mass balance and climate;
5. Using the geodetic method, based on the results of ground-based GNSS surveys and archival remote sensing data, the mass balance of the Vøringbreen glacier in 2013–2019 was determined, which turned out to be significantly more negative than in the 70s and 80s of 20th century, when monitoring was carried out on that glacier [Terekhov et al., 2020a, p. 61]. The degree of personal participation of the author in obtaining/achieving this result: conducting ground GNSS survey, data processing, calculation of geodetic mass balance;

6. The mass balance of the Austre Dalfonna glacier was determined using the geodetic method, and it was shown that in 2013–2019 the glacier mass loss was larger than in the previous period of 2008–2013. [Terekhov et al., 2022, p. 377, table 3]. The degree of personal participation of the author in obtaining/achieving this result: conducting ground topographic survey, data processing, calculation of geodetic mass balance;

7. Based on the bootstrap method, empirical curves were obtained to determine the relative error of the average snow depth on the studied glaciers, depending on the coefficient of variation of snow depth and the density of the measurement grid [Terekhov, Vasilevich, Prokhorova, 2023, p. 363]. The degree of personal participation of the author in obtaining/achieving this result: development of an algorithm based on the bootstrap method and its implementation.

Thesis statements:

1. *Interannual variability* in the annual mass balance of glaciers in the Barentsburg area has a high correlation with air temperature, and the winter mass balance — with precipitation measured at the Barentsburg weather station. Retrospective homogenization of mass balance measurement series simplifies obtaining these relationships;

2. *Decadal variability* in the mass balance of glaciers in the Barentsburg area, over periods of 5–10 years, coincides with the general variability in the archipelago and therefore is determined by a regional scale factor which is likely a change in atmospheric circulation regimes. Consequently, the glaciers considered in this study are a reliable indicator of regional climate changes, being *representative* of the whole island of Western Spitsbergen;

3. Intercomparison of the results of two independent methods for determining the mass balance of glaciers, glaciological and geodetic, makes it possible to quantify the systematic error in the series or show its absence. In the presence of gaps in observations, it also allows control of the accuracy of reconstructed values. Therefore, it is advisable to organize long-term mass balance monitoring with these two methods in parallel.

Chapter 1 Glacier mass balance monitoring

1.1 Role of glaciers in the structure, dynamics and functioning of landscapes

The main idea of physical geography at the present stage of development of science is the mutual connection of the natural geographical components that make up the outer spheres of our planet. Geographical components are interconnected both in space and time, therefore their dynamics and development occur in tandem [Isachenko, 1991].

The role of terrestrial glaciation in the structure, dynamics and functioning of landscapes in polar and high-mountain territories is paramount. Glaciers are the most extensive component of these landscapes, which is especially typical for Arctic archipelagos. Thus, glaciers occupy about 60% of the territory of Spitsbergen, 79% of the territory of Franz Josef Land, about a third of the area of the Novaya Zemlya islands and approximately 45% of Severnaya Zemlya [Moholdt, Wouters, Gardner, 2012]. However, from the point of view of interrelations in the geosystem, it is not the share of the glaciated area itself that is important, but the fact that glaciers determine a number of landscape-forming factors associated with matter fluxes.

Terrestrial glaciation is an important part of the hydrological cycle of Arctic landscapes, since it redistributes the runoff on the intra-annual time scale. The maximum amount of precipitation in the Svalbard archipelago is observed during the winter months, so river flow in summer is almost completely governed by the glacier ablation. In addition, the rapid retreat of glaciers observed in recent decades leads to the formation of periglacial lakes on the archipelago. Currently, Svalbard is characterized by the fastest rate of formation of new periglacial lakes in the world, which is one of the most striking manifestations of structural changes in the landscapes of the archipelago caused by climate change [Wieczorek et al., 2023].

The participation of glaciers in the formation of freshwater runoff also leads to their indirect influence on marine ecosystems, which includes not only in the desalination of seawater, but also the nutrient influx from land. For example, a recent study shows that up to 12% of the iron carried by glaciers to the sea is potentially bioavailable. As a result of the biogeochemical cycle, iron in Arctic fjords is converted into more labile forms, which further increases its bioavailability for phytoplankton. Therefore, glaciers are the most important supplier of nutrients for marine ecosystems at high latitudes [Laufer-Meiser et al., 2021].

Climate is distinguished as a special geographical component in the Russian landscape science, which, however, does not represent a separate natural body, being a set of certain properties and processes of individual air masses. Nevertheless, climate plays a crucial role in the formation and functioning of geocomplexes [Isachenko, 1991], and a significant part of this research is devoted to the impact of climate on the mass balance of glaciers in the Barentsburg area. However, reverse feedback mechanisms are also known: glaciers are able to influence the the micro- and regional climate. This occurs through their cooling of the surface layer of air, a change in the albedo of the underlying surface, and the formation of stable anticyclones (the latter is typical for the largest glaciers like the Greenland Ice Shield) [Paterson W. S. B., 1994]. These effects undoubtedly influence other components of the geosystem.

On larger time scales, glaciers are one of the main geomorphological factors determining the relief of the territory of the Arctic archipelagos. Glaciation forms both exaration and accumulative landforms. Many valleys in the Svalbard archipelago that are currently ice-free are trough-shaped, U-shaped, having been occupied by major glaciers in the recent past, prior to the peak of the Little Ice Age [Farnsworth et al., 2020]. Other widespread glacial landforms are cover and pressure moraines, formed over the last century and covering a significant part of the deglaciated valleys of Spitsbergen [Kokin and Kirillova, 2017].

Glaciation affects not only processes occurring on the surface, but also the spatial distribution of permafrost. There is a hypothesis that under most of the glaciers of Spitsbergen there are taliks, the existence of which is due to the presence of liquid water in the lower horizons of polythermal glaciers common in the archipelago. The existence of taliks is supported by typical cryogenic processes, such as the appearance of periglacial ice in winter, which would be impossible if permafrost prevented underground flow from glaciers [Demidov et al., 2020].

In addition to other impacts on landscape components, glaciers also influence human activity, even limiting anthropogenic interference in the natural-territorial complexes of the archipelago. Permanent settlements on Svalbard would be impossible without reliable sources of fresh water, which is especially important for areas in the northeast, since the amount of atmospheric precipitation decreases rapidly from the western coast. For Barentsburg, the source of fresh water in the early and mid-20th century was the Aldegondabreen glacier, from which a water pipeline was laid into the settlement. In the second half of the 20th century, due to the rapid retreat of the glacier deeper into the valley, the water supply system was forced to be redesigned and laid again from the lake Stemme [Mavlyudov and Kudikov, 2018]. A reliable assessment of the water balance of Lake Stemme has not yet been carried out, however, it is obvious that it is partially fed by the meltwater of the glaciers surrounding its valley.

Thus, the impact of glaciers on adjacent natural geographic components of the Arctic landscapes manifests itself at different spatial and temporal scale levels. Therefore, terrestrial glaciation, which influences all the main landscape-forming factors, plays a critical role in the structure, dynamics and functioning of Arctic natural systems.

1.2 Need for glacier monitoring

Since the start of glaciological monitoring, the 125th anniversary of which is highlighted by the recent report of the World Glacier Monitoring Service (WGMS) [125 years of internationally coordinated glacier monitoring: achievements and future challenges, 2020], the main observable parameters of glaciers were their length and area. Only two decades after the beginning of the targeted and coordinated collection of information about glaciers [Forel, 1895], their mass balance values also became the goal of measurements [Huss et al., 2021]. Over the century since then, it has become obvious that glacier changes are closely related to climatic fluctuations of varying duration and scale (from global to local), and, in turn, are important indicators of the amplitudes and trends of these fluctuations. Let's look at why mass balance is more useful for monitoring from a practical standpoint than much less labor-intensive variables to measure, such as glacier area and length.

Area and length are among the most reliably determined variables when mapping glaciers from space and aerial photographs [Paul et al., 2013]. The exception is ice bodies that are largely covered by moraine or colluvium, for which it is difficult to establish precise outlines. Available archival terrestrial photographs, topographic maps, and text sources allow us to reconstruct the boundaries of glaciation over the historical period, and geomorphological evidence in the form of push or stadial moraines extends this period into the past to several thousand or tens of thousands of years, albeit with much less temporal resolution.

Oerlemans, in his 2005 study, attempted to reconstruct a series of variations in global air temperature since the beginning of the 19th century based on data on glacier length changes. Using all 169 available time series of glacier lengths around the world, he quantified the warming for the first half of the 20th century at 0.5 Kelvin [Oerlemans, 2005]. As for the Spitsbergen archipelago, Lavrentyev showed in his dissertation that changes in the area of the Aldegondabreen glacier correlate well with changes in summer temperature, thereby establishing that this glacier can be a reliable indicator of climate changes in the Barentsburg region [Lavretyev, 2008]. However, in the general case, the glacier area may not be related to climatic parameters, in support of which the following arguments can be given:

1) today the existence of surging glaciers is an indisputable fact, since the surges were directly observed by people. The active phase of glacier surging can vary significantly in duration, ranging from a few minutes, as exemplified by the Kolka Glacier disaster [Evans et al., 2009], to periods of several years. It is obvious that during instantaneous glacier advance, its area may increase drastically while its mass remains unchanged. In this case, an area's growth cannot indicate an improvement (from the point of view of glaciation) in climatic conditions. If the period of glacier advance lasts several years, an increase in the area can also occur with a decrease in the total volume, that is, with an overall thinning

of the glacier. This example is described in [Murray et al., 2018] for the Fridtjovbreen glacier, located in the study area to the south of Barentsburg. This is not the only surging glacier in this area: the work [Kokin and Kirillova, 2017] substantiates the possibility of the surging of the Vestre Grønfjordbreen glacier in historical times. In the archipelago as a whole, according to various estimates, from 10 to 90% of glaciers can be pulsating [Wangensteen, Weydahl, Hagen, 2007];

2) tidewater glaciers, which are many of the large glaciers of the archipelago today, regularly lose their area due to calving. This process largely depends on the mechanical action of water on the edge of the glacier and the strength of the ice. Thus, the loss of area by glaciers is not always direct evidence of climate warming or a decrease in the amount of solid precipitation.

In the context of studying global climate changes, glacier mass balance monitoring is a source of long-term series that carries a climate signal. In addition, according to modern concepts, glaciers outside the Antarctic and Greenland shields are responsible for 30–45% of the eustatic sea level rise (Figure 1.1). Calculation of such practical consequences of present-day glaciation dynamics (not only the global sea level rise but also the assessment of changes in freshwater and hydropower resources) requires knowledge of *the mass of water* stored or lost by glaciers.

Mass balance series are also not without shortcomings: in the latest WGMS report, one of the most pressing problems in the analysis of mass balance series was identified as a significant change in the area–altitude distribution of many mountain glaciers. Ongoing warming contributes to the rapid loss of the low-lying glacier ablation zones entirely, after which the melt of the surviving upper reaches slows down. The influence of this factor, called "geometric" or "morphometric," can make it difficult to isolate the climate signal in mass balance series [Charalampidis et al., 2018; Vincent et al., 2017].

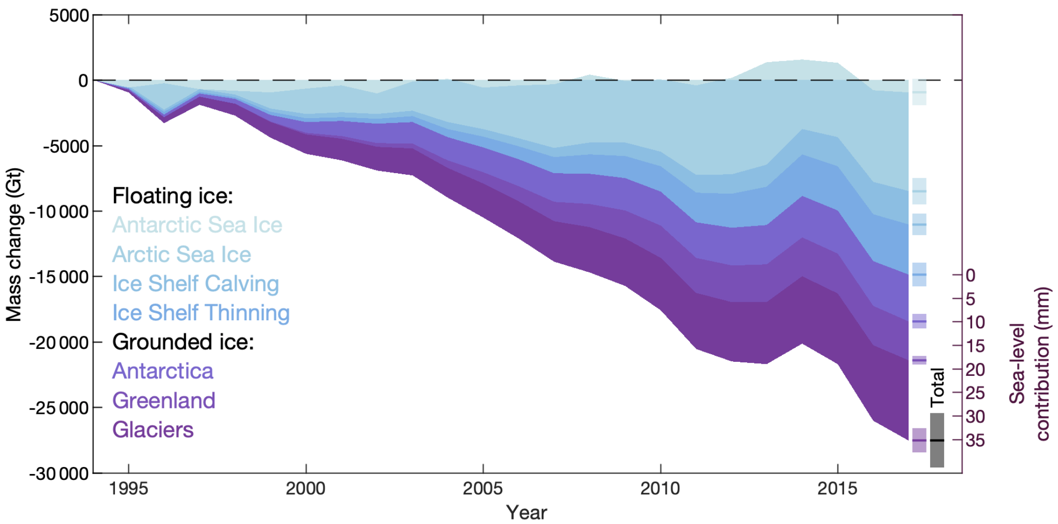


Figure 1.1 — Global ice losses since 1995, and their contribution to the sea level rise (from [Slater et al., 2021])

To understand the current state of mass balance monitoring in the Svalbard archipelago (and in general throughout the world), it is first necessary to consider the history of the development of ideas about the mass balance of glaciers, methods for its estimation, and principles for organizing monitoring work, which predetermined modern practices in this area.

1.3 History of glacier monitoring

1.3.1 First half of the 20th century: formation of the idea

The history of observations of glacier mass balance goes back a little over a hundred years. Even though the concept of glacier mass balance and the terms associated with it were first developed by the Swedish glaciologist Hans Ahlman in the 1920s, quantitative measurements of melting and accumulation processes on glaciers were carried out earlier. An example is the reanalysis of a 106-year (1914–2020) series of observations published in 2021 at two points (“upper” and “lower”) on the Claridenfirn glacier in Switzerland, which is currently the most a long series of this kind [Huss et al., 2021]. However, the development of glacier mass balance measurements in the 20s and 30s of the last century is associated mainly with the short and episodic expeditions of H. Alman. Most measurements were carried out during one balance year on each of the glaciers visited [Ahlmann, 1953; Black, 1948], and therefore cannot be called “monitoring”. The international name of the historically first method of observing mass balance, based on measurements of ablative stakes and snowpits — “direct glaciological” — goes back to Alman’s work.

C.C. Wallén was one of the first to recognize the practical need for organizing *long-term* mass balance observations and carried out the first such series of measurements over five years (1942–1948) on the Kårsa glacier in Swedish Lapland [Wallén, 1949a; Wallén, 1949b]. At the same time, in 1946, regular observations were started on the Storglaciaren glacier, also in Lapland [Schytt, 1962]. These observations, continuing to date, were the longest series of measurements [Braithwaite, 2009; Holmlund, Jansson, Pettersson, 2005] until the publication of the above-mentioned data series from the Claridenfirn glacier.

On the territory of the USSR, the first measurements of the mass balance of glaciers were carried out by P. A. Shumsky during expeditions to the Franz Josef Land archipelago in 1947–1949, but they did not become regular [Grosval’d, Kotlyakov, 1969].

In parallel with the beginning of the application of the “glaciological method,” ideas about the use of geodetic technologies developed. One of the pioneers of photogrammetry, the German mathematician Sebastian Finsterwalder compiled the first large-scale topographic maps of the territory of the Ötztal Alps in 1922 using a phototheodolite. Finsterwalder carried out the most detailed surveys on the surface of several glaciers and rock glaciers and then repeated them in subsequent years to compute the speed of movement of these objects [Braithwaite, 2009]. Several decades later, the survey materials were used to calculate the mass balance characteristics of glaciers.

1.3.2 Second half of the 20th century: development of methods

The start of regular mass balance studies around the world and the beginning of international cooperation in matters of glaciology was given during the International Geophysical Year in 1957–1959. At this time, the concept of a “benchmark glacier” was established in glaciology [Fountain et al., 2009]. It was assumed that the organization of long-term monitoring of mass balance on a correctly selected glacier (based on “average” morphometric characteristics for a given glaciated region) would make it possible to extrapolate observations to the entire area. Under the influence of this concept, the first monitoring programs were organized in many countries around the world. In 1958, the first program under the auspices of the US Geological Survey was launched on the South Cascade glacier in Washington state [Meier, Tangborn, 1965]. Regular series of observations were started also in the USSR, on the IGAN and Obruchev glaciers (Polar Urals), as well as on the Central Tuyuksu glacier (Trans-Ili Alatau) [Grosval’d, Kotlyakov, 1969]; Currently, these series were interrupted.

In the Svalbard archipelago, the first systematic mass balance measurements were carried out between 1950 and 1966. on the Finsterwalderbreen glacier, located in the Van Keulen fjord area. These measurements were carried out once every two years since this was the frequency of Norwegian scientific expeditions [Hagen, Liestøl, 1990].

The next powerful impulse to expand the geography of monitoring studies and improve their organization was received in the 1960s when UNESCO (United Nations Educational, Scientific and Cultural Organization) and the World Meteorological Organization declared the International Hydrological Decade (IHD) [Intergovernmental Meeting of Experts for the IHD - Final report , 1964]. Particular emphasis was placed on studying the spatial distribution of the world's freshwater resources and their rational use [Keller, 1976]. This international project became the first comprehensive program to study the global hydrological cycle [First session of the Intergovernmental Council (of the) International Hydrological Programme (IHP), Paris, 9-17 April 1975: final report, 1975], attracting the attention of the scientific community to the assessment of water reserves in terrestrial ice and the impact of climate change on these reserves [Narasimhan, 2009].

As part of the IHD, the number of mass balance monitoring objects has increased significantly. Thus, several new “benchmark” glaciers were selected in the USA [Meier et al., 1971], and the Moscow State University started observations of the Dzhankuat mountain–valley glacier in the Central Caucasus [Lavrentyev et al., 2015; Popovnin and Petrakov, 2005]. The first continuous mass balance observations were organized within the Spitsbergen archipelago. In the 1966/67 balance year, monitoring began on the Austre Brøggerbreen glacier, and a year later, observations were also expanded to the neighboring Austre Lovenbreen glacier [Hagen, Liestøl, 1990]. These two series remain by far the longest in the archipelago. Also in 1966/67, Soviet glaciologists carried out one-time measurements on the Vøringbreen glacier in the vicinity of Barentsburg. After a break of several balance years, from 1973, measurements became regular, but in the late 1980s were interrupted again.

During the IHD, topics on organizing mass balance monitoring, as well as assessing errors in its results, begin to be actively developed. This is facilitated by the accumulation and synthesis of factual material, which was reflected in the first UNESCO review published in 1967 [PSFG: Fluctuations of Glaciers 1959-1965, Vol. 1, 1967]. A little later, in 1969, the first English-language collection of glaciological terms and definitions was published [Mass-Balance Terms, 1969].

Meier et al. [1971] noted a paradox emerging in monitoring practice in those years: the smaller the glacier, the denser the observation network installed on it. This fact is illustrated by the example of a US monitoring program when a network of 38 ablation stakes was installed on the Maclure glacier with an area of 0.2 km^2, and only 3 stakes were measured on the much larger Wolverine glacier (17 km^2) [Tangborn et al., 1977]. The number of stakes per square kilometer of area varied in this case by about a thousand times. This gave rise to a discussion about the number of stakes required to determine the mass balance of a glacier, as well as about methods of inter- and extrapolation of measured point values to the glacier surface.

One of the first studies discussing in detail the issue of the required number and location of ablation stakes [Campbell, 1966], was based on the prevailing idea at that time of the need to cover the glacier with a regular network of ablation stakes. Through statistical analysis, Campbell attempts to determine which network density is required to ensure that the sample average mass balance (that is, measured at the stakes) differs from its true value by no more than a specified amount of error. As Campbell himself pointed out, the proposed approach had several shortcomings, in particular, it was based on the assumption that all point measurements are independent and normally distributed, which is, in general, incorrect. In addition, regular observational networks are not suitable for large glaciers due to the obvious labor intensity.

In parallel with the glaciological method, other methods for measuring mass balance are also being developed, although they were used sporadically in practice and are not considered by researchers as suitable for monitoring. H. Hoinkes [1970], who continued S. Finsterwalder's research in the Ötztal Alps, notes that the mass balance of a mountain glacier can be measured not only by the "direct glaciological method of H. Alman", but also by "hydrological" and "geodetic" ones. The author concludes that hydrological calculations, through which one can find the glacier mass balance as a residual term in the water balance equation, apparently cannot provide acceptable accuracy of the result, and the "geodetic" method, although potentially better in accuracy, is very labor intensive.

1.3.3 End of the 20th century: generalization of results

In the second half of the 1970s and during the 1980s regional overviews of glacier observations are being published en masse. In particular, for the Svalbard archipelago, the studies “Glaciation of Spitsbergen (Svalbard)” [1975] and “Glaciology of Spitsbergen” [Glaciology of Spitsbergen, 1985], as well as a review work by Hagen and Liestol [1990], were published. These generalizations contributed to further revealing the relationships between glacier mass balance and climate. A consensus has been found that mass balance correlates well with altitude for most mountain glaciers, which is explained by vertical gradients of heat and precipitation in the atmosphere [Paterson W. S. B., 1994]. Exceptions to this general pattern were also described: on those glaciers whose width greatly exceeds their length, the influence of wind redistribution of snow is close in magnitude to the vertical precipitation gradient [Chinn, 1985]. However, even in these cases, mass balance shows a significant correlation with altitude. Later, this conclusion made a significant contribution to changing the organization of monitoring work. In 1984, the Glaciological Dictionary was published [Alekseev et al., 1984], which was not only the first comprehensive collection of Russian-language terminology in the field of glaciology but also explained in detail the essence of the processes and phenomena associated with glaciological studies.

In 1986, the World Glacier Monitoring Service (WGMS) was founded, now being the main center for accumulating data on the dynamics of glaciers around the world. WGMS collects standardized observations of changes in the mass, volume, area, and length of glaciers (called glacier fluctuations), as well as statistical information about the spatial distribution of land ice (glacier inventories). These data not only are a fundamental source of knowledge for glaciology, geomorphology, and Quaternary geology but are also the starting point for modeling the hydrological cycle, including for assessing the effects of global climate change. WGMS draws attention to the fact that the spatial unevenness in the collection of glaciological data, which began a century ago, continues to this day: the largest amount of information is collected in Scandinavia and the Alps, where glaciological research was started earlier [About WGMS, 2021].

In 1991, based on joint Norwegian-Canadian efforts, the first guide to organizing and conducting glaciological fieldwork was published [Østrem, Brugman, 1991]. The authors, summarizing the world monitoring experience, summarize that on small mountain glaciers with an area of up to 20 km2, ablation stakes usually are installed in such a way as to provide more or less uniform surface coverage, while on large glaciers they are installed with one longitudinal profile covering the entire altitudinal range of the glacier. Thus, the authors recognize the existence of two ways to transition from point measurements to the glacier-averaged value: by drawing mass balance contour lines (that is, spatial interpolation of point values) and using the altitudinal mass balance profile.

The theoretical basis for the "profile method" of converting point measurements into glacier averages appeared only in 1999, immediately bringing this method to the forefront in comparison with the method based on manual or automated drawings of contour lines. The study [Graham Cogley, 1999] examined the cross-correlation of point measurements of mass balance on the glacier surface, which makes these measurements not independent in a statistical sense. Based on extensive factual material, the authors concluded that the measurements are better correlated, the smaller the altitude difference between them. This assumes that any of the point measurements are sufficiently representative in the lateral direction and adding more ablation stakes to the same elevation bin is not productive. Consequently, the number of ablation stakes could be reduced in many monitoring programs.

In the same year, a paper [Fountain, Vecchia, 1999] was published, highlighting in detail two debatable aspects: a) to what extent the profile method was better or worse than the more common approach based on balance contour lines (called by the authors “traditional”) and b) how the number of ablation stakes and their installation scheme affects the final result and how to quantify the resulting error. The authors acknowledged that the relationship between mass balance and altitude was a long-known fact, which justifies using different forms of mass balance regression, fitting a curve of one form or another into the actual point measurements using the least squares method. In this case, to objectively quantify the error of the average glacier mass balance value, a well-known statistical apparatus can be used to estimate the error of the regression model.

Thus, by the end of the last century, the following basic principles of mass balance monitoring were formulated: measurements are carried out using the glaciological method; For most mountain glaciers, indeed, the surface mass balance distribution correlates well with altitude; a dense regular network of ablation stakes is not necessary; profile method may be used to recompute point observations to the glacier-averaged value, that is, a regression with the altitude as a predictor; the same regression can be used to estimate the uncertainty of the resulting values. However, until the early 2000s mass balance values determined based on ablation stakes were usually reported without assessing random and systematic errors; sometimes the authors limited themselves to mentioning only instrumental errors (for example, for a glacier in Alaska [Conway, Rasmussen, Marshall, 1999] or glaciers of Svalbard [Hagen, Liestøl, 1990]).

Almost until the end of the 20th century, the geodetic method was not considered a competitor to the glaciological method in monitoring [Ostrem, Haakensen, 1999]. However, two advantages of the geodetic method were always recognized. Firstly, it allows the mass balance to be estimated retrospectively using archival data like topographic maps and aerial photographs, which were created for other purposes rather than studying glaciers [Huss et al., 2021]. The use of the geodetic method for calculating mass balance based on archival data allows us to expand our understanding of the mass balance of Svalbard glaciers until the beginning of the 20th century, when, along with the economic development of the territory, the creation of the first topographic maps on a fairly large scale began, and then, in the 30s, aerial photography. The second advantage of the method, thanks to ground-based, airborne, and satellite-based photographic systems, is the possibility of its application for fairly large areas obtaining the regional mass balance assessments. Nevertheless, at the end of the 20th century, the geodetic method of measuring mass balance was still not considered suitable for monitoring single glaciers, due to labor intensity, accuracy requirements, and, often, the high cost of data acquiring.

1.3.4 Beginning of the 21st century: development of the geodetic method. Glaciological reanalysis

At the turn of the century, the first attempts were made to compare the results of glaciological and geodetic methods for mountain glaciers ([Andreassen, 1999], [Krimmel, 1999], [Cox, March, 2004]). The focus in these works was shifted towards comparing the methods themselves and assessing which of them is better. The most indicative study in this regard is the work entitled “Comparison of maps or traditional mass balance measurements: which method is better?” [Ostrem, Haakensen, 1999].

However, since the beginning of the 21st century, the development of geodesy, topography, remote sensing of the Earth, and computer technology has made it possible to significantly reduce the labor costs of using the geodetic method. As a result, a huge amount of material concerning changes in the topography of mountain glaciers began to accumulate. This was due to the coincidence of several factors that removed obstacles to the *regular and targeted use* of the geodetic method in monitoring, as opposed to the occasional use of available archival materials:

– accurate measurements using the global navigation satellite system (GNSS) GPS became available to civilian users as a result of the removal of deliberate signal coarsening in 2000. Later, other GNSS systems (GLONASS, Galileo etc.) were put into operation, making it possible to carry out surveys at a distance from existing geodetic networks and out of direct visibility with them [Antonovich, 2005];

– a significant increase in computing power and improvement of software, including the ones for processing aerial and ground-based stereo photography, facilitated and accelerated the process of constructing digital elevation models (DEMs);

– the emergence and development of scanning ranging systems (scanning lidars) increased the productivity of acquiring precise coordinates of the terrain and made it possible to obtain point clouds of previously unattainable density;

– the development of uncrewed aerial vehicles and their significant reduction in cost, made it possible to reduce the budget of aerial surveys;

– the development of satellite radio interferometry, altimetry, and gravimetry allowed to obtain mass balance estimates on a global level, and also provided data for the validation of other Earth remote sensing (ERS) data.

The first of the studies which addressed the issue about the correct comparison of geodetic and glaciological mass balances was carried out by [Cogley, 2009; Thibert, Vincent, 2009]. At the same time, the uncertainty assessment for mass-balance computations is also being developed. The idea of using the geodetic method as a reference method to identify and quantify systematic bias in glaciological monitoring series appears in the work of Thibert et al. [2008]. The assessment of errors arising during geodetic calculations is also being improved: for example, Rolstad, Haug, and Denby [2009] estimated the influence of autocorrelation of errors arising when subtracting DEMs, and developed a framework for their quantitative assessment based on geostatistics.

Since the calculation of the “geodetic” mass balance was often carried out based on archival data, this led to the need for comparison with glaciological series for previous years. Analysis of the most extended series of data leads researchers to the idea that monitoring results need periodic revision: the work is carried out by different performers, different techniques and not always the most relevant auxiliary data are used, producing heterogeneous series. In 2009, the article [Huss, Bauder, Funk, 2009] proposed a method for *homogenizing* series of mass balance variables, which consists of retrospectively recalculating glacier-averaged mass balance values based on all available source data using a unified calculation method and the most relevant morphometric data. This approach implies that the annual mass balance indicators are not “calculated” once and for all, but when more relevant auxiliary data for the object under study appear, they should be recomputed taking them into account, that is, homogenized.

A methodological apparatus for comparison of direct and geodetic mass balance series was proposed five years later. During this time, international terminology in the field of glaciology was revised taking into account the current state of mass balance monitoring, resulting in a glaciological dictionary published in 2011 [Cogley et al., 2011]. The updated dictionary finally fixed the terms of homogenization and the names of two methods for determining mass balance, geodetic and glaciological. The idea of periodically recalculating long-term mass balance series was further developed thanks to the work of [Zemp et al., 2013], which outlined a technique that the authors called glaciological reanalysis. This title is given by analogy with reanalysis in climatology, where this concept means obtaining model global fields of meteorological quantities using complete sets of observational data available at the time of calculations from various platforms, including data received with time delays. The mass balance values obtained by both methods, if a statistically significant difference between them is identified, must be brought into compliance to ensure their equality within their uncertainties.

In subsequent years, this technique has been used to reanalyze the mass balance series of glaciers in the Pamirs [Barandun et al., 2015], the Western Alps in Switzerland [Sold et al., 2016], ten glaciers in continental Norway [Andreassen et al., 2016], to the glacier of the Canadian Arctic [Thomson et al., 2017], to the Italian glacier in the Southern Limestone Alps [Galos et al., 2017], to the glacier of the Ötztal Alps [Klug et al., 2018], to the five benchmark glaciers in the territory USA [O’Neel et al., 2019], to a high-altitude glacier in the Central Himalayas [Wagnon et al., 2020]. The question of which of the two methods is better is no longer raised. The consensus is that mass balance monitoring should be carried out in parallel by two independent methods: glaciological, on an annual basis, and geodetic — at five- or ten-year intervals. The results should be periodically compared with each other to identify and quantify systematic bias. Correction of the bias improves the quality of the obtained data for establishing relationships between mass balance and climatic variables, for trend analysis, and for use in mathematical modeling for calibration and validation of models [Zemp et al., 2013].

Summary

Establishing and quantifying regional trends in the mass balance of terrestrial glaciation is still one of the pressing problems of glaciology [IPCC, 2021; About WGMS, 2021]. The reasons for this are the extremely uneven distribution of mass balance measurements around the world and the insufficient number of long series [Zemp, Hoelzle, Haeberli, 2009], and the complex nature of the response of glaciers to climate change [Roe, 2011]. Modern remote sensing tools make it possible to obtain a spatially distributed picture of the state of glaciation for large areas of the Earth [Vincent et al., 2021], but direct measurements on the surface of glaciers still remain an indispensable tool for identifying short-period fluctuations, contributing to the process-based understanding of mass balance variability of glaciers, that is, based on an understanding of mechanisms and connections [O'Neel et al., 2019].

The history of glacier mass balance monitoring goes back over a hundred years, during which not only ideas about the effective organization of monitoring programs developed, but also the two main methods for determining the mass balance, glaciological and geodetic, as well as the technical means and mathematical apparatus required for their application [125 years of internationally coordinated glacier monitoring: achievements and future challenges, 2020]. The World Glacier Monitoring Service notes that such a historically determined variety of methods for collecting and processing data complicates the comparison of glacier mass balance values obtained at different times and in different regions of the Earth [Zemp, Hoelzle, Haeberli, 2009]. Several methods are currently used to calculate the average mass balance value for a glacier: based on drawing mass balance contour lines (for example, [Carturan et al., 2016; Galos et al., 2017]), based on the vertical mass balance profile [Fountain, Vecchia, 1999], based on selecting the most representative site for installing several ablation stakes (index-site method) [Beusekom Van et al., 2010; O'Neel et al., 2019] and their numerous modifications. As a result of changing calculation methods and using various, not always the most up-to-date auxiliary data, inhomogeneities may arise in observation series, leading to systematic errors, and series from different glaciers may not be comparable [Zemp et al., 2013].

A comprehensive assessment of the errors that arise during long-term glaciological monitoring was not adopted until the end of the first decade of the 21st century [Huss, Bauder, Funk, 2009]. Currently, such an assessment serves as the basis for a statistical comparison of mass balance series obtained by two independent methods, which is part of the glaciological reanalysis methodology aimed at finding and eliminating systematic errors in observational series [Zemp et al., 2013].

Chapter 2 Glaciers of the Barentsburg area as an object of monitoring

2.1 Current state and monitoring of the Svalbard glaciation

The climate of Svalbard, located at the southwestern limit of winter sea ice and the end of the northeastern branch of the North Atlantic Current, primarily depends on ice cover trends in the surrounding seas and the prevailing directions of air mass transport [Pelt van et al., 2019]. As a consequence, climate changes are heterogeneous throughout the archipelago, and its different parts demonstrate slightly different trends in slope [Isaksen et al., 2016]. This feature determines the general patterns of spatial variability of the glacier mass balance. Nordenskiöld Land, located in the central part of the island of Spitsbergen, where the settlements of Barentsburg and Longyearbyen are located, is characterized by the lowest percentage of glaciation of the territory [Möller, Kohler, M Möller, 2018], and, at the same time, the most rapid rate of deglaciation (Figure 2.1): from 1936 to 2019 the western part of Nordenskiöld Land lost about 50% of the glaciation area [Chernov and Muravyev, 2018].

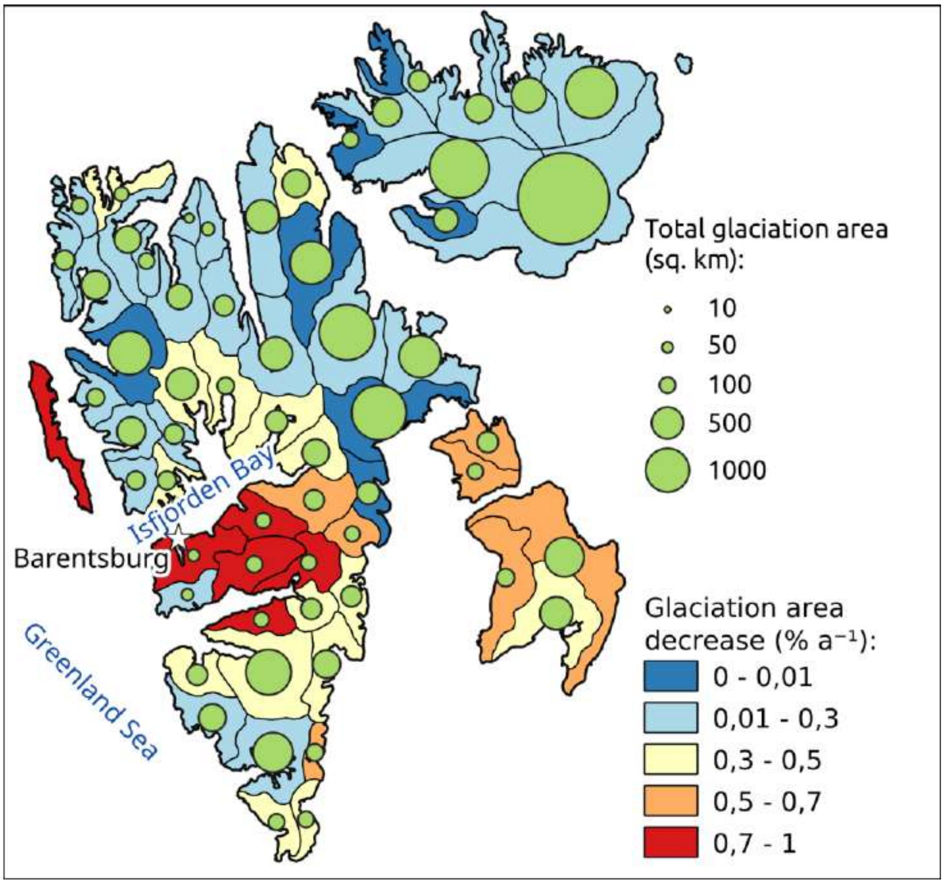


Figure 2.1 — Distribution of glaciation over the territory of Svalbard and the rates of area changes (from [Norsk Klimaservicesenter, 2019], modified by the author)

The influence of the climatic factor on the study area is enhanced due to the regional features of ocean circulation. Recent oceanographic studies [Bloshkina, Pavlov, Filchuk, 2021] and numerical modeling show that Isfjord, a wide Arctic bay washing Nordenskiöld land from the north, is more susceptible to inflows of warm Atlantic current water than other fjords of the archipelago [Nilsen et al., 2016]. This not only reduces the duration and extent of sea ice in the fjord [Muckenhuber et al., 2016] but also affects the terrestrial air temperature [Day et al., 2012]. Thus, the Barentsburg area, located close to the mouth of Isfjord, is interesting for studying the dynamics of glaciers, as it is the most exposed to modern climate changes due to its spatial location.

In addition, recent studies show that, besides the climatic factor, the speed and unevenness of the glacier mass loss on the archipelago are also influenced by their morphometry. Thus, Noël et al. [2020] draw attention to the low elevation of the Svalbard glaciers relative to other glaciated regions in the Arctic. The peak of the averaged hypsometric curve, at about 500 m above sea level, coincides today with the maximum snow line altitude in the archipelago, making approximately half of the glaciation area located in the ablation zone. Schuler et al. [2020] also revealed an empirical dependence of the mass balance of Svalbard glaciers on their size: the smaller the glacier, the more negative its mass balance. Indirectly, this shows the dependence on height: the largest glaciers are located at the highest hypsometric levels. There is no doubt that the patterns common to the entire archipelago are also valid for the glaciers of Nordenskiöld Land, where the glaciers are both low-elevated, even relative to the rest of the glaciation of Spitsbergen (Figure 2.2), and small in area, which enhances the influence of the climatic factor on their mass balance.

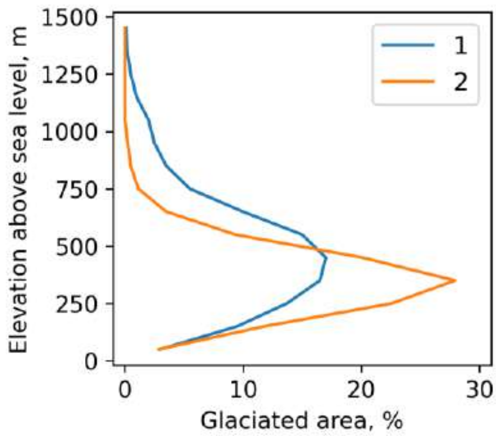
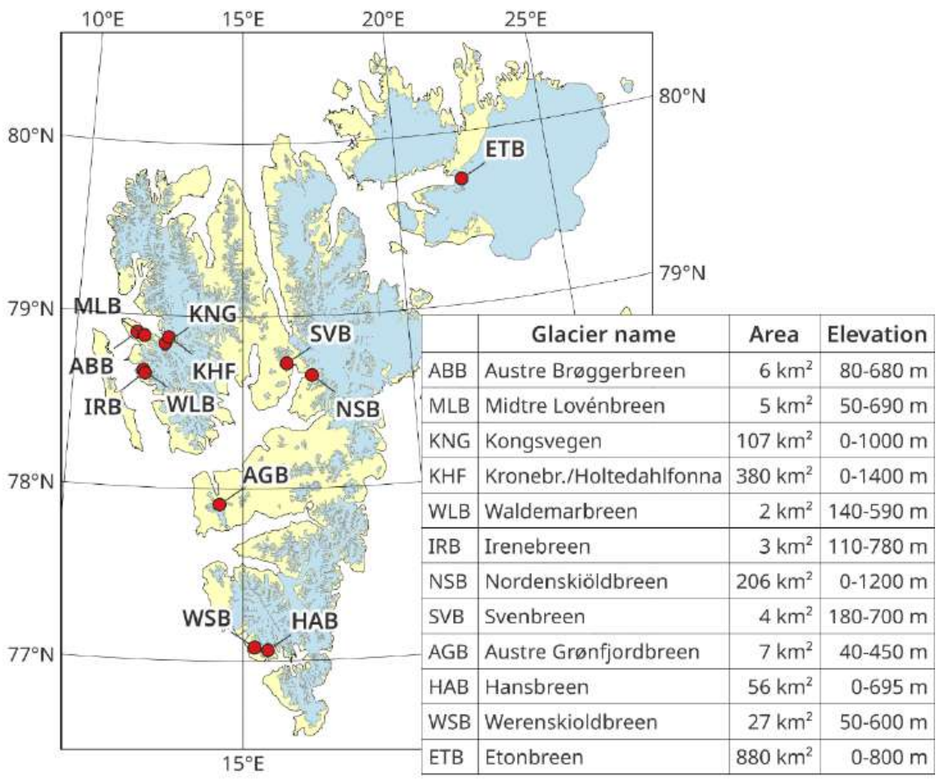


Figure 2.2 — Generalized hypsometric curves of Svalbard glaciation.
1 — the whole archipelago (from [Noël et al., 2020]), 2 — western part of the Nordenskiöld Land

Recent modeling studies of the future dynamics of Svalbard glaciation indicate that the mass of terrestrial ice on the archipelago will steadily decline. The results of mathematical modeling until 2060 [Pelt Van et al., 2021] indicate that following both boundary baseline greenhouse gas emission scenarios RCP 4.5 and 8.5, the rate of ice loss on Svalbard will accelerate, and the area of the accumulation zone could drop to zero by 2030.

Besides episodic observations and interrupted series, as of 2023, within the archipelago, there are twelve long-term, more than five years in a row, monitoring programs for direct measurements of the glacier mass balance (Figure 2.3). These programs are carried out by foreign organizations, as well as the Institute of Geography (Russian Academy of Sciences, Moscow, Russia). Monitoring of two more glaciers, discussed in detail in this work, is carried out by employees of the Arctic and Antarctic Research Institute within the framework of scientific Task 5.1.4 of Roshydromet in the area of Barentsburg. Until recently, the results of these two programs were only partially published (for example, [Terekhov et al., 2020b]) in Russian-language journals, and remained unknown abroad. This is evidenced by the fact that these results were not included in the latest regional reviews of glacier mass balance, and the Barentsburg area was represented only for three years near the Linne glacier [Pelt Van et al., 2019; Schuler et al., 2020].



	Glacier name	Area	Elevation
ABB	Austre Brøggerbreen	6 km²	80-680 m
MLB	Midtre Lovénbreen	5 km²	50-690 m
KNG	Kongsvegen	107 km²	0-1000 m
KHF	Kronebr./Holtedahlfonna	380 km²	0-1400 m
WLB	Waldemarbreen	2 km²	140-590 m
IRB	Irenebreen	3 km²	110-780 m
NSB	Nordenskiöldbreen	206 km²	0-1200 m
SVB	Svenbreen	4 km²	180-700 m
AGB	Austre Grønfjordbreen	7 km²	40-450 m
HAB	Hansbreen	56 km²	0-695 m
WSB	Werenskioldbreen	27 km²	50-600 m
ETB	Etonbreen	880 km²	0-800 m

Figure 2.3 — Glacier mass balance monitoring programmes of Svalbard: 1 — other institutions, 2 — Arctic and Antarctic Research Institute
(from [Schuler et al., 2020], modified by the author)

As for the application of the geodetic method at the single-glacier level, there were both individual mass balance measurements (see, for example, [Holmlund, 2020; Terekhov et al., 2020a]) and attempts to qualitatively compare the results obtained by the geodetic method with the glaciological one [Błaszczyk et al., 2019; Terekhov et al., 2020b], with the latter used as a control.

The Arctic and Antarctic Research Institute has accumulated a large amount of data on the mass balance of the Aldegondabreen and Vestre Grønfjordbreen glaciers, since 2002 and 2013, respectively.

The mentioned glaciers belong to the drainage area of Grønfjorden Bay and are within transport accessibility from the village of Barentsburg throughout the year, which has led to their relatively high level of study. In addition, the proximity of a permanently operating meteorological station with a long continuous series of observations makes it possible to analyze the relationship of mass balance indicators with climatic factors. The results of these studies are valuable for the global scientific community, but the data require preliminary processing to check systematic bias in the series and to assess the random errors, which is one of the objectives of this study. Comparison of mass balance values of glaciers of the archipelago without taking into account random and systematic errors can lead to incorrect interpretation of the results from the point of view of the interaction of the cryosphere with the climate system [Huss, Bauder, Funk, 2009].

In domestic practice, comparisons of the results of the glaciological and geodetic methods are found as an exception (for example, [Elagina et al., 2021]), and the ongoing monitoring of benchmark glaciers is based solely on the direct method. As a consequence, there are no works by domestic authors devoted to the adaptation and application of the reanalysis technique, as well as assessments of random and systematic errors of the obtained series; there are often no estimates of uncertainties in glacier-averaged values, for example, for the glaciers of Spitsbergen, see [Sidorova et al., 2019; Chernov et al., 2019].

The facts stated above confirm the need to organize and conduct mass balance monitoring in the central part of the island of Spitsbergen, near the town of Barentsburg. This is facilitated not only by the proximity of the base of the Russian Scientific Center on the archipelago, which provides logistics and the technical side of the work but also by the unique location of the area in terms of the combination of climatic and morphological factors. The issue of representativeness of monitoring results for the entire archipelago is discussed in detail in Chapter 4 based on comparison with other available data on the modern dynamics of Svalbard glaciation.

2.2 Study area

2.2.1 Climatic features of the study area

In the study area, there is a permanent meteorological station located in Barentsburg at an altitude of 76 m above sea level (WMO ID number 20107). The weather observation series has been available since 1934 and has not had long gaps since 1993 [Demidov et al., 2020]. The straight line distance to the edge of the Aldegondabreen and Vestre Grønfjordbreen glaciers is about 10 and 15 km, respectively (Figure 2.4).

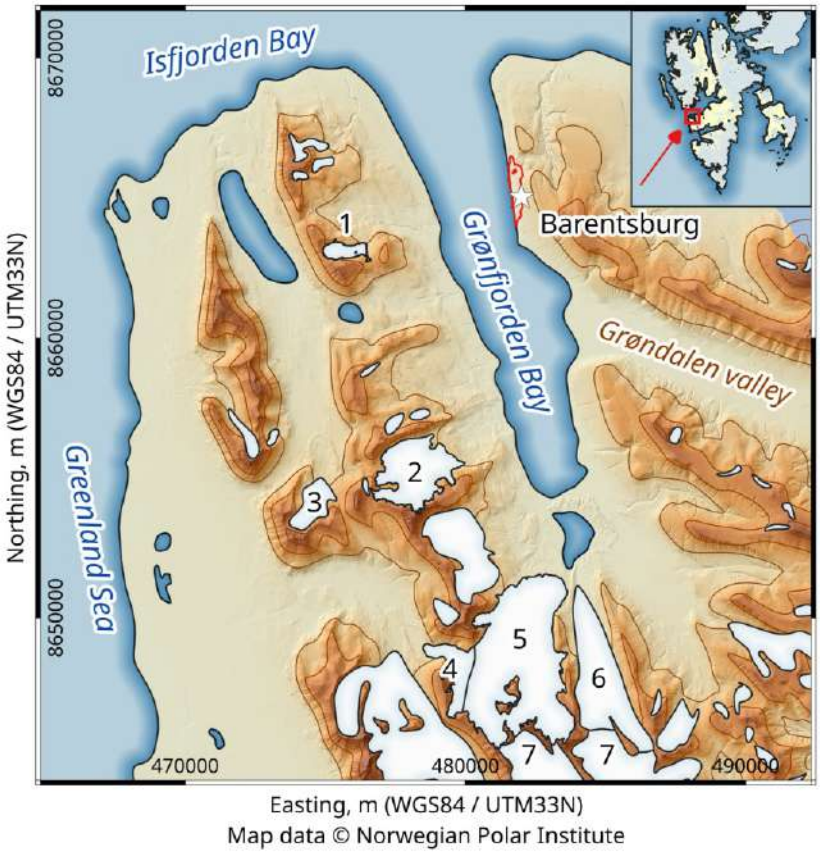


Figure 2.4 — Study site. Glaciers of the Barentsburg area: 1 — Vøringbreen, 2— Aldegondabreen, 3 — Linnébreen, 4 — Austre Dahlfonna, 5 — Vestre Grønfjordbreen, 6 — Austre Grønfjordbreen, 7 — Fridtjovbreen

The main climatic features of the study area and their trends over the last three decades of the last century (1971–2000) were summarized in the report [Norsk Klimaservicesenter, 2019]. The average annual and average summer air temperatures were 5.5°C and +4.0°C, respectively. Linear trends for air temperature were +0.26°C per decade (annual averages) and +0.16°C per decade (for summer) for the entire observation period, and increased significantly since 1971, amounting to +0.81 °C per decade (annual averages) and +0.33°C per decade (for summer). In 1971–2000 the average annual precipitation was 581 mm with maximums in October and November and no statistically significant trends.

The main climatic variables for the period of mass balance monitoring in 2001–2020 were summarized by the author based on data from the Barentsburg weather station. Since the beginning of the 21st century, four months a year have had average positive air temperatures, from June to September inclusive. Annual precipitation amounts varied from 495 to 795 mm with an average of 580 mm. The maximum precipitation occurs in December–January, and the minimum in June and July. The wind roses below (Figure 2.6) show that the distribution of prevailing wind directions is bimodal for both the warm and cold seasons. Winds from the northern direction have the greatest frequency; the second highest mode occurs in the south-southeast (SSE) or southeasterly (SE) winds. During the ablation season, SE and SSE winds are characterized by higher speeds than winds of other directions, but practically no speeds above 10 m/s are observed. In the cold season, speeds in all directions are higher than in summer.

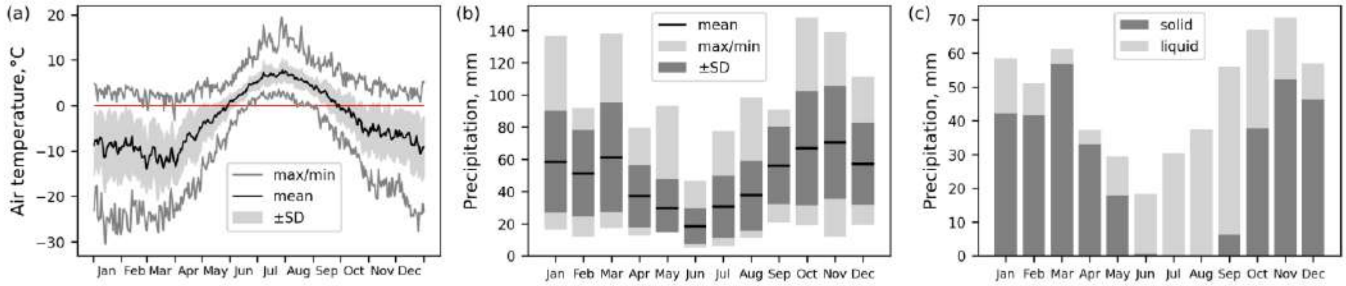


Figure 2.5 — Averaged intra-annual variability of the main climatic variables in Barentsburg (2000–2020)
a) air temperature, b) precipitation amount, c) liquid and solid precipitation.

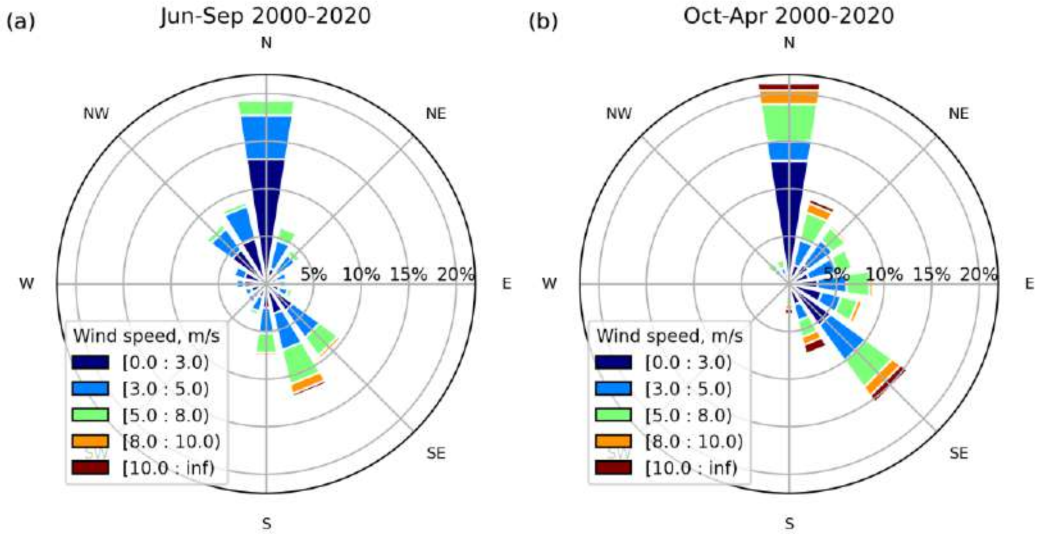


Figure 2.6 — Frequency of winds of different directions at the Barentsburg weather station in 2000–2020, as a percentage of observations
a) warm period, b) cold period

2.2.2 Physiographic description of studied glaciers

Let us describe the studied glaciers Aldegondabreen, Vestre Grønfjordbreen, Vøringbreen, and Austre Dalfonna. Regular measurements of the mass balance are being carried out on the Aldegondabreen and Vestre Grønfjordbreen glaciers. On the Austre Dalfonna and Vøringbreen glaciers, there are no direct measurements. However, the author carried out fieldwork on geodetic surveys of their surface, as well as aerial photographs (only the Vøringbreen glacier), after which the geodetic mass balance of these glaciers was calculated. The results obtained are discussed further (Chapter 4) in the context of the analysis of spatial patterns of ice ablation (Vøringbreen glacier), as well as for the periodization of long-term variability in mass balance (Austre Dalfonna glacier).

Aldegondabreen Glacier (number 3470 in the database of World Glacier Monitoring Service, WGMS) is a terrestrial-terminating mountain-valley glacier located on Nordenskiöld Land on the island of Spitsbergen. It is the second farthest glacier from Barentsburg, located approximately 10 km to the southwest, and the closest of the polythermal ones [Борисик et al., 2021a] (Figure 2.4). The glacier surface lies in the altitude range from 140 to 650 m (with 99% of the surface located below 500 m) and has an area of 5.3 km^2 (2019) [Terekhov et al., 2023]. The highest inaccessible part of the glacier is located in the south. The only tongue stretches from southwest to northeast and descends towards Grønfjorden Bay, currently not reaching its coast. The glacier was tidewater until the 1930s, retreating since then about 2.5 km [Holmlund, 2020]. According to the GPR survey of 2018, the volume of the glacier was 0.278 km^3 with a maximum ice thickness of 166 m. The greatest ice thickness was measured within the southern side of the glacier [Borisik et al., 2021b].

The Vestre Grønfjordbreen glacier is located approximately 15 km south of Barentsburg. The surface of the glacier is located in the altitude range from 50 to 600 m, its area equals 16.4±0.3 km^2 [Terekhov et al., 2022]. According to radar-sounding data [Martín-Español et al., 2015], the average and maximum ice thickness in 2010 were 107±1 and 215±5 m, respectively. The main tongue has an overall northern aspect and descends towards Grønfjorden Bay, without currently reaching its coastline. The melt waters of the glacier feed Lake Bretjorna located to the north of its terminus (also in Russian-language publications *Ledovoye*, "Icy"). One much smaller tongue descends steeply to the northeast into the neighboring valley occupied by the Austre Grønfjordbreen glacier, resting on its lateral moraine. In the eastern part of the glacier, there is an ice divide with the Austre Dalfonna glacier, which descends to the northwest into the Orustdalen valley. Until the beginning of the 2000s, the Vestre Grønfjordbreen glacier also included ice bodies located to the northwest, now completely separated from the main body and divided into two small glaciers with a total area of less than 3 km^2. In this study, following recent practice, these glaciers are not considered as part of Vestre Grønfjordbreen.

The upper reaches of Vestre Grønfjordbreen are located in two glacial cirques, separated by a nunatak. At the top of the western one, there is an ice divide with a larger surging-type Fridtjovbreen glacier, descending south towards the Van Mayen fjord [Murray et al., 2018]. Over the past decades, the surface of the Vestre Grønfjordbreen has been almost completely cleared of snow at the end of summer, with a few exceptions (2019). As a result, there is no pronounced firn zone on the glacier. According to GPR survey, the area of the firn remnants is only 3–4% of the total glacier area [Terekhov et al., 2022].

The Austre Dalfonna is a mountain-valley glacier with an area of about 2 km^2, located approximately 15 km southwest of Barentsburg. The glacier occupies an altitude range from 100 to 550 m, descending from the ice divide with the larger Vestre Grønfjordbreen glacier into the Orustdalen valley, which belongs to the Greenland Sea drainage basin. The average ice thickness as of 2019 is 82 m, and the maximum is 170 m. Based on comparison with archival remote sensing data, it is shown that over 12 balance years the glacier lost 16% of its volume, which is equivalent to a mass loss of 12.05±0.85 m w.e. [Terekhov et al., 2022].

The Vøringbreen glacier is a cirque-valley glacier on the left bank of Grønfjorden Bay, the smallest of the glaciers under consideration. Its total area in 2019 was 0.75 km^2, the altitude range was from 180 to 400 m, the average surface height was 280 m. It was showed recently that over the past century, the area of the glacier has decreased by approximately 4.5 times [Terekhov et al., 2020a].

2.3 Overview of the previous mass-balance studies

The first episodic mass balance observations in the Grønfjorden Bay area were carried out by the Institute of Geography of the USSR Academy of Sciences in the mid-1960s. Measurements were made on the Vestre Grønfjordbreen glacier in 1965/66 (WGMS 2019) and on the Vøringbreen glacier in 1966/67. Regular observations were organized a few years later, starting in 1973 on the Vøringbreen glacier closest to Barentsburg and lasting fourteen balance years [Hagen, Liestøl, 1990]. The only known measurement of the annual mass balance of the Aldegondabreen glacier in the 20th century, carried out in the 1975/76 balance year, dates back to the same time period [Guskov and Gordeychik, 1978]. After the monitoring program was curtailed in the late 1980s, mass balance measurements using the glaciological method were not carried out in the study area until the beginning of the 21st century.

An attempt to revive mass balance monitoring in this area was undertaken in the 2002/03 balance year. Thus, from the publications [Mavlyudov and Solovyanova, 2007] and [Solovyanova, Mavlyudov, 2007], the results of measurements on the Aldegondabreen glacier for 2002/03–2005/06 are known, and for the Vestre Grønfjordbreen for 2003/04–2005/06. The results of these works are analyzed in this study but are not homogenized, because the original field data remain unknown. In addition, these articles did not mention the auxiliary data necessary for calculations, on ice density, the start and end dates of balance years, methods for determining the altitude distribution, and the glacier outlines.

Since 2003/04, observations have been carried out on the Austre Grønfjordbreen glacier in the Barentsburg area [Чернов et al., 2019]. These observations do not follow the generally accepted measurement system for balance years: the start and end dates for calculating the “annual” mass balance may fall in the middle of the ablation season (July–August), as a result of which “balance years” may include either half or one and a half of the actual balance year [Elagina et al., 2021]. In addition, a comprehensive uncertainty assessment has not been carried out: only the instrumental accuracy of ablation stakes measurements was estimated [Chernov et al., 2019]. As a result, the correlation with the series from the neighboring glacier, Vestre Grønfjordbreen, was close to zero [Terekhov et al., 2022].

From the publications of foreign authors, it is clear that domestic mass balance measurements in the study area remain little known outside of Russia. For example, in a recent review study looking at long-term trends in climatic glacier mass balance, changes in snow cover, and river flows throughout

Svalbard, the Barentsburg area was represented by the only Linne glacier, which has a six-year record of observations from three ablation stakes, carried out by the NPI in 2004–2010 [Pelt Van et al., 2019].

In addition to stake measurements, there are other estimates of the mass balance of the studied glaciers. The glacier's proximity to Barentsburg and its polythermal structure have made the Aldegondabreen glacier the subject of several geophysical studies. The results of more recent detailed ground surveys, were summarized in the work of Borisik et al. [2021a]. It was found that in the period from 1999 to 2018–2019, the volume of Aldegondabreen decreased from 0.437 to 0.278 km^3 (or by 36%), while the decrease in area was 23%, from 6.94 to 5.34 km^2.

The availability of archival aerial and satellite photographs of the Aldegondabreen glacier also made it possible to calculate its mass balance in the past using photogrammetry methods. Navarro [2005] analyzed changes in glacier volume from 1936–1990, and Holmlund [2020] extended this period to 1910–2016, concluding that the glacier had decreased in volume over the last century by 79±6%, halving in length and ceasing to be tidewater.

Summary

Over the past decades, a steady increase in air temperature has been observed within the Svalbard archipelago, with the most pronounced trends for the winter season, and a consequent decrease in the solid precipitation amount [Isaksen et al., 2022]. As a result of these climate changes, the glaciers of the archipelago are losing mass, and the rate of this loss increases [Schuler et al., 2020].

The ongoing glacier monitoring programs of the archipelago are grouped into several main clusters around a few settlements. The area considered in the study, located in the vicinity of Barentsburg town, is in the central part of the island of Western Spitsbergen, where warming is most intense due to oceanic and atmospheric circulation patterns. In addition, due to the relatively low relief, the glaciers in this part of the archipelago are almost entirely below the modern snowline altitude [Noël et al., 2020]. These two factors, climatic and morphological, are associated with a rapid, record-breaking reduction in the glaciation area in this area — almost half since 1936 [Chernov and Muravyev, 2018]. Therefore, monitoring the mass balance of glaciers in the Barentsburg region is of exceptional scientific interest.

Previously known mass balance data in this area relate mainly to longer periods, on a scale of decades, since they were calculated from the results of repeated geophysical surveys (for example, [Borisik et al., 2021b]) or by the geodetic method based on archival remote sensing data and topographic maps [Holmlund, 2020; Martín-Español et al., 2015]. This feature of the available data does not allow us to make any conclusions on the short-term, interannual variability of the mass-balance values of glaciers in the study area.

Chapter 3 Glaciological reanalysis: materials and methods

3.1 Concepts and terminology used

3.1.1 Glacier mass-balance values

A review of the recent studies on the topic of mass-balance monitoring (see Chapter 1) shows that in most ongoing programs, direct measurements are carried out according to *the floating-date time system*. The main advantage of this approach over *a fixed balance year* is the ability to attribute the entire seasonal volume of ablation and accumulation to one balance year [Zemp et al., 2013]. The glacier mass balance over one balance year is usually called *the annual glacier mass balance*, abbreviated B_a. It is also common to distinguish between *seasonal mass balance values* — winter mass balance B_w and summer mass balance B_s, by dividing the year into two unequal periods [Cogley et al., 2011]. The date that separates the balance year into its "summer" and "winter" parts is most often also floating, and the seasons do not coincide with the calendar [Zemp et al., 2013]. Seasonal values are recorded in addition to the annual Ba value not on all glaciers where monitoring is carried out, since this increases the labor intensity of the work [O'Neel et al., 2019].

The floating-date time system is used in two monitoring programs of the AARI on the Spitsbergen archipelago, on the Aldegondabreen and Vestre Grønfjordbreen glaciers: the end of the balance year is selected depending on the time course of melting; the annual balance of B_a is measured using ablation stakes, and at the end of spring, before the start of snowmelt, snow surveys are carried out to deduce the winter balance of B_w. The second seasonal component, the summer B_s balance, is obtained arithmetically.

The glaciers considered in this work, due to their low-elevated AADs, have recently been below the snow line. All or almost all of the snow that fell during the winter on the Aldegondabreen, Vestre Grønfjordbreen, Austre Dalfonna, and Vøringbreen glaciers melts over the subsequent summer, and after the disappearance of the snow cover, glacial ice melts and the glaciers lose mass. From a practical point of view, this means the following: the winter balance B_w is identical to the accumulation, the annual balance B_a represents ice ablation, and the summer balance B_s is the total ablation of snow and ice.

All of the above-mentioned mass balance values can be measured in two forms: as a specific glacier mass balance, measured in meters of water equivalent (m w.e.), or as a total mass balance, equal to the change in mass of the glacier in tons. In this work, all values are reported in the form of specific values, as they are more suitable for comparison with each other and with other glaciers, being independent of the glacier area. In addition, the mass balance can be determined for the entire glacier, or it can refer to a specific point of the glacier (in Russian there are no adequate terms for *point mass* *balance* and *glacier-wide mass balance*). In this study, "glacier mass balance" is understood as the first option — a characteristic of the glacier as a whole, except for separately specified cases when the author discusses the spatial distribution of the "balance measured at a point."

For brevity's sake, the author replaces the term "glacier mass balance" with "glacier balance" or simply "balance", since other types of balances (for example, energy balance) are not considered in this study.

The author notes the insufficiency of the Russian-language conceptual apparatus in the field of mass balance research. The last "Glaciological Dictionary" in Russian was compiled about forty years ago, when IT and GIS technologies, as well as the remote sensing industry, were at a previous stage of development. Progress in methods and means of glaciological monitoring over the past decades has been reflected in the collection of English-language terminology [Cogley et al., 2011], but similar work has not yet been done for the Russian language. Therefore, the concepts enshrined in the "Glaciological Dictionary" turn out to be outdated to describe modern generally accepted approaches to mass balance monitoring, forcing the author to use literal translations of foreign terms.

3.1.2 Methods for glacier mass balance computation

In this paper, two methods for determining the mass balance of glaciers are considered and applied, direct glaciological and geodetic. Historically, these methods have become the most applicable for organizing mass balance monitoring around the world, due to acceptable labor costs and uncertainties. Consideration of other existing methods for calculating mass balance, such as hydrological, gravimetric, etc., remains beyond the scope of this study.

The glaciological method is based on measurements of ablation and accumulation directly on the surface of the glacier using poles drilled into the ice (or installed in snow or firn), which are called ablation stakes. Readings are taken as a distance from the top edge of the stake to the observed surface of the glacier. To convert readings to water equivalent units, measurements of the density of melted or accumulated material are necessary. Based on the difference in measurements on the same stake, point mass balance values are obtained, which are then inter- and extrapolated to the entire surface of the glacier. To obtain annual B_a mass balance values, it is necessary to carry out at least one measurement at the end of each balance year, however, in practice, several such measurements can be made during the melting season if the thickness of the melted layer over a certain period is greater than the depth of installation of the stakes. In this case, measurements are carried out together with their re-drilling. The number and installation pattern of ablation stakes may vary. Since the spatial distribution of mass balance over long periods most often depends on the altitude, the stakes are distributed according to elevation. They can be positioned along a longitudinal profile, which is more typical for large glaciers such as the

Vestre Grønfjordbreen, or distributed more evenly over the entire surface - as, for example, on the Aldegondabreen glacier. The stakes can also be grouped into cross-sections to estimate ice fluxes across the cross-section, which may be useful in studying frontal ablation of tidewater glaciers due to iceberg calving.

There are several ways to recompute point mass balance measurements to glacier-averaged ones. The first technique is based on calculating the vertical mass balance profile, which is the approximation based on actual measurement data. Next, the surface of the glacier is divided into elevation bins (for example, of one hundred meters of altitude), and the ratios of their area in the total area of the glacier are multiplied by the average mass balance of the corresponding altitude interval, obtained from the regression fit. The resulting weighted sum is the desired glacier-averaged specific mass balance value. Some details of the implementation of this technique may differ: different approximating equations can be used to obtain an elevation profile, and the height of the intervals can also vary. In the English-language literature, this method of calculation is called the profile method [Cogley et al., 2011].

The second way to compute the glacier-averaged value is to spatially interpolate the stake readings. In the past, this technique was used as follows: mass balance isolines were constructed between the stakes at equal intervals, then the areas enclosed between adjacent isolines were calculated using a planimeter or an overlay grid, and the desired value of the average specific balance was calculated by summation. Currently, GIS allow interpolation of measurements in digital form, obtaining a raster and subsequent summation of all its pixels. This procedure is practically equivalent to the “historical” one. In the English-language literature, this method of calculation is called the contour line method [Cogley et al., 2011]. The contour line method is not applicable for those objects where the stakes are installed with one longitudinal profile, and, in addition, it often prevents the detection of dependencies of the spatial distribution of melting with height or other morphometric quantities that are not taken into account during interpolation [Kaser, Fountain, Jansson, 2003].

There is also a third option, which is most widespread in monitoring programs in the United States. The method consists of selecting two or three of the most representative ablation stakes, that is, those where the measurements are closest to the glacier average values. The method is intended to reduce labor costs during fieldwork on large glaciers. In the English-language literature, this method is called the index-site method [O’Neel et al., 2019].

The results of calculations obtained by different methods based on the same field measurements may differ. This fact is one of the reasons for the possible heterogeneity of series during mass balance monitoring. This is especially true for long-term programs that last for decades while the technical means develop and performers change from year to year.

The geodetic method for determining mass balance is based on calculating changes in the volume of a glacier over a certain period of time by subtracting digital elevation models (DEMs), followed by converting volume units into mass units, which requires the researcher to have a density value of the glacial material composing this volume. The change in glacier volume ΔV obtained by subtracting two DEMs is equal to:

$$\Delta V = r^2 \sum_{k=1}^{k} \Delta h_k \quad (1)$$

where r is the size of the DEM pixel, k is the number of pixels involved in the calculations, Δh_k is the elevation change of the corresponding DEM pixels. In the next step, the change in glacier volume is recalculated into units of mass by multiplying by the appropriate coefficient equal to the ratio of the average density of glacial material to the density of water:

$$B = \frac{\Delta V}{S} \rho \quad (2)$$

where S is the glacier area averaged over the period under consideration, ρ is the density conversion factor.

DEMs for calculating glacier mass balance can be represented either by archival materials (for example, topographic maps) or created intentionally for a specific study. The range of methods for obtaining relief data for constructing DEMs of the surface of glaciers today is extensive and includes land surveys using optical instruments or GNSS receivers (eg [Hagen et al., 2005]); aerial or satellite imaging of the optical range with subsequent stereophotogrammetric processing (for example, [Berthier et al., 2007]); satellite SAR interferometry (for example, [Magnússon, 2005]); ground- or air-based laser (lidar) scanning [Abermann et al., 2009]; satellite laser altimetry (for example, [Moholdt et al., 2010]). For large objects, for example, ice domes, data on the surface topography may not have complete coverage, but may be represented by separate profiles, which are most often confined to the central longitudinal lines of glaciers in ground-based surveys, or to satellite orbits. In this case, when assessing errors, it is necessary to take into account spatial inter- and extrapolation of measurements, as for the glaciological method.

Comparison of the results of glaciological and geodetic methods. The author proposes to call the results obtained based on glaciological and geodetic methods glaciological and geodetic glacier mass balances, respectively [author's note: there are no adequate terms in Russian]. In Russian practice, the corresponding names indicating the method of obtaining results are not used [Alekseev et al., 1984]. However, such a division is important when interpreting the spatial distribution of balances, since in general, the point geodetic and glaciological balances are not completely identical. The point glaciological mass balance is measured relative to the glacier surface and therefore depends solely on the amount of surface melt or accumulation. The geodetic balance, which shows the change in the absolute height of the glacier, is in contrast affected by surface deformation due to ice flow, internal and basal melting/accumulation processes. Thus, introducing separate names to distinguish geodetic and glaciological balances is quite justified.

However, being integrated over the entire glacier surface, the values of the glaciological and geodetic balances must coincide according to the law of mass conservation. The glaciological reanalysis technique, aimed at finding and eliminating systematic errors in long-term monitoring series, is based on an assumption that internal and basal melt/accumulation is negligible.

3.1.3 Glaciological reanalysis methodology. Homogenization of mass-balance series

In the description of the glaciological reanalysis technique presented below, the author relies on the work of Zemp et al. [2013], according to which glaciological reanalysis is a technique for mutual comparison of glacier mass balance series obtained by the glaciological and geodetic methods for the same time intervals, aimed at identifying and eliminating bias in results.

The first stage of reanalysis of monitoring results is the procedure of *homogenization* of series, proposed in [Huss, Bauder, Funk, 2009]. From a practical point of view, concerning long-term observations, the existence of several calculation methods can lead to the fact that different performers can use different methods at different periods of time. In this case, a comparison of indicators obtained in different years would require an assessment of the accuracy and comparison of all methods used. However, in practice, it is easier to recalculate all available source data using one unified method. In this study, for all calculations of annual mass balance values, the vertical profile method was chosen, because it is exclusively suitable for the Vestre Grønfjordbreen glacier, where the stakes are installed along one altitudinal profile. In addition, calculations of glacier-averaged values require the availability of auxiliary input data, such as the outlines of the glacier and the AADs of its surface. These data often become available with a time delay, so retrospective homogenization makes it possible to use more accurate values for these parameters than were available previously.

After the homogenization of the series, the next step in the reanalysis technique involves a comprehensive assessment of the random errors of the existing mass-balance indicators. This is necessary for further comparison of the cumulative balances obtained by the two methods for similar periods of time, taking into account their confidence intervals. The assessment of errors should take into account the maximum number of factors influencing the accuracy of the calculation of balance values, and not be limited only to instrumental error, as was done, for example, in the work of Chernov et al. [2019]. As numerous studies show (for example, [Galos et al., 2017], [Klug et al., 2018]), errors arising when extrapolating point measurements to the entire glacier area are usually an order of magnitude greater than the errors in the stake readings. The sources of random errors differ not only for the values obtained by different methods, but also for the annual values obtained based on ablation stakes, and the winter values calculated from snow surveys. Section 2.4 is devoted to a comprehensive assessment of random errors for the studied glaciers.

Further, the reanalysis technique involves a statistical comparison of mass balance values obtained by two independent methods. If a comparison taking into account confidence intervals reveals a statistically significant difference between the two methods, then this difference is assumed to be a systematic error. If such a bias is detected, the authors of the methodology propose iterative calibration of the mass balance series, i.e. introducing amendments to them. Corrections must be made to the results of both the glaciological and geodetic methods — thus, both methods are treated as “equal”. The revision of the mass balance values is repeated until the systematic error is eliminated.

3.2 Overview of source data

Annual balance. The first step of the reanalysis methodology is the homogenization of the mass balance values, aimed at obtaining a homogeneous series, which requires the researcher to have at his disposal all the initial data, including field measurements, and their metadata. The source of this information was annual reports on fieldwork stored in the funds of the Arctic and Antarctic Research Institute, as well as the results of the author's measurements.

The annual mass balance of the Aldegondabreen and Vestre Grønfjordbreen glaciers is carried out using the direct glaciological method. The ablation stakes are made of wood, are 2–3 meters long, and are set up in holes drilled into the surface of the glacier with a manual-powered ice auger drill. Readings are taken from mid-July to mid-September. The frequency and number of glacier visits vary per season depending on the melt rate in a particular year. The end of the previous and the beginning of the next balance year is the date corresponding to the last observation in the season. Usually, this date is close to mid-September and is timed to coincide with a stable transition to negative air temperature, as well as the beginning of solid precipitation.

At Aldegondabreen Glacier, regular observations of ablation stakes were initiated in 2002/03, but raw data are available for only 14 balance years (2007/08 to 2009/10 and 2013/14 to 2021/22) with one three-year break, after which the stake network was changed (Figure 3.1). The stakes were redistributed over the surface to reduce their number in the most extensive and flat zone in the center of the glacier but to better cover the most elevated part, where observations had not previously been carried out. The total number of stakes was gradually reduced from 18 to 14 pieces. In the summer of 2023, two bottom stakes were lost due to glacier retreat, reducing their number to twelve.

For the Vestre Grønfjordbreen glacier, where monitoring work started much later, data from nine balance years without any gaps are available, from 2013/14 to 2021/22. Given the significant size of the glacier, the stakes are installed in one longitudinal profile, extending into the eastern cirque and covering the entire range of surface elevation (Figure 3.2). The lowest stake was lost in the summer of 2017 due to the retreat of the glacier's terminus. In some years, readings on the two upper stakes are not carried out, since they become inaccessible due to crevasses.

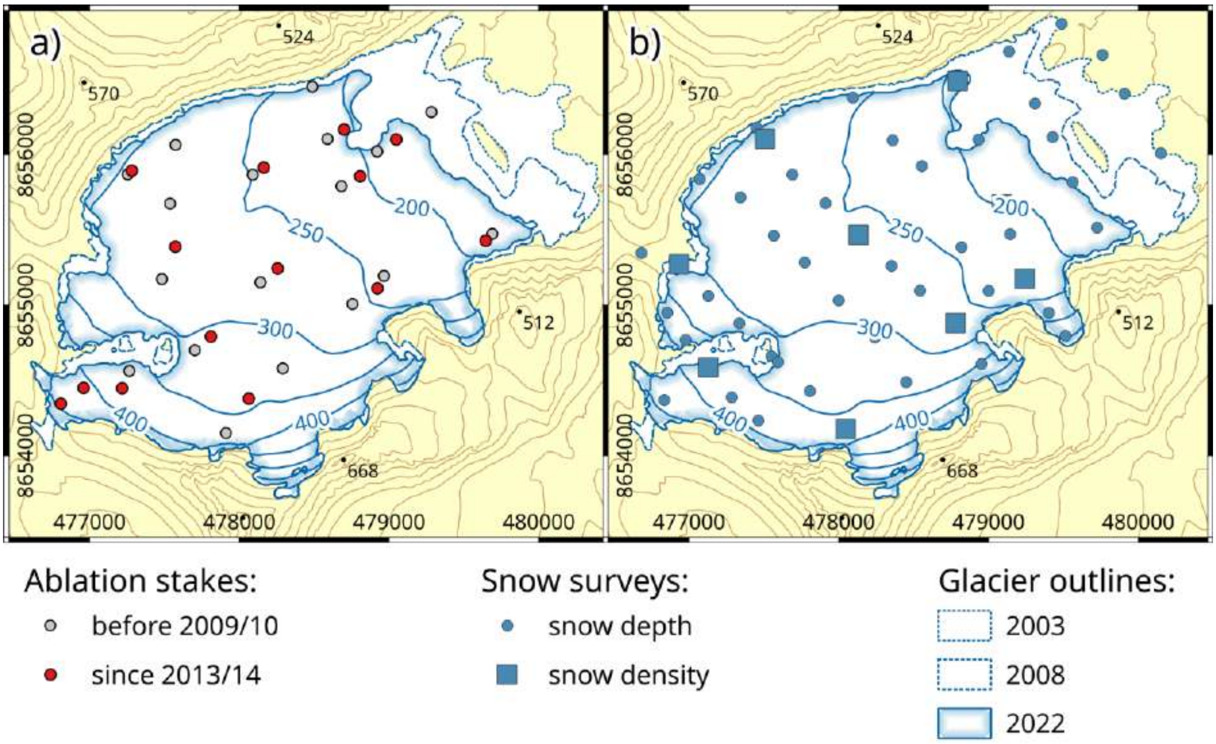


Figure 3.1 — Observational network on the Aldegondabreen glacier, and it's surface elevations a) ablation stakes, b) typical scheme of snow surveys

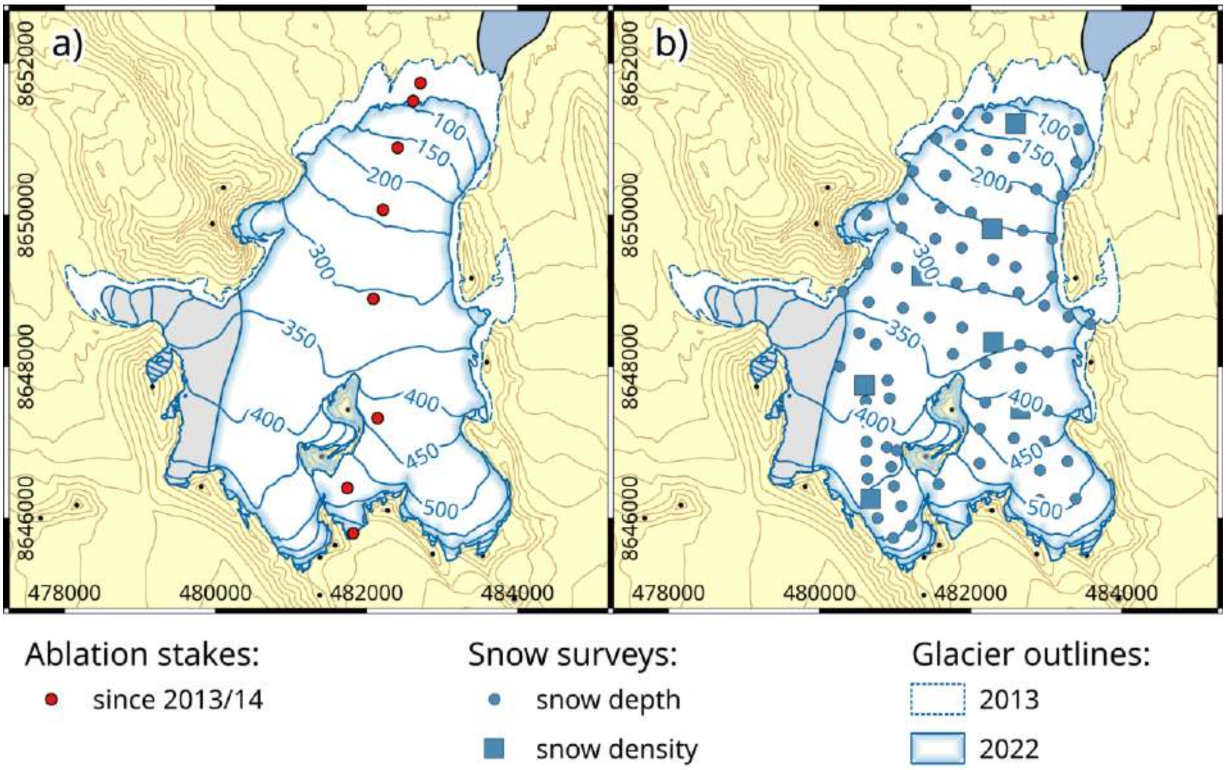


Figure 3.2 — Observational network on the Vestre Grønfjordbreen glacier, and it's surface elevations a) ablation stakes, b) typical scheme of snow surveys

Winter balance. For both glaciers, data are also available from spring snow surveys carried out from the 2001/02 balance year on the Aldegondabreen glacier, and from 2013/14 on the Vestre Grønfjordbreen glacier. Typical snow-measuring schemes for recent years, starting from 2013/14, are shown in Figures 3.1 и 3.2. Snow depth measurements are carried out on a quasi-regular grid, while the location of the pits to determine snow density varies: on the Aldegondabreen glacier they are also spatially distributed, but on the Vestre Grønfjordbreen they are carried out in a Y-shaped profile, divided in the upper reaches into eastern and western cirques.

The exact number of measurements of both snow depth and bulk density varies from year to year (Table 3.1 and Table 3.2). Potentially, this could lead to heterogeneity of the winter mass balance series, negatively affecting the analysis of the relationship with climatic variables. In addition, for several years of monitoring the exact coordinates of the snow depth sampling points were lost, and in some cases even the approximate location of these measurements is unknown. Therefore, analysis of the spatial distribution of snow cover on the surface of glaciers is possible only for part of the series.

Table 3.1 — Number of snow survey measurements on the Vestre Grønfjordbreen glacier

Balance year	Snow depth measurements, points	Measurement density, points per km^2	Pits for measuring snow density	Precise coordinates available
2013/14	Unknown		7	No (depth) / yes (pits)
2014/15	Unknown		7	No (depth) / yes (pits)
2015/16	82	5	7	Yes
2016/17	81	5	7	Yes
2017/18	82	5	7	Yes
2018/19	58	3,5	6	Yes
2019/20	23	1,4	3	Yes
2020/21	42	2,6	6	Yes

Table 3.2 — Number of snow survey measurements on the Aldegondabreen glacier

Balance year	Snow depth measurements, points	Measurement density, points per km^2	Pits for measuring snow density	Precise coordinates available
2001/02	Unknown		8	No, layout unknown
2002/03	Unknown		Unknown	No, two transsects across the glacier
2003/04	60	9,2	Unknown	Yes (depth) / no (density)
2004/05	86	13,4	Unknown	No, layout unknown
2005/06	9 (in pits only)	1,4	9	No
2006/07	45	7,2	6	Yes
2007/08	32	5,2	9	Yes
2008/09	47	7,8	9	Yes
2009/10	50	8,4	9	Yes
2010/11	Unknown		9	Yes
2011/12	39	6,7	3	Yes
2012/13	No observations			
2013/14	35	6,1	9	No
2014/15	53	9,3	9	No
2015/16	43	7,6	9	Yes
2016/17	42	7,5	9	Yes
2017/18	42	7,6	9	Yes
2018/19	37	6,8	9	Yes
2019/20	19	3,6	2	Yes
2020/21	43	7,8	9	Yes
2021/22	42	7,8	9	Yes

Geodetic balance. To calculate the geodetic mass balance of glaciers, the results of GNSS surveys made by the author were used. Surveys were carried out not only on the glaciated surfaces, but also in their immediate vicinity, to adjust the vertical reference of other used DEMs.

The GNSS surveys were carried out on August 7–8 and 13, 2018 on the Aldegondabreen glacier and in the second half of August 2019 on the Vestre Grønfjordbreen glacier. The surveys were made using kinematic method with post-processing. Multi-channel satellite receivers Sokkia GRX1 and GRX2 were used. The survey routes are shown in Figure 3.3. Work on the Vestre Grønfjordbreen glacier, due to its larger area, took a long time, therefore, to minimize the effects of ice melting and seamlessly combine the results for different days, the survey was started from the upper reaches, where the ablation ceased, to the lower reaches, obtaining the position of the glacier terminus at the end ablation season.

Based on the results of the GNSS survey, after preliminary filtering of all points with an error in altitude coordinates more than 10 cm, digital elevation models were created. For interpolation, the Thin Plate Spline algorithm, implemented in SAGA GIS, was used.

To compute changes in volume for each of the glaciers, some more DEMs for the past moments are also needed. During the organization of mass balance monitoring, no more surveys were carried out. Therefore, the author was limited to archival remote sensing materials from third-party sources.

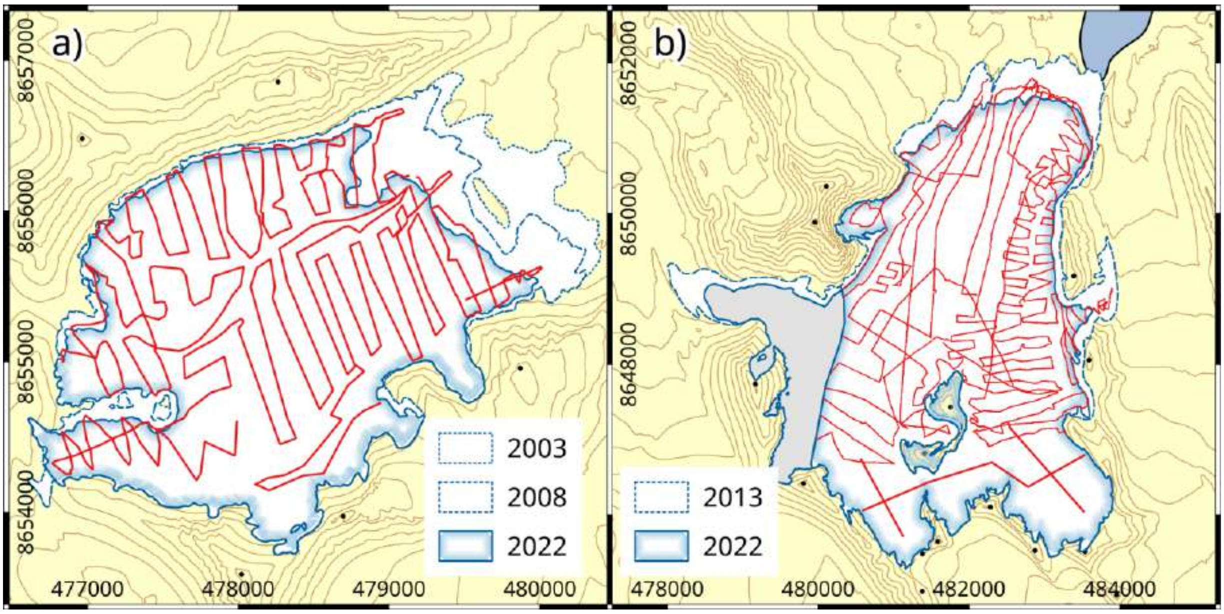


Figure 3.3 — Routes of GNSS survey carried out by the author on the glaciers: a) Aldegondabreen (2018), b) Vestre Grønfjordbreen (2019)

ArcticDEM is a multi-temporal DEM with a spatial resolution of 2 m, built from stereo pairs of super-resolution images acquired by Maxar's (formerly DigitalGlobe) WorldView and GeoEye satellites. Recently, the ArcticDEM dataset for the period from 2012 to 2017 became available. Since the initial photography was carried out in the visible range of the electromagnetic spectrum, the choice of DEM fragments (so-called “strips”) for the study area is greatly limited by the presence of clouds at the time of the satellites’ flight. Thus, the only fragment that completely represents the surface of Vestre Grønfjordbreen without large gaps was the DEM for July 20, 2015, which almost completely covers the monitoring period on this glacier. For the Aldegondabreen glacier, a fragment of ArcticDEM was selected for August 17, 2013. To extend the calculations of the geodetic balance of Aldegonda further into the past, the author also selected another DEM with a spatial resolution of 5 m, built based on aerial photography from 2008 and representing part of the S0 Terrengmodell data set of the Norwegian Polar Institute.

Thus, the DEMs available for glaciers form one time interval for calculating the geodetic mass balance for the Vestre Grønfjordbreen glacier and two for the Aldegondabreen glacier. These calculation intervals in all three cases are close to five years, as recommended in the study of Zemp et al. [2013], devoted to the issues of mutual comparison of the results of glaciological and geodetic methods.

3.3 Mass balance computation

3.3.1 Homogenization of annual mass balance values

Obtaining the glacier's average annual mass balance (B_a), the main variable based on which the interannual variability is analyzed and compared with other glaciers requires intermediate calculations based on measurements from individual ablation strips [Zemp et al., 2013]. Even though some of the average glacier values had already been calculated, including in expedition reports, the author recomputed all available initial data using a unified methodology, using the most relevant auxiliary data at the time of the study (the outlines of the glacier, the AADs, the altitudes of the ablation stakes). Such a homogenization [Huss, Bauder, Funk, 2009], included the following procedures: 1) clarification of the heights of ablation stakes, 2) clarification of the contours of glaciers, 3) clarification of the AADs of the glacier surface, 4) inter- and extrapolation measurements of point mass balance values over the entire area of glaciers. Let's look at performing homogenization step by step.

Precise geopositioning of ablation stakes. The altitudes of the ablation stakes on the Aldegondabreen and Vestre Gronfjordbreen glaciers were obtained with centimeter accuracy by the author at the end of the 2018 ablation season using the GNSS static method with subsequent post-processing. When compared with the approximate altitudes that were obtained in 2013 by a Garmin navigator and subsequently used in expedition reports, it was found that: a) for the majority of the stakes (12 out of 14) on the Aldegondabreen glacier, their elevations were overestimated by a few meters to a few tens meters; b) the maximum differences in elevation were 30 and +37 meters on the Aldegondabreen glacier (stakes #10 and #15, respectively); c) the elevations of all stakes on the Vestre Grønfjordbreen glacier were underestimated by 9 to 16 meters (Figure 3.4). Note that the identified errors have different signs and therefore cannot be explained by differences in the elevation systems or by the glacier surface lowering due to ice melt. Such differences may be due to the low altitude accuracy of hand-held navigators [Antonovich, 2005] and may contribute to a systematic error in glacier-averaged mass balance. The altitudes of the ablation stakes of the previous observational network that existed on Aldegondabreen before the break in observations (that is, before 2010/11), were determined from the S0 Terrengmodell DEM based on their plan coordinates, which, in general, are determined more accurately by a non-professional navigator.

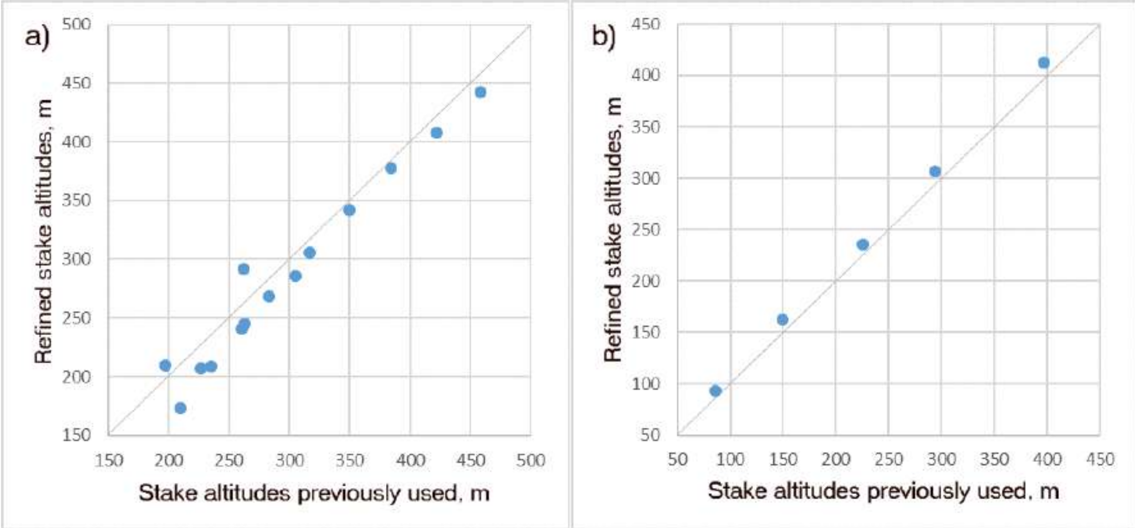


Figure 3.4 — Comparison of the altitudes of the ablation stakes previously used in the reports of the Arctic and Antarctic Research Institute and their exact altitudes obtained by the author
а) Aldegondabreen, б) Vestre Grønfjordbreen

Glacier outlines. The contours of glaciers at moments of time corresponding to the DEMs available to the author were necessary to clarify the altitudinal distribution of the surface. Therefore, outlines for the Aldegondabreen glacier were determined for 2008, 2013, and 2018, and for the Vestre Grønfjordbreen glacier — for 2015 and 2019.

The earliest outline of the Aldegondabreen glacier, as of 2008, was taken by the author from digital topographic maps of TopoSvalbard at a hundred thousandth scale, the largest available. The maps were compiled by the Norwegian Polar Institute based on aerial photography. For time points in 2013 and 2015, corresponding to fragments of the ArcticDEM DEM, the glacier outlines were identified from these fragments themselves. Although the author does not have the original ultra-high resolution imagery at his disposal, the surface of the glaciers on the DEM differs sharply in its roughness from the surrounding terrain. To calculate the roughness, the Terrain Ruggedness algorithm of the open GIS QGIS was used. Glacier contours for 2018 and 2019 are a combination of the author's GNSS survey and, in inaccessible upper reaches, the results of visual interpretation of Sentinel-2 satellite images with a resolution of 10 m per pixel.

The spatial position of the ice divide separating Vestre Grønfjordbreen from the neighboring Austre Dalfonna glacier was taken by the author from the latest version of the Svalbard glacier inventory [Nuth et al., 2013] and assumed constant over time.

Clarification of the AADs of glaciers. Until recently, the most relevant source on the surface topography of the studied glaciers was the S0 Terrengmodell DEM, created by the Norwegian Polar Institute based on aerial photography in 2008. However, now more relevant sources of elevation data: the ArcticDEM, consisting of multi-temporal fragments, built on the basis of ultra-high resolution satellite imagery (Noh and Howat, 2015; Porter et al., 2018), as well as the results of GNSS survey carried out by the author. This makes it possible to retrospectively clarify the altitudinal distributions of glaciers and use the most relevant data for each year for calculations.

After intersecting the glacier outlines with the elevation contour lines constructed from the selected DEMs, five AADs were obtained, three for Aldegondabreen and two for Vestre Grønfjordbreen. As a result of the analysis of temporal changes in altitude distributions shown in Figure 3.5, the following facts were established for the monitoring period. First, for the Aldegondabreen glacier, the percentage of areas in lower altitudinal intervals increases. The greatest change is observed in the central part of the glacier, in the altitude ranges of 250–300 m (+10% per ten years) and 300–350 m (minus 8% per ten years). Taking such changes into account, the altitudinal distribution for the Aldegondabreen glacier was interpolated for each of the balance years. Secondly, for the Vestre Grønfjordbreen glacier, the percentage of area ratios in elevation bins does not vary over time, despite the obvious retreat of the glacier terminus (up to 200 m for the main snout). The largest identified change was only +1.5%, which cannot be confidently attributed to real changes in the altitudinal structure since it is indistinguishable from the error in the mutual reference of two DEMs at different times. Therefore, it was decided to use the AAD averaged between 2015 and 2019 for further calculations, assuming the error in determining the ratio of each interval to be 2% of the total area.

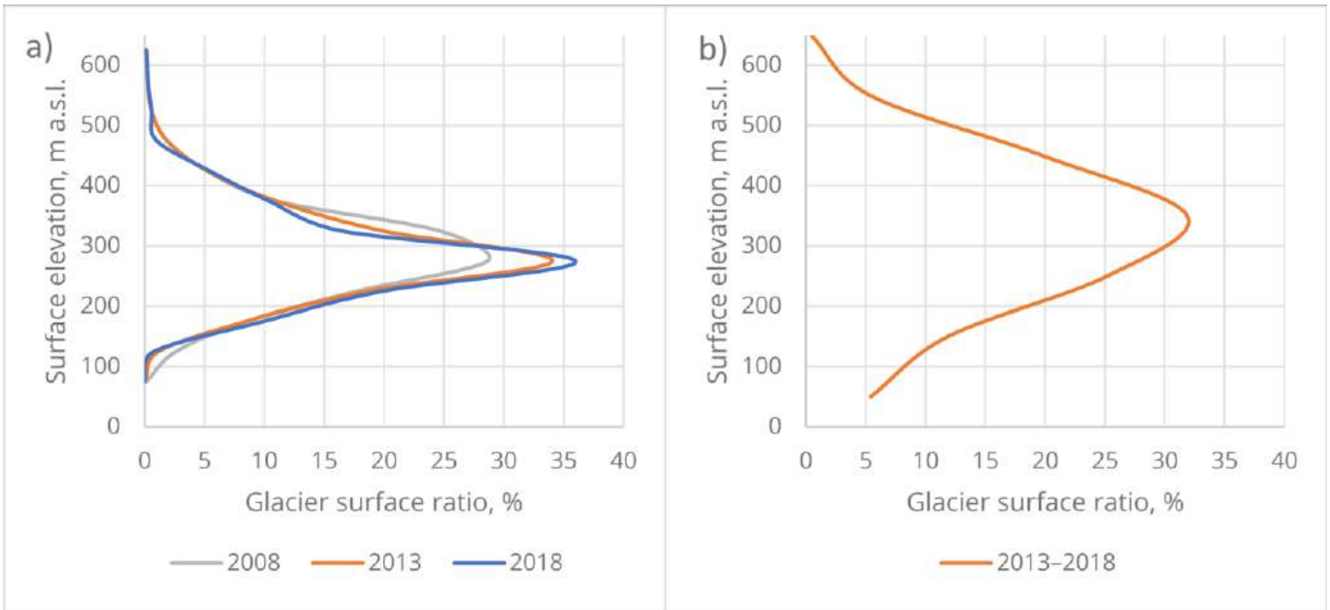


Figure 3.5 — Changes in the area–altitude distributions of the glaciers: a) Aldegondabreen, 2008–2018; б) Vestre Grønfjordbreen, 2013–2018

Glacier-averaged annual mass balance values. When applying the vertical profile method, fifty-meter elevation bins were used for the Aldegondabreen glacier and one-hundred-meter elevation intervals for the Vestre Grønfjordbreen glacier. The choice was dictated by the number of ablation stakes: if, for example, fifty-meter intervals for Vestre Grønfjordbreen are selected, then in most of the intervals there will not be a single actual measurement. Secondly, the shape of the curve approximating the altitudinal mass balance profile can also be different [Oerlemans, 2008]. A linear relationship was used; when passing through zero, the balance was assumed being zero:

$$\begin{cases} b = ah + c & if < 0 \\ b = 0 & if\ b \geq 0 \end{cases} \quad (3)$$

The use of a piecewise given function is justified for two reasons: the percentage of the area in the upper reaches that is covered with snow at the end of the ablation season is small and amounts to no more than a few percent of the total area of glaciers; There are no snow surveys at the end of the ablation season, so it is not possible to determine the actual amount of remaining snow. This feature of the calculations is one possible source of systematic error, making the annual mass balance somewhat more negative than it actually is.

The choice of the form of dependence remains debatable. In some years, the use of convex or concave polynomial functions may provide a better coefficient of determination. However, for functions other than linear, it is difficult to justify the physical meaning of the coefficients, and a greater or lesser spread of the measured values from the approximating curve is in any case taken into account when assessing the error of the annual value. Therefore, formulas (3) were chosen to unify the calculations.

Ice density. Ice melt readings are taken from ablation stakes in centimeters. To convert these readings into units of water equivalent it is necessary to multiply the measured values by the ice density. No field measurements of density were carried out directly on the glaciers under consideration. To convert units, the author used the value assumed to be 850±60 kg/m^3. It was shown by [Huss, 2013] that this value, covering a larger range of densities of the material composing the glacier, from firn to congelation ice, is suitable for most glaciers. For comparison, in glaciological observations on the Austre Grønfjordbreen glacier, a value of 880 kg/m^3 is used without taking into account the error [Chernov et al., 2019].

Comparison of results before and after homogenization. A comparison of how the annual mass balance values changed after the homogenization procedure is shown in Table 3.3. The table contains results only for some years of monitoring. Firstly, for several years the glacier-averaged values were calculated for the first time since these values had not been calculated in the expedition reports. Secondly, measurements on the Aldegondabreen glacier before 2007/08 cannot be homogenized due to the loss of source data. From the presented comparison it is clear that the absolute value of the differences is mainly a few decimeters of water equivalent. Consequently, the error in calculating the glacier-averaged balances cannot be lower than a few decimeters, and the indication of the mass balance with an accuracy of up to a millimeter w.e., used in several domestic articles concerning the mass balance of Svalbard glaciers (see, for example, [Sidorova et al., 2019; Chernov et al., 2019]), has excessive accuracy.

Table 3.3 — Comparison of the annual mass balance of the Aldegondabreen and Vestre Grønfjordbreen glaciers before and after the homogenization procedure

	Annual mass balance value, m w. e.					
	Aldegondabreen			Vestre Grønfjordbreen		
Balace year	Before homogenizat ion	After homogenizat ion	Difference	Before homogenizat ion	After homogenizat ion	Difference
2007/08	–0,558	–0,32±0,14	+0,24			
2008/09	–1,54	–0,58±0,15	+0,96			
2009/10	–0,34	–0,24±0,14	+0,10			
…			No observations			
2013/14	–0,836	–0,67±0,16	+0,166	—	–0,60±0,18	—
2014/15	–1,159	–1,03±0,23	+0,129	—	–0,88±0,24	—
2015/16	–2,048	–1,88±0,25	+0,168	–1,256	–1,19±0,21	–0,08
2016/17	–1,959	–1,89±0,25	+0,069	–1,613	–1,92±0,23	+0,24
2017/18	–1,835	–1,70±0,22	+0,135	–1,287	–1,19±0,22	–0,02

3.3.2 Homogenization of winter mass balance values

The winter balance B_w was calculated as the product of its two components — the area-averaged snow depth and its bulk density. In turn, the average snow depth is determined as the arithmetic mean of all survey measurements on the glacier surface. Since snow depth measurements are carried out on glaciers on a quasi-regular grid, this procedure is practically equivalent to linear interpolation of measurements. The average density is also calculated as the arithmetic mean between all pits within the glacier.

The approach for calculating the winter balance and its elements, based on dividing the glacier into altitudinal intervals, is not used intentionally: it is further shown that the spatial distributions of snow depth and density do not demonstrate stable dependencies on altitude. Interpolation of values over the glacier surface is also not used since data on the spatial position of depth measurements was partially lost. In this case, the only calculation method that allows maintaining uniformity for all years of monitoring is arithmetic averaging of measurements.

3.3.3 Geodetic mass balance computation

In the case of the glaciers under consideration, the geodetic mass balance is calculated as the product of the area-averaged surface lowering and the ice density. The area-average surface lowering is found by dividing the change in glacier volume ΔV over a period of time by the glacier area corresponding to the beginning of the period. The volume change is calculated by subtracting two DEMs at different times, and its equation has the following form [Zemp et al., 2013]:

$$\Delta V = r^2 \sum \Delta_{hk} \tag{4}$$

where r is the pixel size of the DEM, k is the number of pixels involved in the calculations, and Δ_{hk} is the change in height in the corresponding pixels. To convert volume change to mass balance, the following equation was used:

$$B = \frac{\Delta V}{S} \rho \tag{5}$$

where ΔV is the change in glacier volume, S is the average area of the glacier between the beginning and end of the calculation interval, and ρ is the density value, the choice of which was justified earlier and assumed as 850±60 kg/m^3.

Before starting the calculations, all DEMs obtained from remote sensing data were preprocessed. Firstly, using the DTM Filter algorithm implemented in the SAGA GIS GIS, obvious outliers, which were artifacts of stereophotogrammetric processing, were eliminated from the models. Secondly, small gaps of missing data a few pixels in size, caused by the presence of cloudiness or extremely contrasting shadows/highlights within the photographic images, were interpolated using the Thin Plate Spline algorithm.

Preprocessing also included a stage without which a correct calculation of changes in the volume of a glacier is impossible, called co-registration of DEMs, which consists of eliminating their systematic vertical bias, i.e., it is aimed at *eliminating systematic errors* in the calculations of changes in volume.

3.4 Uncertainty assessment

3.4.1 General information on uncertainties

Uncertainty propagation. In assessing the random error in determining the mass-balance values of the studied glaciers, well-known formulas for uncertainty propagation are used. The basic equation for the general case, from which all formulas in the paragraphs below are derived, is the following: the error σ_f of calculating the function *f* from several approximate numbers $x_1, x_2 \ldots x_n$ is equal to the root of the sum of the products of the errors of each variable and the partial derivative of the function *f'* with respect to this variable [Fornasini, 2008]:

$$\sigma_{f(x1,x2\ldots xn)} = \sqrt{\sigma_{x1}^2 f_{x1}'^2 + \sigma_{x2}^2 f_{x2}'^2 + \cdots + \sigma_{xn}^2 f_{xn}'^2} \tag{6}$$

Formula (6) shows how knowing the error of each of the parameters involved in the calculations separately, one can obtain the total error of the desired mass-balance value.

Accumulation of errors in data series. Errors that arise when calculating mass balance values can be both systematic and random. The accumulation of random and systematic errors occurs in different ways. The values of random errors over a certain period can be calculated using known rules for the propagation of errors. If b_1, b_2 … b_n are the annual values of the glacier mass balance, where n is the serial number of the year of observation and σ_1, σ_2 … σ_n are the corresponding standard deviations of these indicators, the total standard deviation of the entire series will be equal to:

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \cdots + \sigma_n^2}$$

In a case when standard deviations of the annual mass balance values are approximately equal, the formula simplifies to the following:

$$\sigma = \sigma_i \sqrt{n}$$

Thus, the random error in the mass balance series accumulates proportionally to the square root of the number of years of observations. The law of accumulation for an absolute *systematic error* has a different form:

$$\delta = \sum_1^n \delta_i$$

where δ_i is the systematic error of the annual mass value. If we assume it is approximately equal for each of the years under consideration, the formula may be reduced to the following form:

$$\delta = \delta_i n$$

Thus, systematic errors, unlike random ones, accumulate proportionally to the number of years, not their squared root. If random and systematic errors are equal in magnitude, the latter accumulate in the observation series more rapidly. Therefore, identifying and quantifying systematic bias in observational series is an important topic.

The peculiarity of assessing systematic bias is that it cannot be carried out based on the observation data themselves. It requires a mutual comparison of the results obtained by two independent methods using different source data. For the glaciological method, the role of a similar coupled method is played by the geodetic one. Since glaciological and geodetic methods use different sets of initial data, they inherit errors from different sources. This makes it possible to identify and evaluate systematic error (or show its absence) based on an intercomparison of the results during the reanalysis.

3.4.2 Uncertainty assessment for annual mass balance

A comprehensive uncertainty assessment for the annual mass balance value B_a, which has not yet been carried out in the Barentsburg area (see, for example [Elagina et al., 2021; Hagen, Liestøl, 1990; Sidorova et al., 2019; Chernov et al., 2019]), is a complicated task. Following the methodology proposed by Galos et al. [2017], three primary sources of error in the glacier-average B_a were taken into account: (1) error associated with the limited representativeness of the ablation stake, σ_{point}; (2) the error of the regression model used in the vertical profile method, σ_{model}; and (3) error in determining the areas of altitudinal bins, σ_{WZ}. The values of these three components cannot be quantitatively characterized based on the measurements themselves. Their assessment requires expert knowledge of the study glaciers and some additional measurements [Andreassen et al., 2016; Klug et al., 2018].

Zemp et al. [2013] also proposed to take into account another factor influencing the total error, namely the random error of a single stake reading, induced by the stake tilt, floating or sinking into the snow, or underestimation of superimposed ice. The author neglects this uncertainty since recent studies show that it is much smaller than other factors listed above. Thus, Galos and co-authors [2017] concluded that such an error is 2–3 cm. Chernov and co-authors [Chernov et al., 2019] gave a similar value, taking the measurement error on the Austre Grønfjordbreen glacier to be 2 cm and considering the same value to be a total uncertainty of B_a.

For convenience of calculations, we begin by estimating the mass balance error in *ice equivalent* units, introducing the uncertainty of ice density at the very end of the procedure. This can be done due to the peculiarity of the studied glaciers: their mass loss occurs almost entirely due to the melting of glacial ice, as a result of which a uniform density value can be attributed for all altitudinal bins — the density of glacial ice. Therefore, the uncertainty of this value can be "bracketed" and applied in the final step. From the formula for determining the average mass balance for a glacier, following the known rules for the propagation of errors for the product of two independent variables (6), we obtain:

$$B = \sum_z \frac{S_z}{S} b_z = \sum_z W_z B_z \tag{7}$$

where z is the serial number of the altitudinal bin, S_Z/S is the ratio of the area of that altitudinal bin to the total glacier area, which, for brevity, may be replaced by the dimensionless "weight" of W_Z; b_Z is the specific mass balance within z-th altitude interval measured in ice equivalent units. Then, the total uncertainty of the glacier-averaged mass balance equals to:

$$\sigma_B^2 = \sum_z b_z^2 \sigma_{wz}^2 + \sum_z W_z^2 \sigma_{bz}^2 \tag{8}$$

The error of the "weight" of each altitudinal bin σ_{WZ} cannot be determined directly, and was assumed for all altitude ranges as 0.02 (that is, 2% of the entire glacier surface). This value was not chosen randomly: when considering temporal changes in the AADs of the Vestre Grønfjordbreen glacier according to two DEMs, for 2015 and 2019, it was found that there are practically no differences in the areas of all altitudinal zones, not exceeding 1.5%. Rounded up to the nearest whole percent, this value was taken as the σ_{WZ} for both glaciers.

The error σ_{bz} of the average annual balance in each altitudinal bin was obtained as the root of the sum of the squares of two components: 1) the error of spatial inter- and extrapolation of point measurements to the entire glacier and 2) the heterogeneity of the mass balance distribution over the glacier surface [Galos et al., 2017]. The first component was defined as the standard deviation of actual measurements on ablation stakes in each altitudinal bin from the linear fit of the vertical mass balance profile. This value varies both by year and by altitudinal intervals, varying from 0.06 to 0.36 m (ice equivalent). The assessment of the second component, the error of the heterogeneity of the surface ablation, or the limited representativeness of ablation stakes, required the use of additional field measurements. During the GNSS survey, 30 and 40 (Aldegondabreen and Vestre Grønfjordbreen glaciers, respectively) additional points that did not participate in the construction of the DEM, located between the main survey profiles, were captured on the surface of the glaciers. Comparison of the actual heights of these points with the resulting DEMs is characterized by a normalized median deviation (NMAD) value of 0.32 and 0.30 m for the Aldegondabreen and Vestre Grønfjordbreen glaciers, respectively. To some approximation, these values can be considered a measure of the surface roughness, indirectly characterizing the heterogeneity of ice melting.

Finally, to translate the result to units of water equivalent, we introduce the density uncertainty. It is assumed that in all altitudinal bins, the loss of mass by the glaciers under consideration occurs due to the melting of material of the uniform density — glacial ice. Therefore, the balance is in units of w. e. is calculated for all ablation stakes by multiplying the measured ice melt B by its estimated density ρ:

$$B_{we} = \rho B, \tag{9}$$

Therefore, the final step in estimating the balance error will be as follows:

$$\sigma_{Bwe} = B\sqrt{\left(\frac{\sigma_\rho}{\rho}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2} \tag{10}$$

As for the quantitative assessment or proof of the absence of systematic error in the annual balance series, these are based on comparison with the results obtained by the geodetic method for similar time intervals. The results of this comparison are discussed in 4.4.1 Cumulative glaciological mass balance and the intercomparison with the geodetic one.

3.4.3 Uncertainty assessment for winter mass balance

The winter mass balance B_w is calculated as the product of its two components, the average glacier snow depth d and the bulk density ρ, therefore, the error σ_{Bw} can be found using the formula:

$$\sigma_{Bw} = B_w\sqrt{\left(\frac{\sigma_\rho}{\rho}\right)^2 + \left(\frac{\sigma_d}{d}\right)^2} \tag{11}$$

Equation (11) requires knowing the uncertainties of determining the height of the snow cover and its bulk density, σ_d and σ_ρ, respectively. Let us next consider the process of estimating these two quantities.

As was shown earlier in Tables 3.2 and 3.1, the number of measurement points during snow surveys and their location varied from year to year. It is known that the positioning of measurements across the glacier certainly affects the final result [Galos et al., 2017]. Previously, researchers have proposed several approaches for the uncertainty assessment: starting from the most simplistic, when sample standard deviations are assumed as the uncertainty, and complex field experiments, during which fieldwork was carried out along different routes and by different performers for subsequent comparison [Pulwicki et al., 2018]. There is no possibility of repeating such field experiments on the glaciers under consideration, so it was necessary to estimate the magnitude of errors statistically, based on existing data. To solve this problem, the bootstrap method was used [Efron, 1979], which allowed us to derive an empirical pattern showing how the scheme of snow depth measurements affects the error in determining the average value for the glacier.

The bootstrap-based algorithm was constructed as follows: by interpolating the available height measurements, an empirical distribution of this value over the glacier surface was obtained, in the form of several rasters of snow depth. Then, pseudo-random samples of snow depth values were generated from the rasters, with a different number of points, as if an observer was conducting a snow survey with a different number of measurements. For each number of points, a similar procedure was repeated 5000 times, and the result obtained at each iteration was compared with the raster average, taking the latter as the true distribution of the value. The standard deviation from the “true” result calculated from 5000 values was assumed to be the desired uncertainty for a given number of measurements. The initial hypothesis is as follows: bootstrap allows us to obtain empirical curves of the dependence of the uncertainty on the density of the measurement grid.

The following is a more verbose description of the algorithm, containing technical details that allow it to be easily reproduced [Terekhov, Vasilevich, Prokhorova, 2023]:

1) The first step is to interpolate the snow depth raster based on actual snow survey data. The cell size of two meters is the limit, since the accuracy of a GNSS navigator, which determines the coordinates of measurements in the field, does not allow marking the position of points on the map with better accuracy.

2) The number of pseudo-sample points based on which empirical curves will be constructed is determined. The maximum number of points at which snow depths on the Aldegondabreen glacier have ever been measured and for which their coordinates have been preserved was 60. The study of pseudo-samples that greatly exceed this number in volume does not make much sense, since the reference raster

interpolated based on actual measurements will not reflect the spatial variability of the value with such detail.

3) Based on the glacier outlines, its area S is determined. For a uniform distribution of n points over the surface, each of them must have a neighborhood with an area of *S/n*, which is a square of size $\sqrt{S/_n}$. For example, to distribute 50 points across the surface of the Aldegondabreen glacier, which was 5.54 km^2 in 2018, each point would have to be a square with a side of about 330 m.

4) The purpose of placing points on the surface is not to obtain a strictly regular network with equal spacing, since in real snow surveys it is not possible to adhere to such a scheme. Therefore, inside squares of size $\sqrt{S/_n}$, the "measurement" points should be shifted randomly relative to the centers, which ensures the pseudo-random nature of each sample and models possible changes in survey routes. To ensure that the points remain inside "their" squares, making the network more or less regular, we set the standard deviation of the random shift relative to the neighborhood center equal to ⅕ of half the side of the square. That is, for the example with Aldegondabreen, the maximum shift radius should be no more than 165 m, which means that it is advisable to take the standard deviation equal to 33 m.

5) The process of placing points according to the above instruction should be repeated five thousand times. When extracting snow height values from a raster, a random error is introduced at each point, simulating the error of a single measurement associated with the technical side of measuring depths (for example, with the tilt of an avalanche probe). The standard deviation for the random "measurement" error was assumed to be 2 cm [Réveillet et al., 2017]. Next, at each of the five thousand iterations, the average snow depth is calculated at the pseudo-sampling points and compared with its average value from the reference raster. From five thousand attempts, the root mean square error is calculated, which is accepted as the desired uncertainty for a given number of measurements.

6) Since the Aldegondabreen glacier, from which the empirical curves were calculated, decreases in the area over time, the same number of points in different years will give a different density of the measurement grid. Moreover, the empirical curves must be suitable for use on neighboring glaciers that also differ in area (at least on the Vestre Grønfjordbreen glacier). Therefore, absolute values of the number of measurement points are not suitable for constructing curves. These values were normalized by dividing by the area of the glacier, and the horizontal axis shows the *density of measurements* per square kilometer.

The empirical curves obtained in the manner discussed above were approximated by a mathematical equation, which allows one to calculate the uncertainty of the area-averaged snow depth for any arbitrary number of measurement points and any coefficient of variation, which allows one to solve practical problems. A fractional linear function is best suited for their approximation. It was proposed to use the following equation as an approximation:

$$\frac{30 \times Cv}{x} + 5Cv \tag{12}$$

where x is the density of snow depth measurements (points per km^2), the coefficient values are selected using the least squares method using empirical curves, and the final uncertainty value will be expressed in a relative form, as a percentage of the depth value. An example of smoothed error curves calculated from the equation is shown in Figure 3.6.

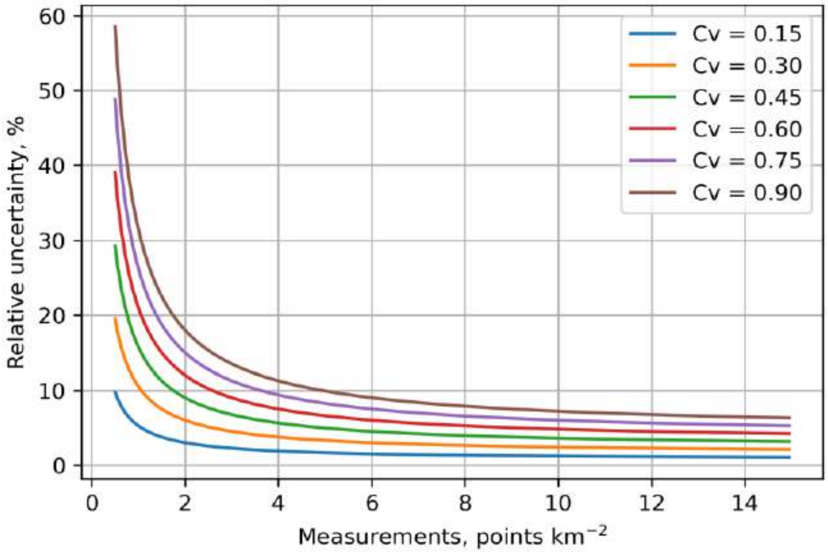


Figure 3.6 — Empirical curves for determining the relative error of the average glacier snow depth (from [Terekhov, Vasilevich, Prokhorova, 2023])

The bend of the curve is located in the area of 7–8 points per km^2: with a number of measurements less than this number, the error begins to increase sharply, and more gradually decreases in the other direction. From a practical point of view, this means that a grid density of 7–8 points per km^2 is optimal when conducting snow surveys on glaciers in the Barentsburg area.

The uncertainty values obtained using equation (12) are comparable to the uncertainties of annual mass balances: typical values are 0.2 m w.e. which is in good agreement with the estimates given in previously published works concerning mass balance monitoring [Galos et al., 2017; Klug et al., 2018; Zemp et al., 2013].

The systematic component of the error is not estimated using the bootstrap method. A systematic bias can arise as a result of an avalanche probe hitting ice layers inside the snow column instead of the glacier surface, underestimation of avalanche accumulation along the edges of the glacier, etc. [Zemp et al., 2013]. In addition, for glaciers on which the snow does not completely melt in the summer, it is possible to make a mistake in determining the surface of the previous year.

The uncertainty of the bulk snow density is assessed using a much more simplified method because there are much fewer of these measurements. The typical number of pits on the Aldegondabreen glacier is nine, and on the Vestre Grønfjordbreen glacier, they are located along two profiles, rather than by area. As a consequence, the bootstrap method, which requires a detailed interpolated raster, is impossible. Therefore, the following method is used: the standard deviation of the density from all pits for each year of monitoring is assumed to be an uncertainty. With a small number of pits (for example, on the Aldegondabreen glacier in 2020 — only 3 pits), such an assessment gives an unrealistically small result. In such years, we conventionally take the maximum historical value as the error.

3.4.4 Uncertainty assessment for geodetic mass balance

Sources of errors when calculating geodetic glacier mass balance may be divided into two groups: those associated with obtaining the initial DEMs and those associated directly with the process of calculating the geodetic balance [Zemp et al., 2013]. The first group includes either errors in the inter- and extrapolation of individual measurements into a continuous elevation raster, if any, which is typical for obtaining a DEM by ground surveys, or errors associated with the sensor and its platform (when obtaining a DEM based on photogrammetric, lidar or altimetry survey). The second group of uncertainties includes errors in the mutual spatial reference of DEMs, their reprojection or resampling, as well as errors in other source data involved in calculations, for example, glacier area. The following describes the process for assessing the uncertainty of geodetic mass balance, which most fully takes into account all these factors.

First of all, the possible *systematic bias* between source DEM is eliminated by the co-registration procedure. To calculate the geodetic mass balance of the Aldegondabreen glacier in 2008–2013 it was necessary to perform a mutual reference between a DEM being part of the S0 Terrengmodell dataset of the Norwegian Polar Institute and a DEM fragment (the so-called “strip”) of the ArcticDEM relief model (resolution 2 m). For this purpose, the “demcoreg” package [Shean et al., 2016] was used, which implements the coregistration algorithm of Nuth and Kaab [2011] in Python, using the S0 Terrengmodell as a reference DEM. The procedure uses only those DEM pixels that do not fall inside the contour of the glaciers, that is, located on a stable surface.

Since the topographic survey of the Aldegondabreen and Vestre Grønfjordbreen glaciers was carried out solely on their surface, it is impossible to apply a similar coregistration procedure to adjust them to the ArcticDEM fragments and calculate balances for the time intervals 2013–2018 and 2015–2019, respectively. Instead, three geodetic points and several linear topographic profiles obtained by GNSS methods outside the glacier were used. The DEMwas shifted by the median value of the absolute altitude deviations of the points in these profiles relative to ArcticDEM.

Next, we consider the process of estimating the *random error* of the geodetic mass balance. From the formula for determining the change in glacier volume by subtracting two DEMs (4), it follows that the random volume error will be equal to:

$$\sigma_{\Delta V}^2 = r^4 k \sigma_{\Delta h} \quad (13)$$

where $\sigma_{\Delta h}$ is the uncertainty in determining the change in pixel height, r is their linear size, and k is their number. The $\sigma_{\Delta h}$ was found in all three cases based on several control points on a stable surface around glaciers, as the standard deviation of the differences in their heights. The obtained values are 0.89 m (2008–2013) and 0.31 m (2013–2018) for the Aldegondabreen glacier, and 0.54 m (2013–2019) for the Vestre Grønfjordbreen glacier.

The next step is to calculate the uncertainty of the glacier-average surface lowering (A), equal to $\Delta V/_{S}$, based on the previously found $\sigma_{\Delta V}$ and the uncertainty in determining the glacier area σ_S:

$$\sigma_A^2 = A^2\left(\left(\frac{\sigma_{\Delta V}}{\Delta V}\right)^2 + \left(\frac{\sigma_S}{S}\right)^2\right) \quad (14)$$

which gives values of 0.06 and 0.07 m for the Aldegondabreen glacier, and 0.04 m for the Vestre Grønfjordbreen glacier. Finally, introducing the uncertainty of glacier density σ_ρ, we obtain the final uncertainty of the geodetic balance in units of water equivalent:

$$\sigma_B^2 = B^2\left(\left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_\rho}{\rho}\right)^2\right) \quad (15)$$

The uncertainties obtained from formula (15) are 0.32 and 0.44 m w.e. for two pentads of the geodetic balance of the Aldegondabreen glacier (about 7% of the balance values), and 0.40 m w.e. for the Vestre Grønfjordbreen glacier, the only calculation interval for which includes about 4.5 balance years.

Summary

The third chapter of this research provides a detailed overview of all available monitoring data collected by the Arctic and Antarctic Research Institute on the Aldegondabreen and Vestre Grønfjordbreen glaciers. The procedure of retrospective homogenization of monitoring results is described, taking into account the most relevant auxiliary data required for glaciological calculations. Based on field measurements, it is shown that the altitudes of the ablation stakes, previously used in annual reports on fieldwork, in some cases, have errors of tens of meters; moreover, the area–altitude distribution (AAD) of the Aldegondabreen glacier changes over time. Using the closest to the needed dates digital elevation models, AADs of studied glaciers were calculated. In addition, the author has carried out geodetic work necessary for precise co-registration of digital elevation models, without which it is impossible to determine the geodetic mass balance with acceptable accuracy.

The differences in mass balance indicators obtained for glaciers earlier, before the homogenization procedure, and after it are compared. It is shown that the typical values of these differences are about two decimeters of water equivalent. Such a comparison confirms the important role of *auxiliary data*, not only the mass balance measurements themselves, in mass balance computations. It also highlights why it is important to search for systematic errors that can arise due to the use of not up-to-date auxiliary data and the mixing of different methods of spatial averaging of mass balance values.

Partial loss of metadata, such as the exact coordinates of snow depth measurements, or the data themselves (measurements from ablation stakes) does not allow further analysis, for example, of the spatial distribution of snow depth and density, for all years of monitoring. The second consequence is the impossibility of homogenizing the early years of monitoring, before 2008, on the Aldegondabreen glacier.

The series of annual mass balance values, like the results of any physical measurements, have some random error, the assessment of which is devoted to a separate paragraph. Until now, a comprehensive assessment of this error for monitoring of the glacier mass balance in the Barentsburg area has not been made. The authors limited themselves to only mentioning the relatively small absolute value of the instrumental error of a single measurement, bypassing the issues of accuracy of inter- and extrapolation of point values to the entire glacier surface, which constitute the dominant portion of the final error. The assessment of random errors is important not only for comparing values obtained on one glacier over different years but also for comparing the cumulative glaciological and geodetic balances for similar periods. Such a comparison is the final step of the glaciological reanalysis procedure, and it is aimed at identifying and quantifying possible systematic errors in measurements.

The author notes that in the Russian version of this study, he is forced to use literal translation from well-known English terms. The last generalization of Russian-language terminology in the field of glaciology was compiled about 40 years ago, and at the present moment, it does not fully reflect generally accepted methods and practices of mass balance measurements. This leads to a situation where the geodetic method for determining mass balance exists and is used by researchers, but does not have an appropriate term in Russian.

The methodology of glaciological reanalysis of the mass balance series was proposed in 2013. However, it has not yet found application in monitoring programs of Russian-based researchers. In this sense, it was first used by the author of this study to process observations from the Aldegondabreen and Vestre Grønfjordbreen glaciers. The results of the reanalysis served as a basis for the conclusions on the spatial and temporal variability of the mass balance of the studied glaciers, which are presented in the next chapter. One of the main activities of Roshydromet, the subordinate organization of which is the Arctic and Antarctic Research Institute, is environmental monitoring, therefore the scientific and practical considerations on the effective organization of mass balance monitoring, formulated in the study, can be introduced into the practice of further research of Roshydromet, for example in the ongoing long-term glaciological monitoring on the archipelagos of Svalbard and Severnaya Zemlya.

Chapter 4 Glacier mass balance variability in the area of Barentsburg

4.1 General overview

The annual (B_a), winter (B_w), and summer (B_s) balances calculated from field measurements for the Vestre Grønfjordbreen and Aldegondabreen glaciers are presented in Tables 4.1 и 4.2, respectively. All the annual values, for 16 balance years of observations on the Aldegondabreen glacier and 9 years on the Vestre Grønfjordbreen glacier, were negative. The Aldegondabreen glacier loses mass more intensively, which is due to the lower elevation of its surface. The least negative Ba values for the period of parallel monitoring on two glaciers occurred in 2013/14 (−0.67±0.16 m w.e., Aldegondabreen and −0.60±0.18 m w.e., Vestre Grønfjordbreen), the most negative in 2019/20 and 2020/22. In the previous period, when observations were carried out only on the Aldegondabreen glacier, the historical minimum ice loss was measured, amounting to only −0.24±0.14 m w.e. in 2009/10.

According to Noël and co-authors [2020], since 1985, the average snow line altitude on the Svalbard glaciers is 450–500 m. From the previously presented graphs of the area–altitude distribution of the surface of the studied glaciers (Figure 3.5), it is clear that only 2% of the Aldegondabreen glacier and about 6% of the Vestre Grønfjordbreen glacier lay above this altitude. Based on linear approximations of the mass balance, which were used to calculate average values for glaciers (equation 3), the point values measured at ablation stakes were extrapolated to the upper reaches inaccessible for observations. In this way, the equilibrium line altitudes (ELA) were obtained for each balance year (Table 4.1 and Table 4.2). From these calculations, we can conclude that the Aldegondabreen glacier has completely lost its accumulation zone today. Its accumulation-to-area ratio (AAR) for all years does not exceed 1%, and in the 2019/20 balance year, the snow line altitude reached the highest point of the glacier, reducing the AAR value to zero. Likely, firn remains still exist in the southern, highest, and inaccessible part of the Aldegondabreen glacier, but their possible area is limited to 1–2% of the total area.

On the Vestre Grønfjordbreen glacier, according to visual observations of the Arctic and Antarctic Research Institute, over the last decade, several percent of the surface in the upper reaches is not completely cleared of snow by the end of summer. The lowest ELA at about 400 m a.s.l., just behind ablation stake #6, was observed at the end of August 2019 (Figure 3.2) However, the Vestre Grønfjordbreen glacier has also almost lost its accumulation zone by now since the snow in the upper reaches does not survive longer than two to three years, and in some years it melts completely. According to the results of a 2019 GPR survey, in the altitude range of 540–550 m above sea level there are remnants of the firn zone with a total area of about 3–4% of the total area of the glacier [Terekhov et al., 2022].

The winter balances computed from snow survey data are summarized in Tables 4.1 and 4.2. Despite the systematic difference in annual mass balance values caused by the lower surface location of the Aldegondabreen glacier, the B_w values of the studied glacier could be treated the same considering their uncertainties. This means that the precipitation in the vicinity of the Vestre Grønfjordbreen glacier is slightly less than closer to Barentsburg. The B_w value varied from +0.36 to +0.75 m w.e. on the Vestre Grønfjordbreen glacier (2015/16 and 2014/15, respectively) and from +0.36 to +0.85 m w.e. on the Aldegondabreen glacier (2001/02 and 2011/12). Data on two components of the winter balance — snow depth and its integral density — are listed separately in Tables 4.5 and 4.6. For the Vestre Grønfjordbreen glacier, the highest area-averaged snow depth of 1.82 m was recorded in the spring of 2014. The lowest snow depth of 1.13 m was observed twice, in the spring of 2016 and 2018. On the Aldegondabreen glacier, the highest area-averaged glacier snow depth of 2.00 m was measured in the spring of 2008. However, the winter mass balance for this year was not the maximum in the monitoring history due to the low density of the snow cover. The lowest snow depth of 1.08 m was measured in the spring of 2018.

Table 4.1 — Mass balance of the Vestre Grønfjordbreen glacier

Balance year	Area-averaged balance, m w.e.			ELA, m (deduced)
	Annual (B_a)	Winter (B_w)	Summer (B_s)	
2013/14	–0,60±0,18	0,67±0,20	–1,27±0,27	490
2014/15	–0,88±0,24	0,75±0,23	–1,63±0,33	470
2015/16	–1,19±0,21	0,36±0,19	–1,56±0,29	570
2016/17	–1,92±0,23	0,60±0,19	–2,53±0,30	850
2017/18	–1,19±0,22	0,44±0,16	–1,63±0,27	450
2018/19	–0,78±0,20	0,56±0,31	–1,34±0,36	390
2019/20	–2,01±0,26	0,48±0,12	–2,46±0,28	640
2020/21	–0,86±0,21	Unpublished	—	410
2021/22	–2,12±0,25	Unpublished	—	790

The negative balance of glaciers during the monitoring period led to a reduction in their area. From Martín–Español et al. [2015] the known area of the Vestre Grønfjordbreen glacier as of spring 2010 was 18.08±1.45 km^2. Comparing this value with the area at the end of the 2019 season, obtained using the results of the author's topographic survey (16.42±0.33 km^2), we found that over the decade the glacier decreased by 1.66 km^2, that is, by 9%. The maximum retreat of the glacier terminus during this period equals 200 meters.

Table 4.2 — Mass balance of the Aldegondabreen glacier

Balance year	Area-averaged balance, m w.e.			ELA, m (deduced)
	Annual (B_a)	Winter (B_w)	Summer (B_s)	
1975/76	−1,10			
...		No observations		
2001/02	—	+0,36	—	
2002/03	−1,61	+0,56	−2,17	
2003/04	−1,71	+0,46	−2,23	
2004/05	−1,41	+0,68	−1,99	
2005/06	−1,31	+0,71	−2,05	
2006/07	—	+0,69±0,12	—	
2007/08	−0,32±0,14	+0,78±0,05	−1,10±0,15	520
2008/09	−0,58±0,15	+0,69±0,05	−1,27±0,15	560
2009/10	−0,24±0,14	+0,73±0,06	−0,97±0,15	440
2010/11	—	+0,79±0,04	—	—
2011/12	—	+0,85±0,12	—	—
2012/13	—	—	—	—
2013/14	−0,67±0,16	+0,63±0,03	−1,30±0,16	530
2014/15	−1,03±0,23	+0,77±0,11	−1,80±0,26	590
2015/16	−1,88±0,25	+0,54±0,12	−2,42±0,27	550
2016/17	−1,89±0,25	+0,63±0,06	−2,52±0,26	590
2017/18	−1,70±0,22	+0,38±0,04	−2,08±0,22	580
2018/19	−1,21±0,23	+0,51±0,08	−1,72±0,25	530
2019/20	−2,19±0,24	+0,44±0,18	−2,63±0,30	650
2020/21	−1,40±0,26	+0,58±0,03	−1,95±0,26	550
2021/22	−2,13±0,25	+0,51±0,03	−2,64±0,25	720

For the Aldegondabreen glacier, the reduction in area during the monitoring period is about 20%: according to the ASTER image closest to the beginning of the monitoring program on July 4, 2003 (resolution 15 m/pixel), the glacier area was 6.66±0.13 km^2. At the end of the 2021 ablation season, the area decreased to 5.26±0.09 km^2 (determined from the Sentinel-2 satellite image), that is, by 1.40±0.16 km^2.

4.2 Spatial variability of mass balance

4.2.1 Annual mass balance

It is widely known that for the glaciers of Svalbard, as for most mountain glaciers in the world, the dependence of the mass balance on the height above sea level is true (see, for example: [Hagen et al., 2003; Pelt van et al., 2019; Schuler et al., 2020]). Graphs of this dependence for the studied glaciers are presented in Figures 4.1 and 4.2. The mass balance approximation lines shown in the graphs, computed using the least squares method, were previously used in calculating the area–averaged value over the glaciers. The equations for the approximating functions are given above (equation 3).

For each of the balance years, the figures also show the value of the coefficient of determination R^2, which shows what proportion of the variability of the studied value, ice melt, is explained by the selected predictor - altitude. From the high values (0.92–0.98) calculated for the Vestre Grønfjordbreen glacier (Figure 4.2), one could conclude that the influence of other environmental factors on ice melt is negligible. However, these values are most likely seriously overestimated due to the characteristics of the sample: the number of ablation stakes on the Vestre Grønfjordbreen glacier is 2–4 times less than on the Aldegondabreen glacier; in addition, their arrangement is such that there are no multiple stakes in any of the elevation bins. Therefore, the significantly lower R^2 values obtained for the Aldegondabreen glacier have less uncertainty and reflect reality better. Note that in some years the R^2 indicator for the Aldegondabreen glacier is less than 0.5, therefore, other factors in such cases “outweigh” the influence of vertical air temperature and precipitation lapses.

Although the relationship between glacier mass balance and altitude is undeniable, it does not explain the entire pattern of spatial variability in ablation, which is complicated by topography and microclimate [Paterson W. S. B., 1994]. These factors, including wind and avalanche redistribution of solid sediments, local effects of relief shading, as well as uneven surface albedo, generally do not depend on elevation [Fountain, Vecchia, 1999; Ivanov et al., 2022]. Previously, in the article by Sidorova et al. [2019], it was hypothesized that differences in the ice melt on glaciers in the study area may be influenced by local factors that determine the insolation of the glacier surface. Such an assumption is quite reasonable given the fact that short-wave radiation predominates in the incoming part of the surface energy balance of the Svalbard glaciers located below the modern snow line altitude [[Arnold et al., 2006; Prokhorova et al., 2023; Zou et al., 2021; Prokhorova et al., 2021].

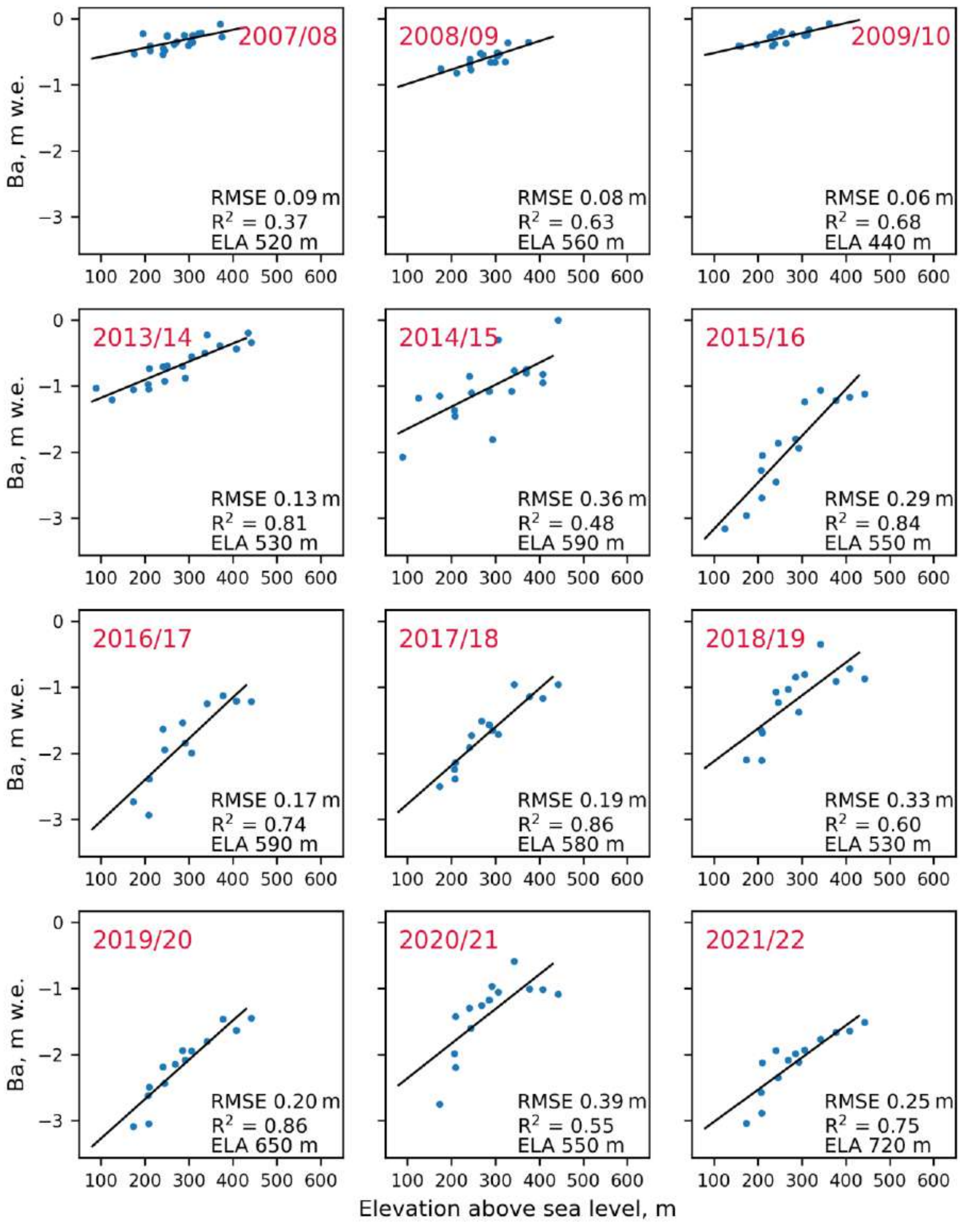


Figure 4.1 — Diagrams of point mass-balance values measured at the ablation stakes on the Aldegondabreen glacier versus altitude above sea level

The diagrams show the values of the standard deviation of the measured values from the linear fit (RMSE), the coefficient of determination of this fit (R^2), and the equilibrium line altitudes (ELA)

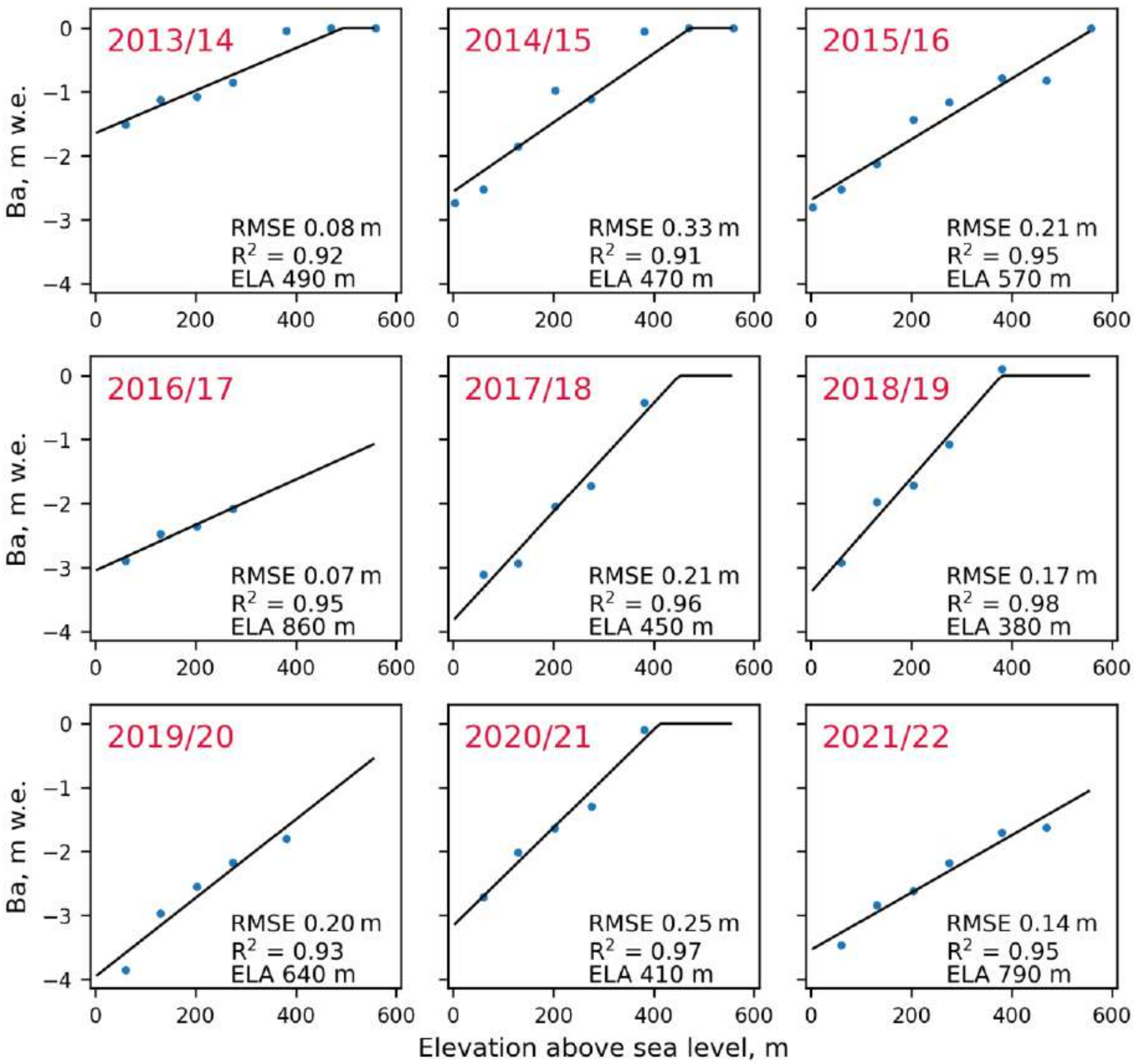


Figure 4.2 — Diagrams of point mass-balance values measured at the ablation stakes on the Vestre Grønfjordbreen glacier versus altitude above sea level
The diagrams show the values of the standard deviation of the measured values from the linear fit (RMSE), the coefficient of determination of this fit (R^2), and the equilibrium line altitudes (ELA)

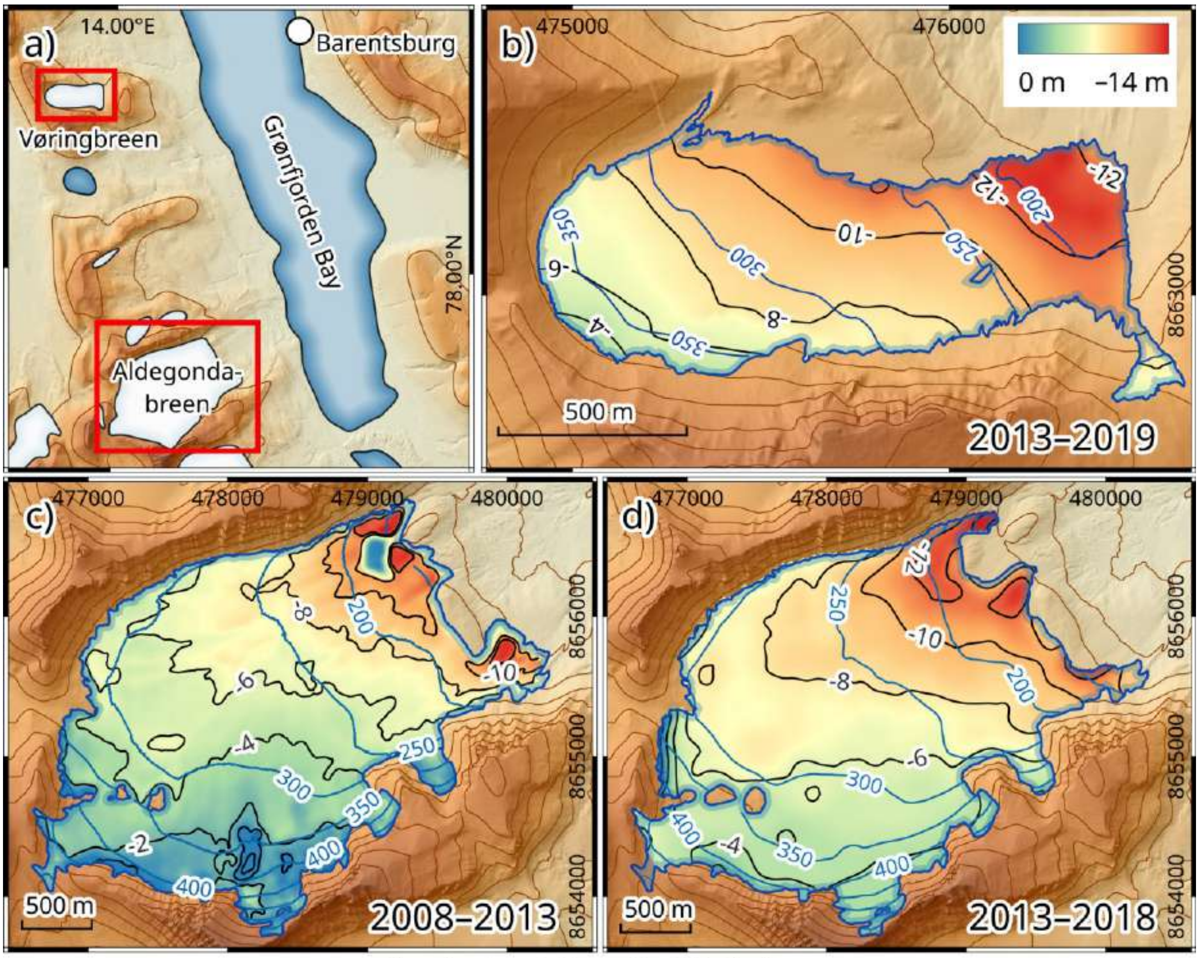
The influence of differences in insolation on the spatial pattern of surface melt was demonstrated earlier for glaciers of both mid- and high latitudes. In particular, [Vincent, Six, 2013], based on monitoring results on the Saint Sorlin glacier in the French Alps, showed that the distribution of the annual mass balance over the surface closely correlates with the incoming shortwave radiation flux under clear skies (also called potential incoming solar radiation). Olson and Rupper [2019] used simulations of the same variable to examine the effects of glacier shading by valley sides in high-mountain regions of Central Asia, concluding that differences in the melt of neighboring glaciers are largely determined by this mechanism. For polar glaciers, a similar relationship was demonstrated in [Hock, 1999] using the example of the Storglaciären glacier in Sweden. The empirical temperature-index ice melt model was supplemented by the calculation of the magnitude of solar radiation flux under clear skies, as a result of which it began to better represent the spatial patterns of ice melting, and more accurately reproduce the daily ablation values.

For the glaciers of the Barentsburg area, such examples illustrating the dependence of the spatial distribution of ice melt on insolation conditions have not yet been demonstrated. The most indicative objects for studying this dependence may be glaciers lying in deep mountain valleys located latitudinally, in such a way that the shading of the sides and differences in exposure create a pronounced contrast in the dynamics of ablation in different parts of the glacier. In the study area, such objects are the Vøringbreen and Aldegondabreen glaciers. The work carried out by the author to determine their mass balance using the geodetic method provides a much more detailed spatial pattern of ice melt than the ablation stakes measurements [Terekhov et al., 2023; Terekhov et al., 2020a].

To obtain a proxy of the spatial distribution of insolation values on the Vøringbreen and Aldegondabreen glaciers, the potential incoming solar radiation flux was calculated based on the eponymous algorithm from the SAGA GIS. The algorithm takes into account both the astronomical factor, that is, the daily and annual movement of the Sun, and the morphometric factor — the exposure and slope of the surface, as well as topographic shading [Böhner, Antonić, 2009]. Computation was performed for both glaciers based on the ArcticDEM strips, for the period from July 15 to September 15, assumed to be the ablation season in the study area: the disappearance of snowcover and the retreat of the snow line up the glaciers begins in the first ten days of July; and in the middle September, the air temperature becomes negative, and ablation on the glaciers stops [Terekhov et al., 2023; Prokhorova et al., 2023].

Figure 4.3 shows that the surface lowering of the Vøringbreen and Aldegondabreen glaciers is expectedly dependent on altitude, demonstrating the largest absolute values (i.e., maximum ice melt) near the glacier terminus, and the smallest in the upper reaches. However, for the Aldegondabreen glacier, it is clear that the patterns of surface lowering are different along the left and right sides (north and south, respectively) at equal heights. This is most pronounced in the central part of the glacier, where melting contour lines extend far up the surface near the left side, and then, crossing contours of 200 and 250 m above sea level, descend much lower at the right side (see Figure 4.3c, d). Thus, the Aldegondabreen glacier is divided by its longitudinal axis into two unequal parts, which are characterized by different relationships between ice ablation and altitude. For the Vøringbreen glacier, a similar pattern is also observed in the central part of the glacier, where the contour line of the surface lowering of 10 m rises in the north almost 50 m higher up the glacier than in the southern, presumably more shaded area.

Figure 4.4 shows the results of calculations of the potential incoming solar radiation flux on the surface of the Vøringbreen and Aldegondabreen glaciers for the period from July 15 to September 15. The insolation values shown in the figure are approximate since they can vary depending on the selected parameters of atmospheric transparency and the solar constant. However, for further tests, the relative changes in the flux over the glacier surface are more important.



Elevation data © Norwegian Polar Institute

Figure 4.3 — Location of the Vøringbreen and Aldegondabreen glaciers (a), and their surface lowering: Vøringbreen, 2013–2019 (b), Aldegondabreen, 2008–2013 (c) and 2013–2018 (d)

For the Aldegondabreen glacier, simulated potential incoming solar radiation flux is overall higher than for the Vøringbreen glacier, with a range of about 100 W/m^2, from 85 to 185 W/m^2 (see Figure 4.4). The maximum insolation occurs in the northern part of the glacier, while the minimum values are distributed along the southern side. The difference in insolation between the northern and southern parts of the Aldegondabreen glacier is explained by the shape of its surface. Due to its concavity, the left side, with an area of about a third of the entire surface, has an exposure close to the south (see Figure 4.4), although the glacier as a whole extends from southwest to southeast. In addition, the right side of the glacier is shaded from the southern side of the valley.

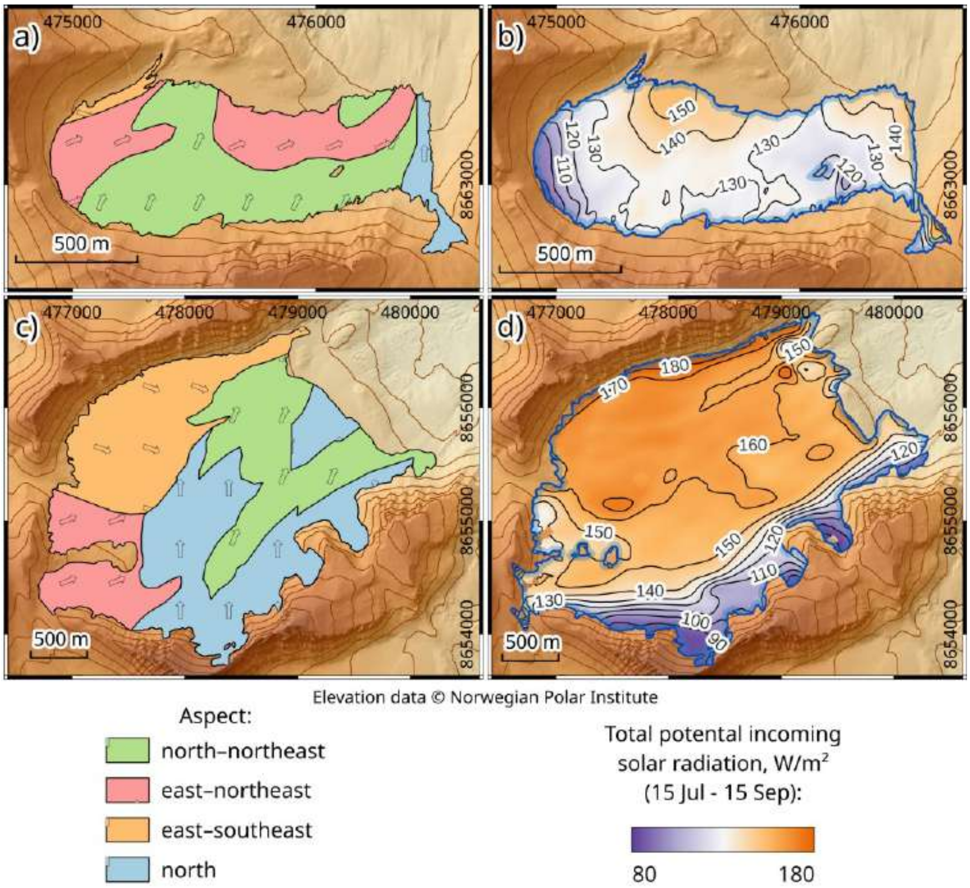


Figure 4.4 — Surface aspect, and the total potential incoming solar radiation on the glaciers: Voringbreen (a, b) and Aldegondabreen (c, d)

The average modeled flux within the northern and southern parts of the Aldegondabreen glacier is 165 and 139 W/m^2, that is, the average difference in insolation is about 26 W/m^2. Note that the given values exceed the actual ones since they were computed for conditions of maximum atmospheric transparency (0.7) and clear skies. In reality, due to the scattering of a significant part of the solar radiation flux caused by clouds, atmospheric gases, and aerosols, the insolation difference between the two glacier parts should be below 26 W/m^2.

The Vøringbreen glacier is characterized by lower insolation values, which is the result of shadowing by the cirque walls. At the same time, despite the uniformity of the surface aspect, the spatial pattern of the incoming flux of solar radiation is quite complex, which is largely due to the features of the surrounding topography. The lowest reaches of the glacier and the area northwest of the center, separated by a more shaded area, have the greatest insolation (see Figure 4.4). The approximate boundary between the more and less sunlit parts of the glacier can be assumed a contour line of 130 W/m^2.

To quantify the influence of the morphometric factor — the combination of surface aspect and its slope, as well as topographic shading — on the surface ablation of the Vøringbreen and Aldegondabreen glaciers, we demonstrate graphs of the dependence of ice melt on altitude above sea level in conjunction with the third value, the potential incoming flux of solar radiation (Figure 4.5).

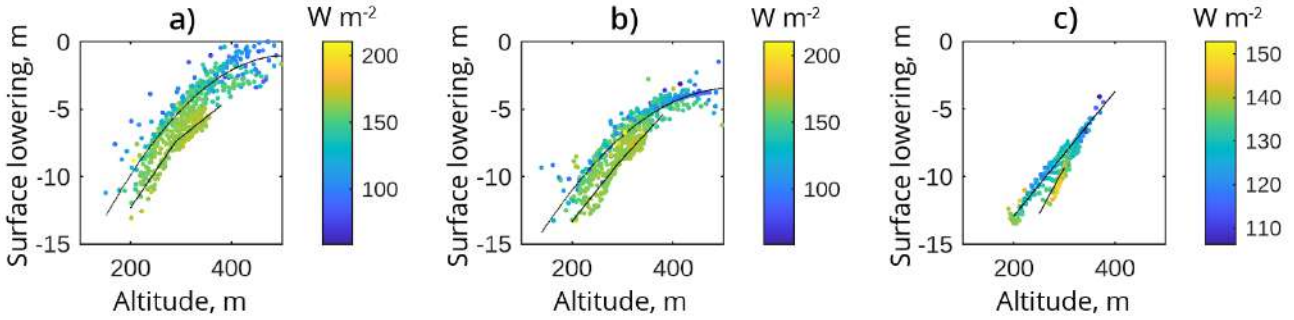


Figure 4.5 — Relationship between the surface lowering, altitude above sea level and the total potential incoming solar radiation flux (a —Aldegondabreen, 2008–2013, b —Aldegondabreen, 2013–2018, c — Voringbreen, 2013–2019)

Figure 4.5 shows that the altitudinal dependence for the studied glaciers has two “branches” following differences in insolation. Points on the surface of the Aldegondabreen glacier, belonging to its more illuminated part along the left side, are indeed subject to greater melting. The difference in the five-year ablation value in the more and less illuminated parts of the glacier, calculated as the difference between the trend lines, is approximately equal in both periods (2008–2013 and 2013–2018) and amounts to 2.1 m. This value is 40 and 30 % of the total surface lowering over five-year periods. The trend lines of ice ablation for the northern and southern parts (see Figure 4.5) are almost parallel to each other, which means that the identified difference does not depend on height. If we divide the resulting total value by five balance years, we get a difference in melting of 0.40 m of ice per year, or, if we assume the density of glacial ice equal to 0.88 kg m^{-3}, of 0.36 m w.e. in a year.

For the Vøringbreen glacier, the graph also shows two main “branches” of the altitude dependence with some points between them (Figure 4.5). The glacier is divided into illuminated and shaded parts in a less obvious way than Aldegondabreen since its surface is more uniform in terms of aspect. The effect of uneven insolation on ice melt can be quantified most clearly at an altitude of 250 m above sea level, where it has the strongest variation (Figure 4.5). The surface lowering at this height varies for 2.2 m ice (7.7 to 9.9 m ice), or 1.85 m w.e. for the entire period under consideration, amounting to 25% of the total surface lowering over the six years.

When analyzing the dependence of ice melt on the amount of potential incoming solar radiation for individual elevation bins (Figure 4.6), it turns out that in each of the fifty-meter intervals, there is a statistically significant trend of ice melt ($\alpha = 0.05$). Correlation coefficients between melt and insolation vary from −0.33 to −0.62 at Aldegondabreen glacier and −0.50 to −0.92 at Vøringbreen glacier (Table 4.3).

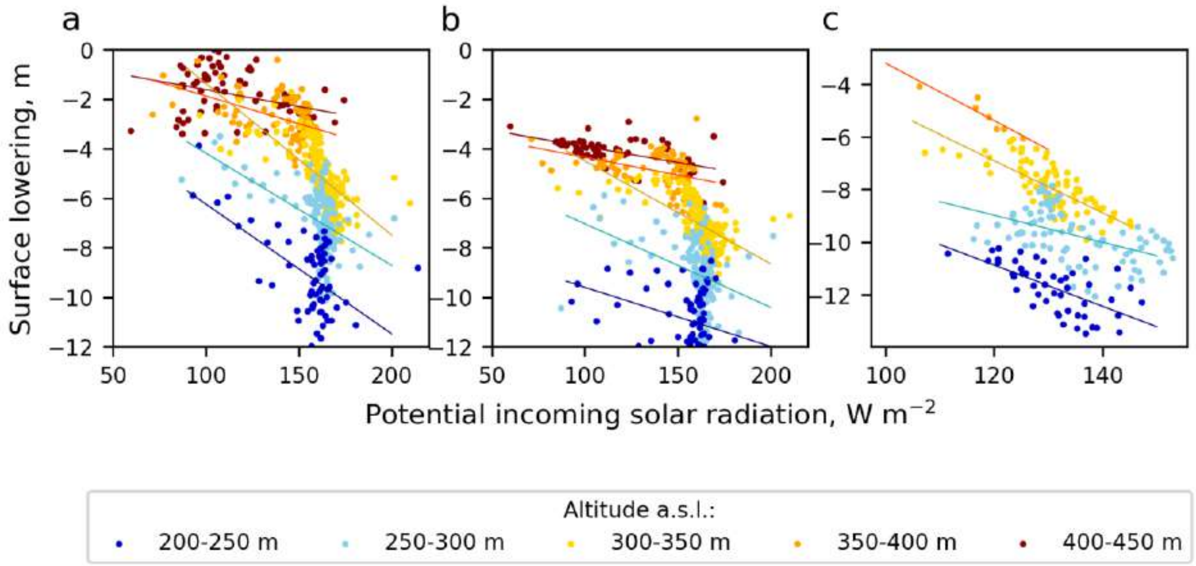


Figure 4.6 — Relationship between the surface lowering and the total potential incoming solar radiation flux, by elevation bins (a —Aldegondabreen, 2008–2013, b, c —Aldegondabreen, 2013–2018, 2013–2019)

Table 4.3 — Relationship between the surface lowering of the Aldegondabreen and Voringbreen glaciers and the total potential incoming solar radiation, by elevation bins

Elevation bin, m a.s.l.	Aldegondabreen				Vøringbreen	
	2008–2013 гг.		2013–2018 гг.		2013–2019 гг.	
	Correlation coefficient	Ice melt gradient, m of ice per 10 W/m^2	Correlation coefficient	Ice melt gradient, m of ice per 10 W/m^2	Correlation coefficient	Ice melt gradient, m of ice per 10 W/m^2
200–250	−0,59	0,52	−0,62	0,24	−0,64	0,78
250–300	−0,52	0,45	−0,40	0,34	−0,50	0,51
300–350	−0,67	0,61	−0,61	0,42	−0,75	0,99
350–400	−0,47	0,22	−0,36	0,14	−0,92	1,09
400–450	−0,37	0,14	−0,33	0,13	—	—

The effect of uneven insolation on surface melt can be characterized by comparison with the altitudinal ablation gradient (Table 4.4). Based on the average melting values within the more and less illuminated parts of the glaciers (see Figure 4.5), the maximum differences in ablation for different insolation areas are 2.1 m of ice over five seasons for Aldegondabreen and 2.2 m of ice over six seasons for Vøringbreen. This corresponds to a difference in the ablation layer of 0.36 m w.e. a^{-1} (Aldegondabreen) and 0.32 m w.e. a^{-1} (Vøringbreen). At the same time, the vertical melting gradient (see Figure 4.5) is: for the Aldegondabreen glacier — 4.0–4.6 m of ice per 100 m of altitude over five years (at an altitude of 275 m above sea level, the peak of the glacier's AAD), or 0.70–0.81 m w.e. 100 m^{-1} a^{-1}; for the Vøringbreen glacier — 4.1 m of ice per 100 m of altitude over five years, or 0.53 m w.e. 100 m^{-1} a^{-1}. Thus, the differences caused by the uneven illumination of the surface of the studied glaciers are equivalent to a difference of 45–60 m in altitude (Table 4.4), which is significant concerning the small elevation range of glaciers in this part of Svalbard [Chernov and Muravyev, 2018].

Table 4.4 — Surface ablation differences, induced by unequal insolation and by vertical ablation lapse, on the Aldegondabreen and Voringbreen glaciers

		Ice melt differences induced by unequal insolation		Vertical gradient of ice melt		Altitudinal difference equivalent to the unequal insolation effect
Glacier	Period	m of ice / period	m w.e. per year	m of ice 100 m^{-1} period	m w.e. 100 m^{-1} a^{-1}	m of altitude
Aldegondabreen	2008–2013	2,1	0,36	4,0	0,70	50
Aldegondabreen	2013–2018	2,1	0,36	4,6	0,81	45
Vøringbreen	2013–2019	2,2	0,32	4,1	0,53	60

Consequently, the ablation layer for the same season may differ on the surface of neighboring glaciers even at the same air temperature and its altitudinal gradient. This allows us to hypothesize that the difference in seasonal melting of glaciers in the vicinity of Barentsburg reaches a maximum in those years when the actual solar radiation flux is maximum, and vice versa: under a small radiation flow, these differences are smoothed out. An example of such a difference in melting was considered in the article by Sidorova et al. [2019], where it is shown that the thickness of the layer of ice melted during the season at equal heights above sea level has a significant difference for three glaciers, Aldegondabreen, Vestre and Austre Grønfjordbreen. Testing this hypothesis is not easy: due to the heterogeneity of cloud cover over the study area, simple extrapolation of actinometric measurements carried out at one point to the entire area would be inaccurate. Therefore, such a verification requires synchronous monitoring measurements of solar radiation on all studied glaciers.

As shown above, the potential incoming solar radiation well reflects the spatial features of surface ablation of glaciers in the Barentsburg area, and, in addition, is quite simple to calculate, since it requires only a DEM as initial data [Terekhov, Prokhorova, Demidov, 2023]. Therefore, it is much more informative to compare the ablation of neighboring Svalbard glaciers based on this indicator, and not just on the direction of the longitudinal axis of the glacier, as was done in previous works [Chernov et al., 2018]. This approach can produce ambiguous results, classifying, for example, the Aldegondabreen glacier as a northeast-facing glacier, although in reality it is not (Figure 4.4). This aspect is typical for only a third of the glacier; another third, on the contrary, has an aspect close to the south, providing, together with the lack of shading, increased melting (higher on average by 0.36 m w.e. a^{-1}).

The obtained result touches on the topic of representativeness of monitoring networks on Svalbard glaciers. On several glaciers of the archipelago, ablation stakes are installed along one longitudinal profile [Aas et al., 2016; Terekhov et al., 2022]. The question of how representative this setup is from the point of view of insolation conditions has never been considered for monitoring programs of the Spitsbergen archipelago. On the Aldegondabreen glacier, ablation stakes are distributed more evenly over the surface, but their number in more and less illuminated parts is in no way proportional to the areas of these parts. All this is an obvious source of systematic bias in the glacier-averaged mass balance values, and as the results show, the error relative to the average value can amount to a few decimeters per year. Therefore, to check the monitoring results, periodic repetition of GNSS or aerial surveys (for example, once every five years) and calculation of geodetic mass balance are necessary.

4.2.2 Winter mass balance

Studies of snow cover on mountain glaciers in the Arctic show that snow accumulation is, to one degree or another, determined by altitude above sea level. This is a consequence of the existence of a vertical gradient of precipitation and partial melting of snow that occurs in the lower reaches of glaciers during thaws preceding snow surveys [Lehning, Grünewald, Schirmer, 2011; Vincent, Six, 2013]. Besides that, researchers used various morphometric values as predictors with varying degrees of success: slope angle, aspect, distance to the glacier outline or centerline, and others [Réveillet et al., 2017]. Since in the case of the Aldegondabreen and Vestre Grønfjordbreen glaciers, the slope angles and aspect themselves depend on the altitude, only the shortest distance to the rock frame was chosen for further analysis.

For the Aldegondabreen glacier, it is possible to analyze the spatial distribution over the surface of both the winter balance b_w and its two components — snow depth and bulk snow density, since they are measured on a quasi-regular grid. Calculation of the relationship between the main parameters of the snow cover of the Aldegondabreen glacier and the selected morphometric characteristics leads to contradictory results (Table 4.5). The snow depth expectedly increases with the altitude above sea level in almost all winters. Correlation with proximity to the valley side has only been observed regularly in the last five years of monitoring but had near-zero coefficients until the observational break in 2012/13. Setting aside any changes in field survey methodology that occurred after the break as a possible explanation, we may suppose that the period before 2012/13 was characterized by different wind redistribution patterns.

For the bulk density of snow cover, the correlation coefficients are generally lower than for snow depth, and in some years they change their sign to the opposite. For example, in the spring of 2006/07, snow density decreased with height, and in the subsequent season, it increased. Thus, a constant dependence of snow density on altitude above sea level cannot be detected. As a result, the relationships between the winter balance b_w and the altitude and distance to the valley side show the linear correlation in some years but are absent in some seasons.

Table 4.5 — Pearson's correlation coefficients for the relationship of main snow cover features and chosen morphometric variables, for the Aldegondabreen glacier

* — max historical value assumed as the uncertainty,
** — computation impossible due to small amount of measurements

Balance year	Snow cover depth			Bulk snow density		
	Area-averaged, m	Correlation with atlitutde	Correlation with distance to valley sides	Area-averaged, m	Correlation with atlitutde	Correlation with distance to valley sides
2001/02	1,00	—	—	362±29	—	—
2002/03	Data lost					
2003/04	1,24	0,0	0,0	374±50	0,4	0,2
2004/05	1,94	0,4	-0,1	351±63*	—	—
2005/06	1,53	0,9	0,0	467±39	0,1	0,2
2006/07	1,84±0,03	0,7	-0,2	374±63*	-0,5	-0,3
2007/08	2,00±0,04	0,6	0,1	390±23	0,6	0,3
2008/09	1,88±0,03	0,4	-0,1	368±25	0,3	-0,2
2009/10	1,69±0,03	0,6	0,0	432±33	0,0	0,1
2010/11	1,96±0,03	—	—	404±20	—	—
2011/12	1,94±0,03	0,5	-0,2	438±63*	—	—
2012/13	No observations					
2013/14	1,72±0,03	—	—	367±14	—	—
2014/15	1,77±0,04	—	—	433±60	—	—
2015/16	1,83±0,03	0,6	-0,4	294±63	-0,2	0,0
2016/17	1,46±0,03	0,5	-0,4	429±43	0,6	-0,7
2017/18	1,08±0,03	0,5	-0,6	352±36	0,4	-0,3
2018/19	1,51±0,03	0,7	-0,5	340±50	0,7	-0,8
2019/20	1,39±0,04	0,2	-0,3	316±63*	—**	—**

For the Vestre Grønfjordbreen glacier, it is only possible to analyze the spatial distribution of snow depth, measured from a much denser network than density. The snow density observation scheme, consisting of two profiles, does not allow for reliable interpolation over the area. Therefore, for the density it is possible to trace the relationship only with altitude, and the spatial distribution of b_w over the surface cannot be analyzed.

Snow depth shows a tight relationship with altitude, which, however, is only found with a large number of measurements (Table 4.6). Similarly, with a larger number of snow survey points, a weak negative correlation (about −0.3) is found with proximity to the valley sides: the closer to the edge of the glacier, the higher the snow depth. Therefore, it is not entirely clear whether interannual changes in the magnitude of the relationship are a consequence of the "technical" features of snow surveys, or reflect fluctuations in climatic factors.

Table 4.6 — Pearson's correlation coefficients for the relationship of main snow cover features and chosen morphometric variables, for the Vestre Grønfjordbreen

Balance year	Snow cover depth			Bulk snow density	
	Area-averaged, m	Correlation with atlitutde	Correlation with distance to valley sides	Area-averaged, m	Correlation with atlitutde
2013/14	1,82±0,06	—	—	374±16	0,54
2014/15	1,81±0,06	—	—	437±38	-0,68
2015/16	1,13±0,04	0,88	-0,28	323±87	-0,45
2016/17	1,60±0,04	0,74	-0,30	371±40	-0,18
2017/18	1,13±0,04	0,84	-0,22	388±30	-0,07
2018/19	1,38±0,05	0,96	-0,15	408±62	0,23
2019/20	1,37±0,10	0,43	-0,03	327±15*	-0,25
2020/21	1,55±0,06	0,66	-0,07	Неопубл.	Неопубл.

The density of snow on the surface of the Vestre Grønfjordbreen glacier does not show any dependence on altitude (Figure 4.7). As a consequence, the value of the winter balance b_w does not show such a dependence, too. For this reason, when calculating the glacier-average winter balance B_w, this study uses the density value averaged between pits, without dividing the glacier surface into altitudinal zones.

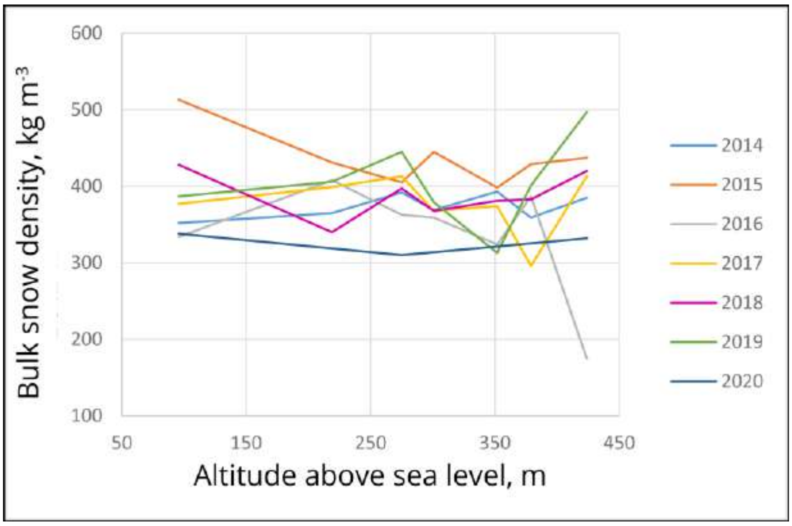


Figure 4.7 — Lack of relationship between the integral density of snow cover and altitude for the Vestre Grønfjordbreen glacier in 2014–2020

Thus, for the studied glaciers, it is shown that the snow depth has a moderate or tight relationship with altitude above sea level and a weaker negative correlation with the distance to the glacier side. However, the values of the correlation coefficients decreased in those years when the number of survey points (see Tables 3.2 and 3.1) was reduced, so it is impossible to unambiguously determine whether any climatic factors are responsible for this, or whether it is apparent due to alterations in the fieldwork. Therefore, from the point of view of analyzing climate relationships, continuity in the field work scheme is important for snow monitoring surveys.

The spatial distribution of snow water equivalent, observed at the end of spring, shows a dependence on height above sea level only in certain seasons. The main reason is the lack of a stable correlation between integral snow density and altitude observed for both glaciers. This fact leads to the difficulty of modeling the winter mass balance of the studied glaciers using spatially distributed methods, making snow surveys an indispensable source of data on snow cover in the Barentsburg area.

4.2.3 Ice flow velocities

The measured annual horizontal displacements of ablation stakes on the Aldegondabreen glacier are presented in Figure 4.8. The glacier is divided lengthwise into two parts: the southern part, where the ice is currently still experiencing some movement, and the northern part, which can be considered stationary (at least moving slower than 10 cm year^{-1}, which is the measurement uncertainty). The observed pattern generally coincides with the slopes of the glacier bed: the highest speed was recorded in the southern, most inclined part. In the lower part of the glacier, the ice flow diverges to the sides from the riegel that was exposed from under the ice in 2008. Thus, changes in the surface geometry of the Aldegondabreen glacier must be entirely determined by its surface mass balance, since ice movement is extremely slow.

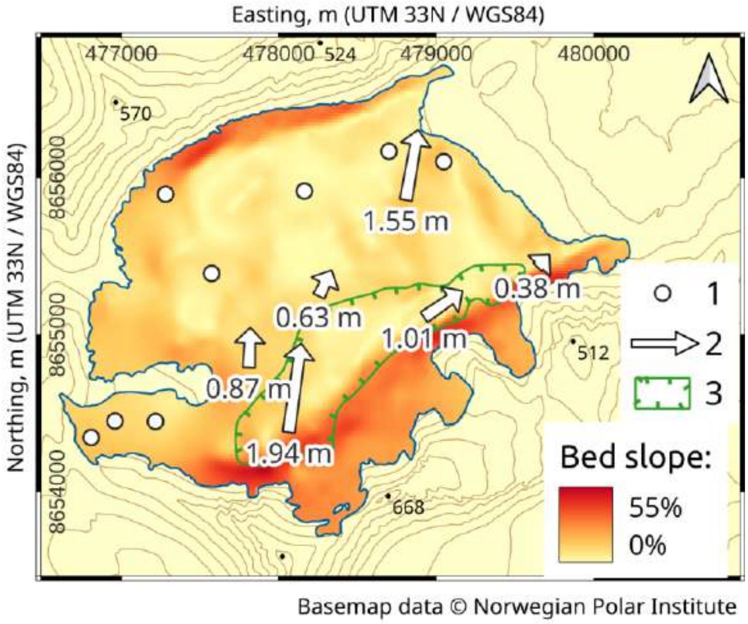


Figure 4.8 — Annual displacements of ablation stakes, measured in 2018–2019 (a) and bed inclination of the Aldegondabreen glacier (b)
1 — insignificant values (less than measurement uncertainty), 2 — significant values, 3 — temperate ice outline

Annual horizontal displacements of ablation stakes measured in 2018–2019 on the Vestre Grønfjordbreen glacier, were larger and increased from the terminus to the top from 0.50±0.10 to 4.50±0.10 m. However, the two uppermost stakes in the eastern square could not be measured due to their inaccessibility on foot (Figure 4.9). The obtained values are slightly larger than those measured at Aldegondabreen, but also extremely small. Presented values may be limitedly representative of the glacier as a whole: the downslope convexity of the surface lowering contour lines shows in Figure 4.9 the partial compensation of surface melt by ice movement along the two main flowlines originating from both cirques. Therefore, measurements taken on ablation stakes between these two flowlines may underestimate glacier flow velocities.

The obtained velocities are relatively low and typical of terrestrial-terminating glaciers with low bed slopes. It remains unknown how and by how much the flow velocity changes by season and from year to year. It is known that some of the Svalbard glaciers are surging-type ones. Quantitative estimates of pulsating glaciers on the archipelago vary over a very wide range, from 15 to 90% [Wangensteen, Weydahl, Hagen, 2007]. It is possible that in the past both glaciers were surging. Thus, Kokin and Kirillova [Kokin and Kirillova, 2017], based on geomorphological and paleogeographic evidence, substantiated the possibility of a rapid surge of the Vestre Grønfjordbreen glacier, which led to the formation of a push moraine from marine sediments of Grønfjorden Bay, during the Little Ice Age. Mavlyudov and Kudikov [2019] hypothesized in favor of the surging of the Aldegondabreen glacier during the same period. However, during the constant presence of humans in the study area, that is, since the beginning of the 20th century, no significant movements of the two glaciers have been documented.

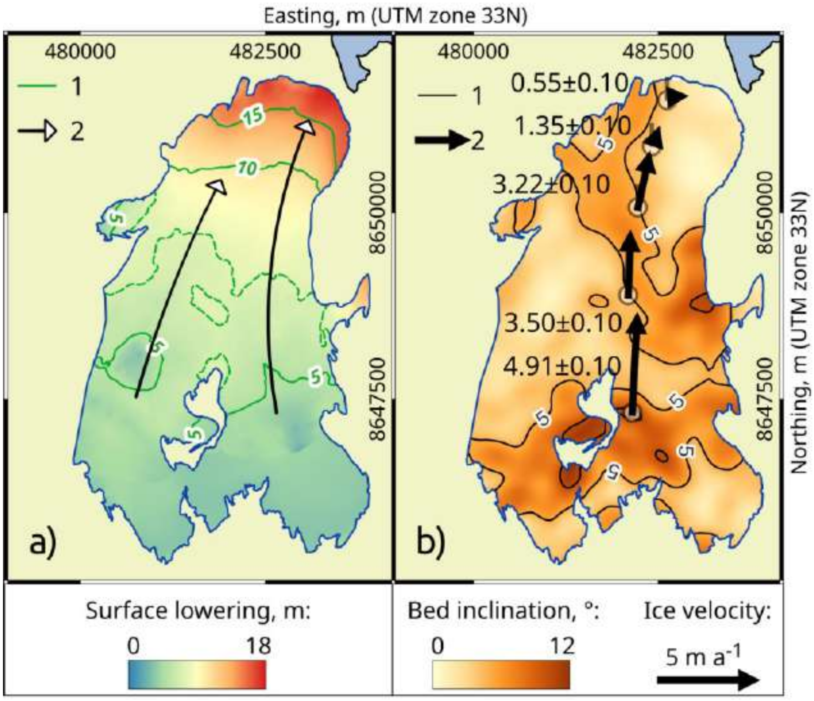


Figure 4.9 — Surface lowering of the Vestre Grønfjordbreen glacier in 2015–2019 (a) and annual ice flow velocities (b)

4.3 Inter-annual variability

4.3.1 Relationship with the main meteorological variables

Numerous studies show that the mass balance of Arctic glaciers is most sensitive to changes in summer air temperature (see, for example, [Gardner et al., 2011; Pelt van et al., 2012]). This value can be quantified by several indicators, such as the average temperature of the summer months or the annual sum of positive degrees-days (*PDD*). In this study, both variables are used, and the interval from June to September inclusive is taken as “summer”, since these four months have an average air temperature above zero. The author's assumption that the sums of degree days can be more informative than the average temperature of June–September $T_{6\text{-}9}$ is based on the greater variability of this indicator over the period of monitoring. Thus, the 2016/17 and 2018/19 balance years are the same in terms of the average temperature $T_{6\text{-}9}$, which was +4.9°C, but the *PDD* values for them differ by approximately 10% (670 versus 610 degree days, respectively).

For the Aldegondabreen glacier, the linear correlation coefficients between B_a and $T_{6\text{-}9}$ and between B_a and *PDD* are equal, amounting to 0.83. The indicated values are calculated for the homogenized part of the mass balance series, consisting of twelve balance years (2007/08–2021/22, with a three-year gap). Adding the first years of monitoring which are non-homogenized due to lost source data (2002/03–2005/06), noticeably reduces the correlation values to 0.60 and 0.65, respectively.

For the Vestre Grønfjordbreen glacier, the linear correlation between B_a and $T_{6\text{-}9}$ is also expectedly negative, but smaller in magnitude than for the Aldegondabreen glacier, equal to 0.68 (2013/14–2021/22). The correlation between B_a and *PDD* over a similar time period is 0.61. Adding the first three balance years of measurements on the glacier, the results of which cannot be homogenized (2003/04–2005/06), significantly reduces the correlation values to 0.51 and 0.50, respectively, as in the case of the Aldegondabreen glacier.

The mass balance values for the Aldegondabreen glacier correlate somewhat better with the meteorological variables measured at the Barentsburg weather station than those of the Vestre Grønfjordbreen glacier, located 5–6 km further from the settlement (Table 4.7). This can be explained by the fact that as the distance from the weather station increases, the representativeness of its observations decreases. However, an analysis of the dependencies shows an anomaly in B_a measured on the Vestre Grønfjordbreen glacier in 2015/16. The graphs (Figure 4.11) demonstrate that the balance measured in this year is the most distant from the identified empirical patterns: the summer was relatively warm, and the previous winter had little snow, but the Ba indicator not only did not become a record negative, but did not even come close to the two existing negative peaks (2016/17 and 2019/20). If we exclude the results of 2015/16 from the correlation analysis, the correlation coefficients for the Vestre Grønfjordbreen glacier improve significantly: for $Ba–T_{6\text{-}9}$ they increase in absolute value from 0.68 to 0.73, for *Ba–PDD* they increase from 0.61 up to 0.84. These values are comparable to those obtained for the Aldegondabreen glacier.

Table 4.7 — The linear correlation coefficients between the mass balance values of the studied glaciers and meteorological variables measured in Barentsburg

Glacier	Time span	Years	B_a–*PDD*	B_a–$T_{6\text{-}9}$	B_w–P_{solid}	B_a–B_w
Aldegondabreen	2007/08–2021/22 гг. (homogenized values only)	12	−0,83	−0,83	0,80	0,76
	2002/03–2021/22 гг. (with non-homogenized values)	16	−0,60	−0,65	0,50	0,72
Vestre Grønfjordbreen	2013/14–2021/22 гг. (homogenized, without 2015/16 г.)	9	−0,84	−0,73	0,69	0,51
	2013/14–2021/22 гг. (homogenized)	8	−0,61	−0,68	0,48	0,40
	2003/04–2005/06, 2013/14–2019/20 гг. (with non-homogenized values)	13	−0,50	−0,51	0,40	0,34

The anomalous B_a value obtained for the Vestre Grønfjordbreen glacier in 2015/16 cannot be considered erroneous. First, all ablation stakes installed on the glacier were measured, which eliminates the possibility of incorrect extrapolation. Secondly, a possible systematic error of 0.7...0.8 m w.e. is too large to be caused by a typo in the field journal or a single mistake in calculations. A similar error value could only be obtained by taking an erroneous reading on every stake, of almost a meter of water equivalent on each, which is hardly possible. Possibly, in some seasons, the representativeness of the Barentsburg weather station for areas south of Grønfjorden Bay decreases dramatically. In the southern part of the Vestre Grønfjordbreen glacier, there is an ice divide with a much larger glacier, Fridtjovbreen. One of the two prevailing wind directions there in summer is south-southeast (Figure 2.6). It could be speculated that the air masses entering Vestre Grønfjordbreen from the other side of the ice divide, which faces the Van Mayen fjord, may have some cooling effect and are poorly characterized by the weather station in Barentsburg. It is difficult to test the hypothesis since there are no constant weather observations near the ice divide.

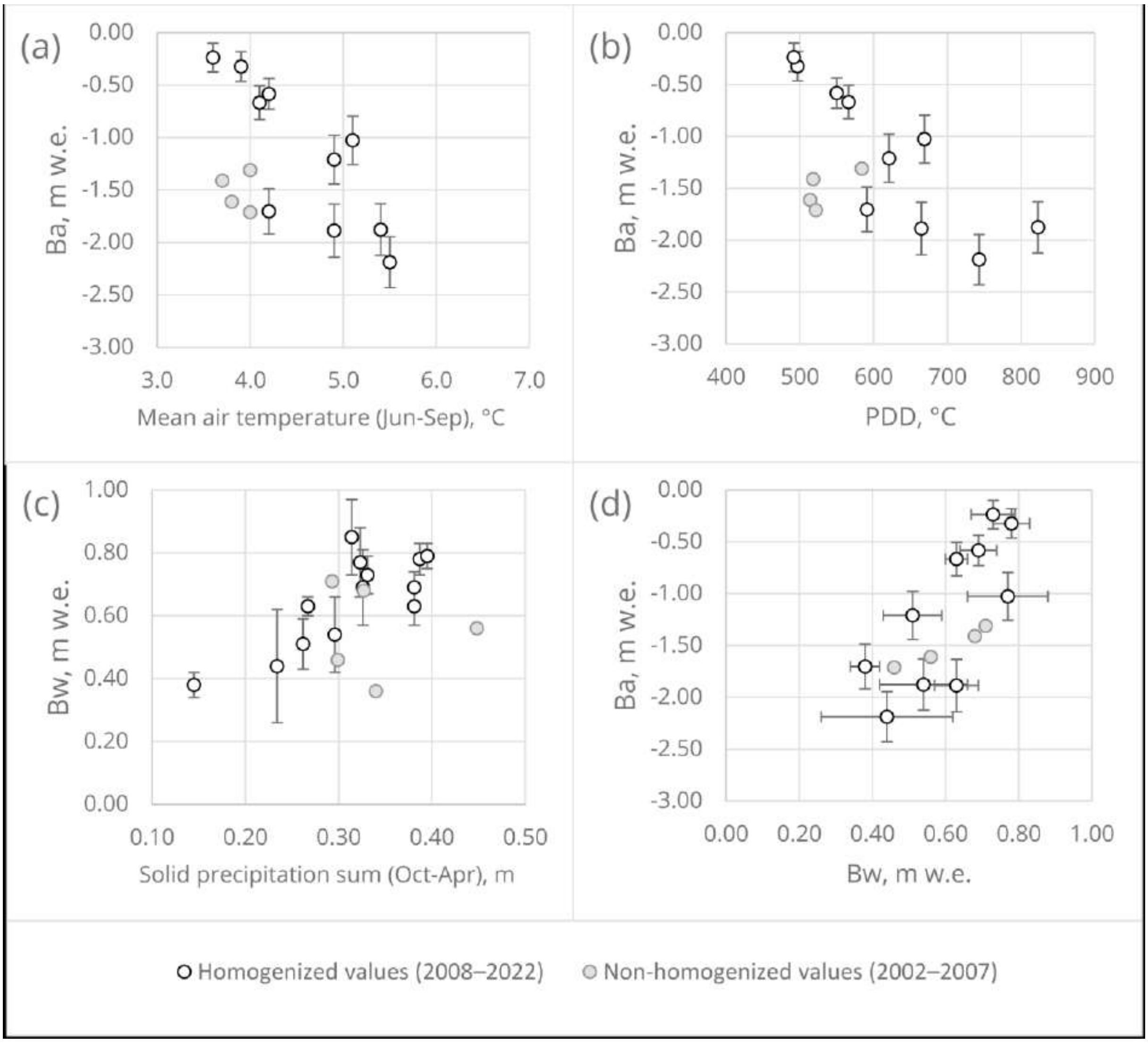


Figure 4.10 — Relationships between mass balance values of the Aldegondabreen glacier and the main meteorological variables measured in Barentsburg

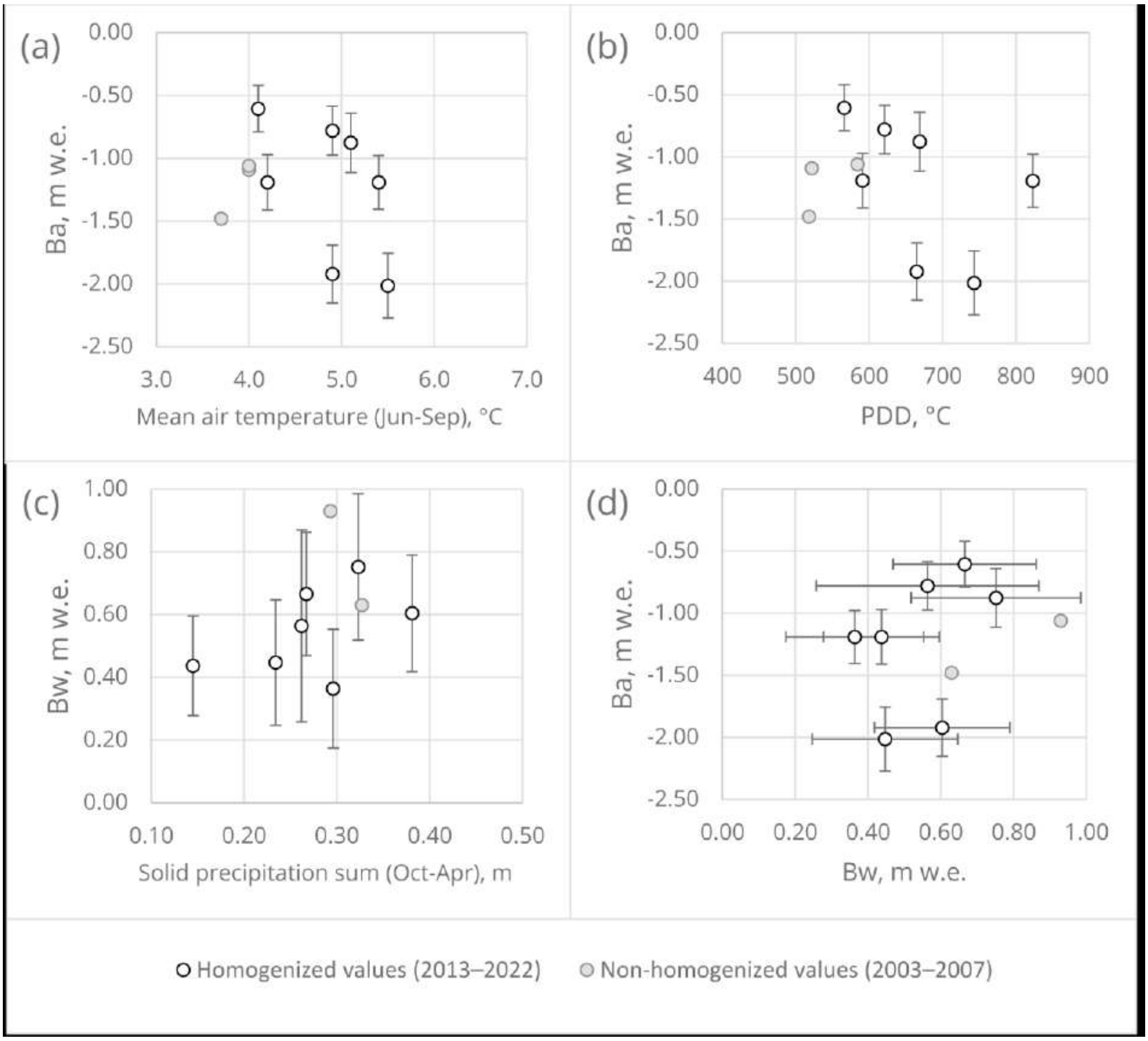


Figure 4.11 — Relationships between mass balance values of the Vestre Grønfjordbreen glacier and the main meteorological variables measured in Barentsburg

Air temperature is not the only meteorological variable that affects the mass balance of glaciers in the archipelago. Lefauconnier and Hagen [1990], based on a series of monitoring observations over 22 years on the Austre Brøggerbreen glacier, showed that its mass balance values also demonstrate a high correlation with the amount of precipitation during the winter season and with the annual amount of downward long-wave radiation. Since long-wave radiation is not measured regularly either in Barentsburg or anywhere else near the studied glaciers, it is only possible to analyze the relationship with solid precipitation.

In the World Data Center, which provides weather data from the Barentsburg weather station, only the amount of precipitation is available for download, but not its form (liquid or solid). Therefore, to estimate the amount of solid precipitation, it is necessary to use some kind of approximation. One possible way to approximate the amount of solid precipitation is by summing up the daily amounts of precipitation for the months from October to April (i.e., months with negative average air temperatures), but only for those days whose average air temperature was below zero.

For the Aldegondabreen glacier, the Pearson correlation coefficient between *Bw* and solid precipitation is 0.80 for the homogenized part of the series, since 2007/08. Adding earlier results, when the snow survey field pattern changed annually, reduces the correlation significantly up to 0.50. For the winter balance of the Vestre Grønfjordbreen glacier the correlation with solid precipitation is 0.48, but excluding the anomalous year 2015/16 raises the value again to 0.69.

The obtained values of the dependence of Bw of the Aldegondabreen and Vestre Grønfjordbreen glaciers on the amount of solid precipitation ($r = 0.79$ and $r = 0.69$) exceed the previously published values for Svalbard. By comparison, Hagen and Liestøl [1990] estimated a similar relationship for the Austre Brøggerbreen to be 0.63, given that the weather station was located directly at the glacier terminus. The search for connections between the winter balance of Svalbard glaciers and measurements at more distant weather stations is complicated by many factors: the nonlinear underestimation of the solid phase of precipitation by gauges, which depends on wind speed and air temperature (Førland and Hanssen-Bauer [2000]), the influence of local factors causing uneven snow accumulation, for example, by the surface roughness of the glacier [Lehning, Grünewald, Schirmer, 2011], the configuration of the valley sides surrounding the glacier [Grabiec, 2005], wind and avalanche redistribution of snow [Huss et al., 2008], inversions of the vertical precipitation gradient [Mernild, Liston, 2010]. In this regard, snow accumulation on the surface of the Aldegondabreen and Vestre Grønfjordbreen glaciers turns out to be quite representative of a similar process in the village of Barentsburg, located approximately 5 and 10 km from the glaciers, respectively.

A previous analysis of a similar relationship carried out by Soviet glaciologists for the Vøringbreen glacier showed a contradictory result: the correlation between the glacier's B_w and the amount of solid precipitation in Barentsburg was close to zero and had a minus sign, amounting to -0.13. This result seems implausible given the fact that Vøringbreen is the glacier closest to the village of Barentsburg in the study area. The complete lack of correlation was explained by the authors with a brevity of the observation interval (nine balance years from 1973/74 to 1981/82), which extends the uncertainty of the correlation coefficient to ±0.2...0.3 [Macheret and Zhuravlev, 1985]. However, even taking into account such uncertainty band, there is no relationship between the winter mass balance and precipitation in Barentsburg in this case.

According to modern calculations from the Vestre Grønfjordbreen glacier, it is clear that even on comparable sample size (seven balance years), the coefficient for such a connection is quite high. We can conclude that the matter is in the chosen method of approximating solid precipitation: when studying the Vøringbreen glacier, the amount of solid precipitation was approximated as the sum of *monthly* precipitation values from September to May. If we calculate the correlation coefficients for the

Aldegondabreen and Vestre Grønfjordbreen glaciers using a similar method, they will also turn out to be low: 0.40 and 0.36, respectively. This example demonstrates the importance of the chosen method for calculating meteorological variables when analyzing the results of mass balance monitoring.

In addition to the connection between the mass balance series from the studied glaciers and the main meteorological variables measured at the nearest weather station, the dependence of the annual mass balance B_a on the winter balance B_w was also analyzed. The mechanism of such interaction is described in the work of van Pelt and co-authors [2016] as follows: the higher the thickness of the snow cover on a glacier at the beginning of summer, when the peak of incoming short-wave radiation occurs, the longer the surface albedo remains high, protecting ice with a lower reflectance from melting. For both glaciers, the expected positive relationship is indeed observed: for the Aldegondabreen glacier the coefficient is 0.76, and for the Vestre Grønfjordbreen glacier it is only 0.40, but the exclusion of 2015/16 again leads to an increase in the coefficient to 0.51. The obtained values indirectly confirm the leading role of short-wave radiation in the input part of the surface energy balance of low-elevated glaciers on Svalbard, as was previously shown in the works of Arnold et al. [2006], Prokhorova et al. [2021] and Zou et al. [2021]. Thus, the record negative rate of glacier mass loss in 2019/20 can be explained not only by the warm summer but also by the extremely low snow accumulation over the previous winter: taking into account the margin of error, the measured value may be the lowest in 20 years of monitoring.

In conclusion, it is worth noting that all expected climatic dependencies for the glaciers under consideration are indeed revealed but for homogenized parts of the series. Adding the non-homogenized part of the series significantly reduces the correlation coefficients (Table 4.7). This demonstrates the need to homogenize the results of long-term monitoring, which, in turn, entails the need for careful preservation of all original data and materials in archives.

4.3.2 Sensitivity to the climate changes. Reconstruction of missing values

The empirical patterns described above make it possible to construct a linear regression relationship with two predictors, connecting the mass-balance of the glaciers under consideration with the meteorological variables measured at the Barentsburg weather station. The proposed regression model is expressed by the following equation:

$$B_a = B_s + B_w = k_1 * PDD + k_2 \times P_{solid} \quad (16)$$

where PDD is the annual sum of positive temperatures, P_{solid} is the sum of daily precipitation for days with a positive average air temperature, from October to April inclusive, k_1 is the widely used degree-day factor, averaged for snow and ice [Hock, 2005; Ohmura, 2001] and k_2 is the scale factor for precipitation. Other meteorological variables, such as short-wave or long-wave radiation, are deliberately not included in the formula, since air temperature and precipitation are the very values that are available for the longest time in the study area, since 1911.

The coefficients calculated based on the real measurements are shown in Table 4.8. The degree–day coefficient k_1 is slightly higher for the Aldegondabreen glacier, that is, at the same air temperature, the surface of Aldegondabreen melts more intensely on average, which is in good agreement with its lower location compared to Vestre Grønfjordbreen. For the k_2 coefficient, which reflects how much more snow falls on average on glaciers compared to the Barentsburg weather station, the result is less expected: Vestre Grønfjordbreen, despite the higher surface height, turned out to be "drier". A logical, in the author's opinion, explanation may be its greater distance from the wide sea bay of Isfjorden.

Table 4.8 — Empirically obtained values of linear regression coefficients for the Aldegondabreen and Vestre Grønfjordbreen glaciers mass balance

Coefficient	Glacier	
	Aldegondabreen	Vestre Grønfjordbreen
Degree–day melt factor, k_1	−2,8 mm w.e.	−2,6 mm w.e.
Precipitation scaling factor, k_2	2,05	1,95
Linear model R^2	0,91	0,86

Based on the regression formula (16), we can derive the zero mass balance equation for the glaciers under consideration. Equating B_a to zero and moving $k1 \times PDD$ to the left side of the expression, we obtain:

$$k_1 \times PDD = -k_2 \times P_{solid} \quad (17)$$

Substituting the previously found coefficients (Table 4.8) gives an equation for the case when winter accumulation completely compensates for melting over the subsequent summer (Figure 4.12). Glaciers lose mass under climate conditions located below the "compensation" line on the graph, and vice versa. Figure 4.12 also shows the minimums and maximums, as well as the average values of *PDD* and solid precipitation since the beginning of the 21st century. It can be seen that the snowiest winter was unable to compensate for even the coldest summer, and on average the amount of solid precipitation turned out to be 2.5 times lower than required to achieve zero balance. Despite the apparent similarity of the graphs of the two glaciers due to the image scale, the Aldegonda zero balance line is shifted higher along the solid precipitation axis by several tens of millimeters, which is consistent with the systematically more negative observed B_a values for it.

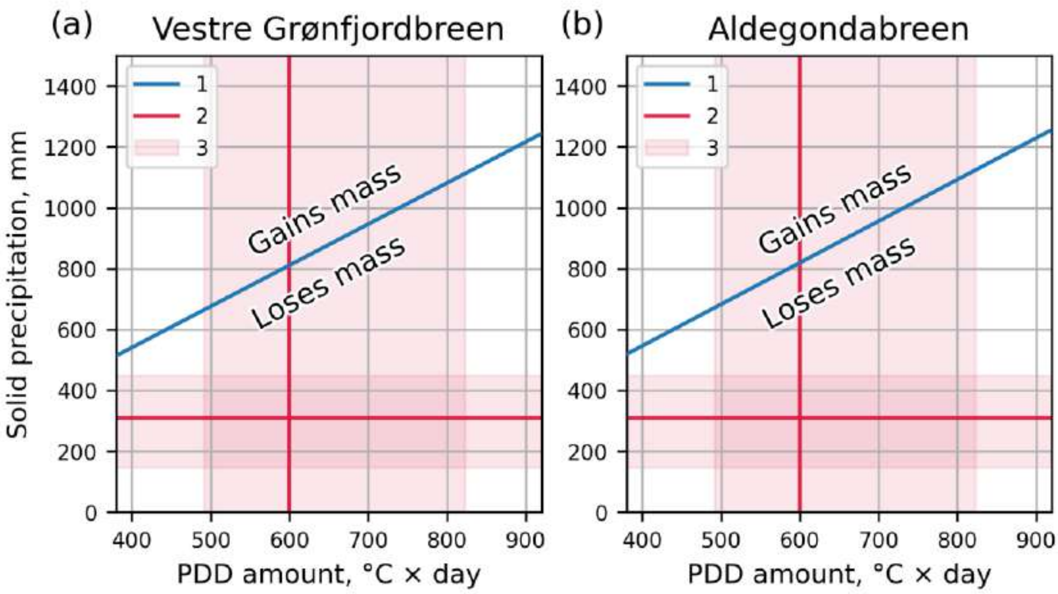


Figure 4.12 — Condition under which winter snow accumulation completely compensates for ablation over the subsequent summer, for glaciers Vestre Grønfjordbreen (a) and Aldegondabreen (b)
1 — zero mass balance line, 2 — mean value, and 3 — min–max range for the main meteorolocigal variables measured in Barentsburg in 2001–2020

Based on the zero balance graphs (Figure 4.12) and current climatic trends, it is possible to speculate of the future dynamics of the mass balance of the two glaciers. Hanssen-Bauer and co-authors, in a review of the climate of Svalbard, showed that the average summer air temperature in the Barentsburg area increases by 0.27–0.46°C decade^{-1} [Norsk Klimaservicesenter, 2019]. This is equivalent to a shift on the graphs deeper in the area of "mass loss" by +25...50 degree–days every decade. At the same time, the amount of solid precipitation will remain unchanged or become less, even though annual precipitation in Barentsburg is also increasing by 2% per decade. The reason is a decrease in the ratio of solid precipitation to the total one due to winter warming. Thus, on average, the mass balance of both glaciers will move further and further away from the equilibrium line.

In addition, an analysis of AAD changes for the Aldegondabreen showed (Figure 3.5) that the glacier is becoming lower. Due to the influence of the morphological factor, Aldegondabreen turns out to be more vulnerable to climate change. Taking into account the current total volume of the glacier, we can conclude that it may completely disappear in three decades, that is, by the middle of this century.

A by-product of the regression model (16) is the ability to reconstruct on its basis the mass-balance values of the Aldegondabreen glacier for the period 2010/11–2012/13 when measurements were not carried out (Table 4.9). The reconstruction allows us to complete a continuous non-interrupted series of B_a and B_w balances for the Aldegondabreen glacier and, firstly, move on to the analysis of long-term variability outlined in the next paragraph, and, secondly, calculate the total mass loss over the monitoring period. For the Vestre Grønfjordbreen glacier, such a reconstruction is not required, since there are no breaks in the observation series.

Table 4.9 — Reconstructed mass balance values for the Aldegondabreen glacier
* — measured values

Balance year	Glacier-averaged mass balance, m w.e.		
	Annual	Winter	Summer
2006/2007	−0,74±0,48	+0,69±0,12*	−1,43±0,49
2010/2011	−1,08±0,48	+0,79±0,04*	−1,87±0,48
2011/2012	−0,97±0,48	+0,85±0,12*	−1,82±0,49
2012/2013	−1,25±0,48	+0,54±0,24	−1,79±0,54

4.4 Decadal variability

4.4.1 Cumulative glaciological mass balance and the intercomparison with the geodetic one

It is possible to demonstrate the absence of a statistically significant systematic error in long-term mass balance monitoring series by comparing cumulative values obtained by two independent methods over longer periods of time [Zemp et al., 2013]. In the case under consideration, such a comparison can be carried out for the period 2008–2018 for the Aldegondabreen glacier and 2015–2019 for the Vestre Grønfjordbreen glacier, using the results of the glaciological and geodetic method presented earlier

For the Vestre Grønfjordbreen glacier, the total mass balance over seven years of glaciological observations (September 2013–September 2020) was 7.67 ± 0.55 m w.e., which corresponds to a total mass loss of 143.2 ± 9.8 million tons. This value is 8±1% of the total mass of the glacier, calculated based on the results of a geophysical survey in 2019 [Terekhov et al., 2022]. A comparison of the results obtained by the two methods (Table 4.10) shows the absence of statistically significant error in the series (α = 95%). The mismatch of the duration of time intervals of geodetic and glaciological balance, which is five days, can be neglected. No calibration of the B_a series is required for the Vestre Grønfjordbreen glacier.

Table 4.10 — Comparison of cumulative balances calculated by two methods for the Vestre Grønfjordbreen glacier

Time span	Glaciological method	Geodetic method
2015–2019	–5,66±0,48 m w.e. (25 Jul 2015–16 Sep 2019)	–5,52±0,40 m w.e. (20 Jul 2015–26 Aug 2019)
2013–2020 (the monitoring period)	–7,67±0,55 m w.e. (10 Sep 2013–23 Sep 2020)	—

For the Aldegondabreen glacier, geodetic mass balance for the periods 2008–2013 and 2013–2018 are listed in Table 4.11. Over a decade both balances coincide within an uncertainty, which means that calibration of the B_a series in the case of the Aldegondabreen glacier is not required.

Table 4.11 — Comparison of cumulative balances calculated by two methods for the Aldegondabreen glacier

Time span	Glaciological method	Geodetic method
2008–2013	–4,42±0,87 m w.e. (10 Sep 2007–10 Sep 2013)	–4,49±0,32 m w.e. (mid-July 2008–17 Aug 2013)
2013–2018	–6,30±0,49 m w.e. (10 Sep 2013–01 Aug 2018)	–6,16±0,44 m w.e. (17 Aug 2013–02 Aug 2018)
2002–2020 (monitoring period)	–21,79±1,26 m w.e. (Sep 2002–Sep 2020 г.)	—

Cumulative mass balance of the Aldegondabreen glacier since the beginning of the moniroting program equals -21,79 m w.e., which corresponds to a mass loss of 129,6 Mt. Considering the total glacier volume (2018–2019) of 0,278 km^3 [Borisik et al., 2021b], the relative mass loss within 18 balance years is 37%. This value is comparable with the results of another, geophysical, method based on two GPR surveys of 1999 и 2018–2019 which yielded 36% mass loss [Borisik et al., 2021b].

The above analysis of monitoring results leads to two conclusions. Firstly, it was shown that the series of the annual mass balance of the studied glaciers are devoid of any significant systematic bias, which became possible due to comparison with the results of the second independent method — geodetic. Secondly, for successful reanalysis of mass balance series in the future, it is necessary either to use longer time intervals for calculating the geodetic balance (for example, a decade instead of five years), which will reduce its uncertainty, or the quality of mutual DEM georeferencing must be radically improved. The latter is realistic in the case of obtaining the surface topography based on ground GNSS survey, or unmanned aerial photography with a geodetic GNSS receiver on board. The fact that the ArcticDEM DEM became available for use in this study is somewhat coincidental, because some of the adjacent areas do not have coverage due to overcast clouds on the optical stereo pairs on the basis of which the DEM fragments were constructed. Since reanalysis has shown its benefits, the author proposes to continue long-term monitoring in parallel with two methods, adding to traditional glaciological work regular, once every five to ten years, surveys of the glacier topography with subsequent calculation of the geodetic mass balance.

4.4.2 Trend analysis. Periodicity

Trend analysis for mass balance values is only possible for the glacier with a longer monitoring program - for Aldegondabreen (Figure 4.13) since a series from Vestre Grønfjordbreen is too short (Figure 4.14). There are two main prerequisites for assuming the existence of a negative trend in the Ba series: firstly, the air temperature on Svalbard has been increasing over the past few decades with a not increasing amount of solid precipitation [Pelt Van et al., 2019]. Secondly, the surface of the Aldegondabreen glacier becomes generally lower, as shown in Figure 3.5. However, analysis of two decades of the mass balance of the Aldegondabreen glacier using parametric and non-parametric tests does not show statistically significant trends for either the winter or annual balance, even at the 0.10 significance level.

The lack of trend in the series can be explained by the archipelago-wide patterns of the glacier mass balance in the early 21st century. An analysis of remote sensing data in the middle of the 2000s showed a significant acceleration in the rate of mass loss for Svalbard glaciers. Bamber et al. [Bamber et al., 2005] based on repeated lidar surveys in 1996 and 2002 found that during this period the average mass balance was –0.19 m w.e. per year, which is 1.6 times lower than in the previous 30 years. In 2003–2005 the glacier thinning became even more intense — 4 times higher than in 1936–1962, which is the first period available for calculation from archival data [Kohler et al., 2007]. Record negative mass balance values were also observed by direct measurements on the glaciers in the vicinity of Barentsburg [Solovyanova, Mavlyudov, 2007; Mavlyudov and Solovyznova, 2007]. The corresponding timespan is indicated for the Aldegondabreen glacier by number 1 in Figure 4.13. It can be seen that the annual mass loss during this period was significant, and winter snow accumulation was low.

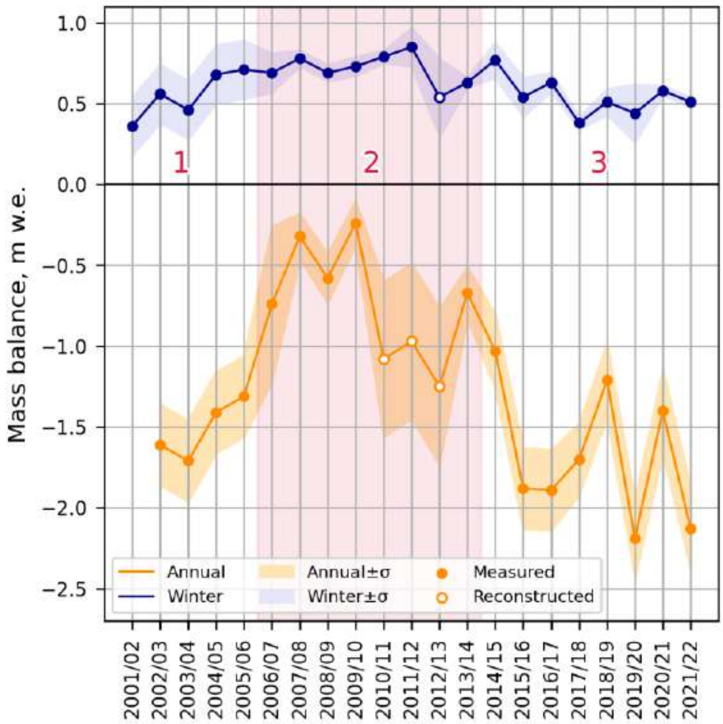


Figure 4.13 — The Aldegondabreen glacier mass balance in the early 21st century
Numbers 1, 2 and 3 indicate periods of different atmospheric circulation over Svalbard

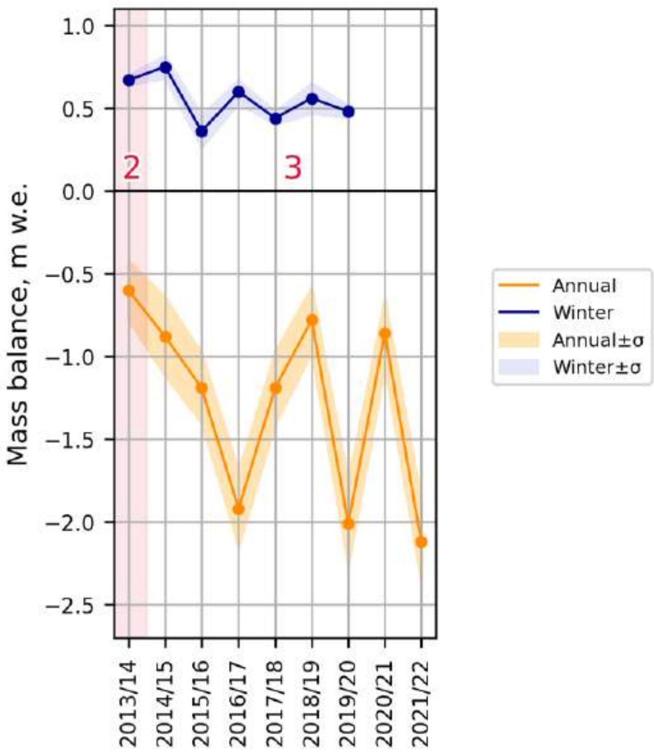


Figure 4.14 — The Vestre Grønfjordbreen glacier mass balance in the early 21st century
Numbers 1, 2 and 3 indicate periods of different atmospheric circulation over Svalbard

During 2005–2012 on Svalbard, the glacier mass balance increased. According to gravimetric data from the GRACE program, it was calculated that in 2005–2012, total ice loss on the archipelago practically stopped [Wouters, Gardner, Moholdt, 2019]. This period is indicated by number 2 in Figure

4.13. It can be seen that the least negative annual values and record snow accumulation are observed on the Aldegondabreen glacier at this time. Since 2013, the mass balance of glaciers in the archipelago was again characterized by more negative values [Noël et al., 2020]. During this period, indicated on the graph by number 3, the Ba and Bw values of the Aldegondabreen glacier also decreased significantly.

Lang et al. [2015], based on reanalysis data, explained the periodicity of the mass balance of Svalbard glaciers in the beginning of the 21st century by shifts in atmospheric circulation patterns. As a result of the shift in 2005–2012, the archipelago was more often dominated by colder Arctic air masses coming from the northwest. Indirect confirmation of the hypothesis of Lang and co-authors is the result of the analysis of the frequency of phases of the North Atlantic Oscillation (NAO) index, presented in [Terekhov et al., 2022]. The positive and negative phases of the index, calculated from the pressure difference between the Icelandic low and the Azores high, are characteristic of the atmospheric circulation in the region. When considering the frequency of positive and negative phases of the NAO during months with positive average air temperatures (June–September), it was confirmed that the more favorable time interval for glaciers was indeed characterized by an increased frequency of the negative phase of the index associated with increased transport of cold Arctic air masses (Figure 4.15).

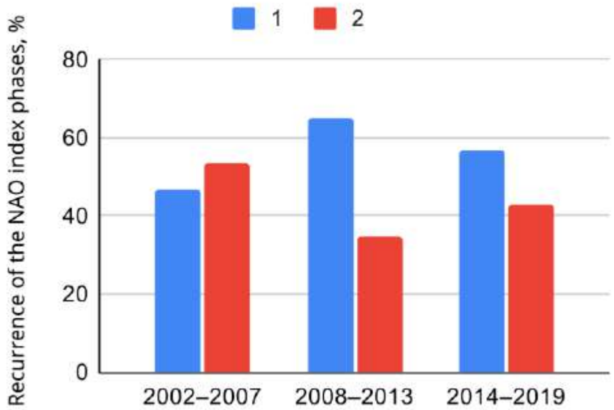


Figure 4.15 — Recurrence of different phases of the North Atlantic Oscillation (NAO) index in the early 21st century: 1 — negative phase, 2 — positive phase

Thus, long-term, decadal-scale variations in the mass balance of the Aldegondabreen glacier reflect the patterns of atmospheric circulation over the Svalbard archipelago. Since this factor has a regional scope, a similar periodicity of mass balance should have been simultaneously observed on other glaciers in the vicinity of Barentsburg. In this area, mass balance estimates for two more glaciers, Austre Grønfjordbreen and Austre Dalfonna, are available for comparison.

Geodetic mass balance of the Austre Grønfjordbreen glacier was –0.97 m w.e. a^{-1} for the period 2008–2013 and –1.45 m w.e. a^{-1} for 2013–2017 [Elagina et al., 2021]. For the Austre Dalfonna, Terekhov and co-authors [2022] estimated the geodetic balance for 2008–2013 at −5.22±0.37 m w.e., and for 2013–2019 at −6.83±0.48 m w.e. (Figure 4.16). Thus, mass loss by both glaciers was indeed lower in the period 2008–2013 than in subsequent years, which confirms the synchronous nature of long-term fluctuations in mass balance series. Thus, the decadal variability of the mass balance of the glaciers of Barentsburg area obeys general patterns that are typical for all glaciers on the island of Western Spitsbergen. This makes the studied glaciers a reliable indicator of climate changes *on a regional scale*.

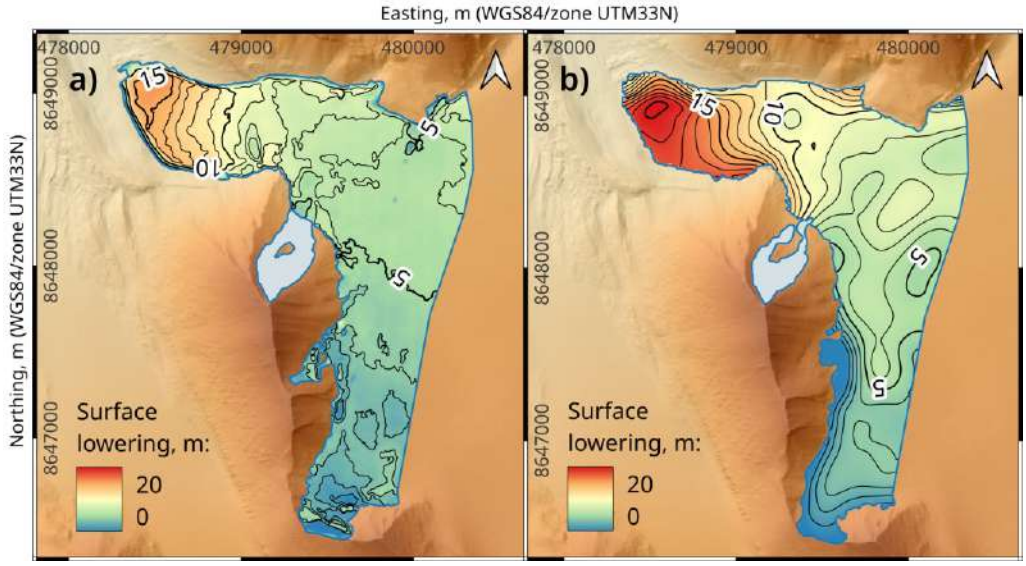


Figure 4.16 — Surface lowering of the Austre Dahlfonna glacier (from [Терехов et al., 2022]): a) 2008–2013, b) 2013–2019

It is worth noting that the author does not dispute the existence of positive long-term air temperature trends within Svalbard. The magnitude of these trends varies somewhat in different parts of the archipelago, but significantly exceeds global average estimates [Isaksen et al., 2022; Nordli et al., 2014; Przybylak, Wyszyński, 2020; Serreze, Barry, 2011]. Analysis of the mass balance series from the Aldegondabreen glacier shows how these trends can be complicated by decadal variability associated with changes in atmospheric circulation regimes. However, in the long term, glaciers in the Barentsburg region can be expected to continue to lose mass, despite the recent episode of short-term increase in balance [Pelt Van et al., 2021].

4.5 Representativeness of the obtained mass-balance series

One of the most important questions that arise when analyzing long-term mass balance series obtained as a result of glacier monitoring is their representativeness. In the mid-20th century, when the need to expand the geography of monitoring programs was realized, the concept of a benchmark glacier was formulated. The term "benchmark" means that the data obtained during the monitoring can be extrapolated to the entire region where this glacier is located. The need to select benchmark objects was dictated by the obvious impossibility of organizing observations on each of the glaciers in the world. According to the concept, measurements at the benchmark glacier should reflect the underlying variations of glacial accumulation and ablation in the region. The choice of a benchmark glacier should be dictated by several factors: it should represent the most common morphological type in the study area, and have a typical altitudinal range and size [Fountain et al., 2009].

The Svalbard archipelago continued to be a relatively inaccessible area throughout the 20th century. Regular annual scientific expeditions began their work there only in the 1960s, and the first monitoring programs were started for those glaciers that were close to populated areas that served as logistics centers. As a result, the longest series to date were obtained for the Midtre Lovenbreen and Austre Brøggerbreen glaciers, located near the village of Ny Ålesund. In the Soviet glaciological research program, the mass balance of the Vøringbreen glacier, the closest to the settlement of Barentsburg, was measured for the longest time. Thus, the choice of objects for mass balance monitoring on the Svalbard archipelago has historically been determined primarily by transport accessibility.

Monitoring programs in the Barentsburg area, resumed by Russian researchers at the beginning of the 21st century, were no exception. The choice of the Aldegondabreen and Vestre Grønfjordbreen glaciers as study objects was made primarily because of the possibility of reaching them from the scientific base in an acceptable time. In addition, the surface of these glaciers is quite homogenous, allowing researchers to walk or ride a snowmobile relatively safely.

Speculations about the “typicality” of the Aldegondabreen and Vestre Grønfjordbreen glaciers in terms of their spatial characteristics lead to disappointing conclusions. The Svalbard archipelago, known for the variety of morphological types of glaciation, is characterized by the widespread occurrence of so-called “net glaciation” (Russian term) that is, large ice fields and caps that almost completely cover the underlying relief [Glaciology of Spitsbergen, 1985] except the mountain tops exposed as nunataks. In this regard, the mountain-valley glaciers Aldegondabreen and Vestre Grønfjordbreen could hardly be considered typical for the archipelago. Moreover, the western part of Nordenskiöld Land, where the study area is located, differs in principle in its glaciation from the rest of the territories of Svalbard, since it is characterized by its lowest proportion and the smallest glacier sizes.

The area–altitude distributions of the studied glaciers also cannot be considered typical for the archipelago: the peak of the averaged hypsometric curve for the Svalbard glaciation occurs at heights of about 500 m, while the peak of a similar curve for the western part of Nordenskiöld Land is approximately 150 m lower (Figure 2.2). While the AAD of the Vestre Grønfjordbreen glacier is close to the generalized curve for Nordenskiöld Land, the Aldegondabreen glacier is located at even lower hypsometric levels, with the predominant proportion of the surface laying between 200 and 300 m above sea level (Figure 3.5).

Thus, based on the morphological properties of the glaciers in the study area, it is impossible to rationalize their representativeness for the Svalbard archipelago. However, the representativeness of obtained data can be demonstrated based on the monitoring results, by analyzing the relationship of the mass balance series with climatic variables.

Analysis of interannual variability showed that the annual and winter values of the Aldegondabreen and Vestre Grønfjordbreen glaciers have high correlations with air temperature and the amount of solid precipitation measured at the Barentsburg weather station. Consequently, the resulting series fully reflects climatic variations, at least in the area of Barentsburg.

Analysis of long-term variability in the mass balance series on time scales of 5–10 years showed that the periodization of the obtained values reflects a general pattern across the archipelago. Likely, this pattern is associated with a regional-scale factor — changes in atmospheric circulation regimes. Long-term periods of increased and decreased mass balance can be identified not only for the Aldegondabreen glacier but also for other glaciers in the Barentsburg region, the balance of which was measured over the required periods. Consequently, on a decadal time scale, the monitoring series presented in this work reflects *regional climate variability.*

Moreover, the mass balance of the Aldegondabreen and Vestre Grønfjordbreen glaciers is influenced to some extent by *global weather events*. Record mass loss observed during the monitoring programs was measured on the studied glaciers in 2019/20 and 2021/22. The air temperature in these two years was extremely high not only in the Barentsburg area but globally. Thus, the summer of 2020 in the Northern Hemisphere became the second hottest on record since 1880 [August 2020 Global Climate Report, 2020]. In Scandinavia and the North Atlantic, the highest temperature anomalies were observed in June, which led to the accelerated disappearance of snow cover on Arctic glaciers [Heatwaves and warm spells, 2020]. In the summer and autumn of 2022, the study area was several times exposed to prolonged heat waves, which anomalously extended the melting season in September–October [Prokhorova et al., 2023]. These large-scale weather events were associated with blocking anticyclones that covered the entire European part of the continent and extended their influence far to the north [Climate bulletins, 2022]. Thus, the record ablation of the Aldegondabreen and Vestre Grønfjordbreen glaciers in 2020 and 2022 was influenced by factors on a broader scale than the regional one, which affected absolutely all the glaciers of the Svalbard archipelago.

From the above analysis, it can be concluded that the mass balance series of the Aldegondabreen and Vestre Grønfjordbreen glaciers obtained from ongoing monitoring at the interannual time interval, as well as at longer intervals of 5–10 years, reflect regional variations in ablation and accumulation on the Svalbard glaciers, and are representative in terms of the cryosphere–climate interaction. In this sense, the benchmark glacier concept is harmful, since according to it neither the Aldegondabreen glacier nor the Vestre Grønfjordbreen should have been chosen as a monitoring object. Thus, representative mass balance series would be lost to science.

Summary

In the Chapter 4, the mass balance values of the Aldegondabreen and Vestre Grønfjordbreen glaciers, obtained by applying the glaciological reanalysis technique to the long-term monitoring series, are analyzed. All the annual B_a values, for 17 balance years of observations on the Aldegondabreen glacier and nine years on the Vestre Grønfjordbreen glacier, were negative. At the same time, the Aldegondabreen glacier loses mass more intensively, which is associated with the lower altitude of the glacier surface. The total mass loss since the beginning of the monitoring period, taking into account reconstructed values for periods of observational gaps, amounted to 37% for the Aldegondabreen glacier over 18 balance years (2002–2020), for the Vestre Grønfjordbreen glacier — 8% over seven balance years (2013–2020).

Analysis of spatial variability confirms that altitude is one of the leading factors influencing the distribution of *Ba* values over the surface of glaciers in the area of Barentsburg. However, in some years the R^2 value for vertical mass balance approximation fits decreases to less than 0.5. This indicates that the contribution of other factors to the variability of the surface mass balance exceeds the influence of vertical lapses of heat and precipitation. By the example of the Vøringbreen and Aldegondabreen glaciers, it is shown that the main factor complicating the altitudinal dependence is the insolation of glaciers. It is calculated that the effect of uneven insolation on surface melt is equivalent to the effect of an altitudinal gradient of 45–60 m.

It is shown that the snow depth on the studied glaciers demonstrates a relationship with altitude above sea level, and a weaker negative correlation with the distance to the edge of the glacier (i.e., near the edge the snow depth is usually higher). However, the spatial distribution of the snow water equivalent (bw) at the end of spring rarely depends on the elevation above sea level. The main reason is the lack of a stable correlation between the integral snow density and altitude, which is observed on both monitored glaciers. This fact leads to the difficulty of modeling their mass balance using spatially distributed methods and makes snow surveys an indispensable source of data on snow cover in the study area.

The values of the linear correlation coefficients between the main parameters of snow cover and morphometric values decreased significantly in those years when the number of snow survey points was reduced. It is impossible to unambiguously determine whether changes in field measurement techniques affect the correlation coefficients, or whether this is a consequence of climatic fluctuations. This illustrates the need to maintain consistency in the monitoring design because the changes in the survey layout make it difficult to analyze the relationship with climate.

Analysis of inter-annual variability shows that Ba values correlate well with both average June–September air temperatures and annual positive degree–day sums. The relationship between the winter mass balance and the amount of solid precipitation at the Barentsburg station is found only if precipitation was calculated from daily rather than monthly totals. The correlation coefficients for the Vestre Grønfjordbreen glacier are generally lower than for the Aldegondabreen glacier, which can be explained by the rapid decline in the representativeness of the Barentsburg weather station with increasing distance from it. For both glaciers, summer ice loss also depends on snow accumulation over the previous winter, which can be explained by the predominant role of short-wave solar radiation in the heat balance of the glaciers in the study area and the difference in the albedo of snow and ice.

In all cases, adding the results of the first years of monitoring, which are impossible to homogenize due to the loss of source data, significantly reduces the correlation coefficients with meteorological variables. This demonstrates the importance of retrospective recalculation of monitoring results using a unified methodology to obtain homogeneous series. The absence of such a procedure complicates the analysis of the relationship between the mass balance of glaciers and the climate in the area. Therefore, when organizing monitoring, it is critically important to pay attention to the issues of reliable storage of initial measurement data, as well as their metadata.

Based on the identified empirical relationships, zero balance equations were calculated, showing how much solid precipitation in winter compensates for the summer melting of the studied glaciers. It was found that the measured values of main meteorological variables since the beginning of the 21st century are far from the zero balance line for both glaciers: the amount of solid precipitation observed during the monitoring period is on average 2.5 times less than that required to compensate for summer melting.

The obtained empirical relationships of the mass-balance values for the glacier with a longer series of observations — Aldegondabreen — allowed the reconstruction of the missing values needed for checking trends. The absence of a significant trend in both the annual and winter mass balances of the Aldegondabreen glacier has been demonstrated, despite 1) modern climate changes in Svalbard and 2) the identified lowering of the area–altitude distribution of the glacier over the past ten years. A comparison of the variability of the glacier mass balance in the study area shows that at time intervals of about 5–10 years, it coincides with the general patterns across the archipelago, which indicates the leading role of a regional-scale factor. Previously published works show that such a factor may be a change in atmospheric circulation regimes, as a result of which in 2005–2012 the Arctic air masses coming from the northeast dominated the archipelago. Other glaciers of the Barentsburg area are no exception to the observed periodization of mass balance characteristics, as shown by the example of the Austre Dalfonna and Austre Grønfjordbreen glaciers. Thus, glaciers in the Barentsburg area are a reliable indicator of *regional climate changes*, which resolves the issue of their representativeness.

Once published, the mass balance series for the Aldegondabreen glacier will be the longest in this part of the island of Western Spitsbergen. Unlike the second longest series from the East Grønfjord glacier, it has a comprehensive assessment of random error and a proven lack of systematic bias, as shown by comparison with the results of the second independent method — geodetic. This study shows three main ways of applying the geodetic method: 1) control of systematic error in series obtained by the glaciological method; 2) analysis of the accuracy of reconstructions of annual glacier mass balance values based on climatic relationships; 3) obtaining detailed spatial patterns of ice melt over the surface of glaciers, needed for analyzing the relationship with morphometric values. The demonstrated usefulness of the geodetic method is evidence that it is most advisable to carry out monitoring using two methods in parallel, organizing a survey of the surface topography of the studied glaciers once every five or ten years.

Conclusion

This study systematizes and presents the main results of measuring the mass balance values of glaciers in the area of the Barentsburg settlement (Spitsbergen Island), and also analyzes the spatial and temporal variability of the mass balance in connection with climate. The main practical result was the two homogeneous monitoring series, for the Aldegondabreen and Vestre Grønfjordbreen glaciers, with a proven absence of systematic bias and with a comprehensive assessment of uncertainties. The series include not only annual but also seasonal mass balance values being located in an area of central Spitsbergen where such data have previously been lacking.

The results of the ongoing monitoring of the Aldegondabreen and Vestre Grønfjordbreen glaciers, as well as episodic observations on the Austre Dalfonna and Vøringbreen glaciers, were analyzed for the spatial pattern of mass-balance values on the surface of the glaciers, their interannual and long-term variability.

It is shown that the predominant share of interannual variability in *Ba* and *Bw* values is explained by the air temperature in the summer season and the amount of solid precipitation in the winter, respectively. This result may seem obvious, but previously it hadn't been obtained in practice because the series of monitoring results in this area were never homogeneous. To demonstrate the relationship between the mass-balance of the studied glaciers and the climate, it was first necessary to carry out a retrospective recalculation of the mass-balance values, the so-called homogenization of the series.

It is shown that the distribution of mass-balance values over the glacier surface is subject to a known altitudinal dependence, however, insolation also has a strong influence: the unevenness of insolation on the Vøringbreen and Aldegondabreen glaciers, induced by topographical shading, slope, and aspect, is equivalent to the action of an altitudinal gradient of 45–60 m.

One of the most important conclusions of the study is that the resulting series **are representative of the entire Svalbard** since the long-term variability of mass balance characteristics coincides with the general pattern for the archipelago, caused by regional-scale factors, much likely to be shifts in atmospheric circulation.

Three possible ways of using the geodetic method in the study of individual glaciers are demonstrated. Firstly, the parallel use of a second independent method during monitoring makes it possible to identify and quantify systematic biases in the final values; secondly, the geodetic method provides a more detailed pattern of the spatial distribution of mass balance on the surface of glaciers than measurements of ablation stakes; thirdly, the method can be used to control reconstructions of mass balance values during forced breaks in monitoring.

The demonstrated benefits of using the geodetic method reinforce the need for further development of the Russian terminology associated with this method. The last Russian "Glaciological Dictionary" was compiled about forty years ago, when computer tech, geoinformatics, and remote sensing were at different stages of development. The development of methods and means of glaciological monitoring over the past decades has been reflected in the collection of English-language terminology, but no similar works have been published for the Russian language. The conceptual apparatus enshrined in the “Glaciological Dictionary” turns out to be insufficient to describe modern generally accepted approaches, forcing the author to use literal translations from foreign words. Thus, the collection of Russian-language terminology in the field of glaciology needs to be updated.

Relevance of this study from the point of view of the structure, dynamics and functioning of landscapes. Components of the geosystem are interconnected both in space and time, which is why their dynamics and development occur in tandem [Isachenko, 1991]. The role of terrestrial glaciation in the structure, dynamics and functioning of landscapes in polar and high-mountain territories is paramount. Glaciers are not only the most extensive component of such landscapes, but also determine a number of landscape-forming factors associated with matter fluxes. Firstly, terrestrial glaciation is the most important component of the hydrological cycle of Arctic landscapes. Secondly, glaciers indirectly affect marine ecosystems by desalinating seawater and transportating nutrients (for example, iron) from land. In addition, on large time scales, glaciers are one of the main geomorphological factors that determine the relief of Arctic territories and influence the distribution of permafrost.

Thus, the impact of terrestrial glaciation on adjacent geographic components of high-latitude landscapes manifests itself at different spatial and temporal scales. Consequently, glaciers, which influence all the main landscape-forming factors, play a critical role in the structure, dynamics and functioning of Arctic natural systems.

Prospects for further development of the topic and the author’s recommendations. The author's main recommendations are related to the methodological side of organizing mass balance monitoring. First, it was shown that preserving all original field measurements and their metadata is critical. Without saving the original data, it is impossible to retrospectively recalculate mass balance values using a unified methodology, which is necessary to eliminate possible inhomogeneities in the series. Secondly, it is also necessary to maintain continuity in fieldwork methods, including field survey designs, since changes also lead to heterogeneity in the resulting series. The emerging inhomogeneities, in turn, significantly complicate the search for connections with climatic variables.

Another recommendation is the targeted repetition of GNSS or aerial surveys within the framework of monitoring, allowing the construction of a digital model of the glacier's relief for further calculation of geodetic mass balance and the application of reanalysis techniques. A reasonable interval for surveying is a pentad since changes in glacier volume over such a period become much greater than the error in their determination. In this work, archival remote sensing data (ArcticDEM DEM) were used for mass balance calculations, but in the future, such data may not be available. In addition, such data refer to an arbitrary date, tied to the time of the satellite flight, and not to the beginning or end of the balance year or the glacier visits of AARI employees. This complicates the comparison with ablation stake measurements.

The last recommendation is to continue the complex of microclimatic and energy balance observations on glaciers in the vicinity of Barentsburg. The work showed the influence of insolation conditions on the spatial pattern of ice ablation. Regular actinometric observations are not carried out at the weather station in the village of Barentsburg, so seasonal measurements by AARI employees on glaciers are the only source of data on the fluxes of short- and long-wave radiation in this area. The analysis of the energy balance of glaciers makes it possible to explain the mechanisms of interaction in the atmosphere–glacier system and make a reasonable prediction of the future dynamics of glaciation.

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List of abbreviations

AARI — Arctic and Antarctic Research Institute

AS USSR — Academy of Sciences of USSR

GLONASS — “GLObal NAvigational Satellite System”, Russian GNSS system

GNSS — global navigational satellite systems (for example: GLONASS, GPS)

ERS — Earth remote sensing

IG RAS — Institute of Geography (Russian Academy of Sciences)

IPCC — Intergovernmental Panel on Climate Change

mln t — millions of tonns

a .s. l. — above sea level

RAE-Sh — Russian Arctic Expedition on Shpitsbergen (AARI department)

FSBI — Federal State Budgetary Institution

DEM — digital elevation model

AAR — accumulation-to-area ratio

GPS — Global Positioning System

NMAD — normalized mean absolute deviation

NOAA — National Oceanic and Atmospheric Administration (USA)

PDD — positive degree–days

USGS — United States Geological Survey

WGMS — World Glacier Monitoring Service

List of terms

Bootstrap — is any test or metric that uses random sampling with replacement, and falls under the broader class of resampling methods. Bootstrapping assigns measures of accuracy (bias, variance, confidence intervals, prediction error, etc.) to sample estimates [Efron, 1979].

Geodetic mass balance — glacier mass balance computed by geodetic method.

Geodetic method (for glacier mass balance determination) — computation of glacier-wide volume or mass changes by differencing repeated determinations of glacier surface elevations obtained from airborne and spaceborne surveys usually over multi-year to decadal periods.

Glaciological mass balance — glacier mass balance computed by glaciological method.

Glaciological (direct) method (for glacier mass balance determination) — the glaciological method involves establishing a grid of ablation stakes across a glacier, measuring accumulation and ablation with reference to the stakes several times per year, and interpolating measurements across the glacier surface.

Homogenization — procedure intended for eliminating the effects which hamper the comparability of annual mass-balance quantities [Huss, Bauder, Funk, 2009].

Dataset — a collection of related sets of information that is composed of separate elements but can be manipulated as a unit by a computer.

Calibration (of mass balance series) — the procedure for eliminating the mismatch between direct and geodetic mass balance series.

Co-registration — adjustment of relative positioning of two or more digital elevation models. Aimed to reduce the systematic vertical mismatch but may also compensate for the horizontal displacement.

Lidar —*Light Detection and Ranging*, technology and a tool for measuring distances using lasers.

Orthorectification — is the process of removing image distortions or displacements caused by sensor tilt and topographic relief.

Reanalysis (glaciological) — a procedure procedure for every monitoring programme to improve data quality, including reliable uncertainty estimates, suggested by Zemp and co-authors [2013].

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