

---

# Glaciers as an Important Element of the World Glacier Monitoring Implemented in Svalbard

---

Sara Lehmann-Konera, Marek Ruman,  
Krystyna Koziół, Grzegorz Gajek and  
Żaneta Polkowska

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/intechopen.69237>

---

## Abstract

Glaciers are not only contributors to the sea level rise but also important players in the circulation of pollutants. Over a billion people apply glacial waters for domestic purposes; hence, both the quality and quantity of this water should be monitored. In this chapter, we concentrate on the archipelago Svalbard in the Arctic, a typical target area for xenobiotics from long range atmospheric transport (LRAT), holding an important share of the Arctic glacial ice cover. Literature review has been conducted over both the cryospheric metrics and the achievements of analytical chemistry in the environmental monitoring. Svalbard is a relatively well-monitored part of the Arctic, with 17 glaciers regularly monitored for mass balance. In the chemical records of glaciers, a variety of substances have been determined, e.g., ions, heavy metals, or persistent organic pollutants (POPs), with the use of precise analytical techniques. However, knowledge gaps persist, preventing a formation of a reliable chemical inventory of Svalbard glaciers. Moreover, detailed studies on the deposition and transport of pollutants, rather than focusing on their presence only, are crucial future research recommendations.

**Keywords:** glacial catchments, anthropogenic pollutants, glacier mass balance, polar ecosystems, environmental contamination

---

## 1. Introduction

Glaciers are not only contributors to the sea level rise but can also accumulate and release pollutants [1, 2], as well as transform the chemical composition of water that originates or flows through them. Since glacial water is used by over a billion people for domestic purposes [3], both the quality and quantity of this water should be monitored. Indeed, such

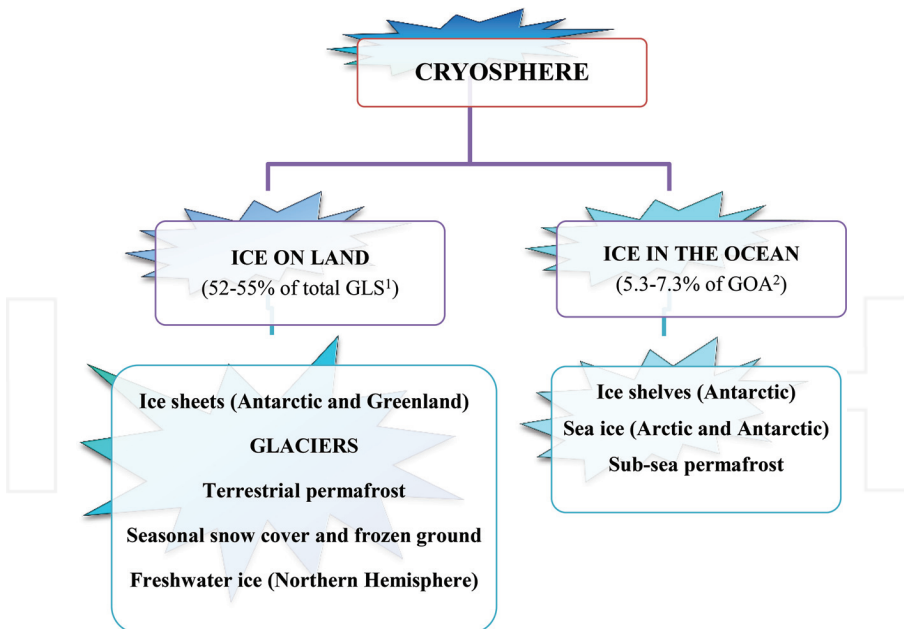
---

studies can be a vast source of knowledge on the processes in the otherwise unavailable subglacial environment. In this chapter, we concentrate on the archipelago Svalbard in the Arctic, a typical target area for xenobiotics from long range atmospheric transport (LRAT), holding an important share of the Arctic glacial ice cover. We show the ways the glaciers of Svalbard are monitored for water losses and quality changes, alongside some benefits already acquired through such studies. A new direction in the research is needed that would deepen the interpretation of the obtained monitoring data.

## 2. Glacier monitoring and projects implemented in the Arctic

### 2.1. Cryosphere

Cryosphere refers to “the part of the Earth’s crust and atmosphere subject to temperatures below 0°C for at least part of each year” [4]. The snow, ice, and frozen ground all constitute the cryosphere, considered a source of climatic diagnosis due to its sensitivity to air temperature and precipitation changes. The most recent intergovernmental panel on climate change (IPCC) assessment [5] emphasizes also the importance of cryosphere in the Earth’s ecosystem as a reservoir of solidified water. Glaciers and the great ice sheets of Greenland or Antarctica are only part of the cryosphere, as shown in **Figure 1**.



**Figure 1.** Division of the cryosphere and its components: <sup>1</sup>Global land surface: 147.6 Mkm<sup>2</sup>, <sup>2</sup>Global ocean area: 362.5 Mkm<sup>2</sup> [5].



The global land surface covered by glaciers (0.5%) is the least abundant cryosphere component. It is referred to as “ice on land.” Nevertheless, the general significance of glaciers for the sea level equivalent (0.41 m a.s.l.) is the highest among the components, except for ice sheets (Antarctic: 58.3 m, Greenland: 7.36 m). Glaciers are long-term components of the cryosphere, with a lifespan exceeding freshwater ice on rivers and lakes (seasonal) and sea ice (several years in the Arctic), but shorter than ice sheets and permafrost, surviving even millions of years [5] (Table 1).

Considering their contribution to the sea-level rise and the lifespan of particular components of the cryosphere, glaciers are of extreme significance for the environment as an indicator of climate change in the context of global warming.

## 2.2. Glacial system

Glaciers occupy 10% of the Earth’s surface. As natural water reservoirs, they represent 75% of freshwater on Earth. The vast majority of the water (99.5%) is stored in the Greenland and Antarctic ice sheets. Ref. [3] has emphasized the great significance of glaciers as a source of freshwater widely used by over a billion people. Glacial waters are not only used for domestic purposes, but also for electricity production and crops irrigation (e.g., in the Alps, Himalayas). However, it is the small glaciers and ice caps of the High Arctic that have been rapidly responding to climate changes in the recent years, and therefore have contributed the most to the sea level rise [4–8].

Although the high latitude regions of the Arctic are distinguished by limited human impact and low emission from local sources, they cannot be considered free from the presence of pollutants. For example in Svalbard, the long range transport of atmospheric pollutants transmitted from Eurasian industrialized and urbanized areas may substantially affect the quality of Arctic waters, since the atmospheric deposition is one of the main factors (next to rock-water interaction) controlling water chemistry in this polar region [9–13].

Due to glacial drainage and the processes by which glaciers are formed, they are an important element in the global water cycle. The accumulation of water as snow and its gradual release in the liquid form determine the importance of glacial controls upon the drainage characteristics of partly glaciated catchments [6].

| Element of the cryosphere | Lifespan                       |
|---------------------------|--------------------------------|
| Snow                      | A day to several months        |
| River and lake ice        | Several days to several months |
| Sea ice                   | Several days to almost a year  |
| Glaciers and ice caps     | Months to a century            |
| Frozen grounds            | A day to a millennium          |
| Ice sheets, ice shelves   | Days to a millennium           |

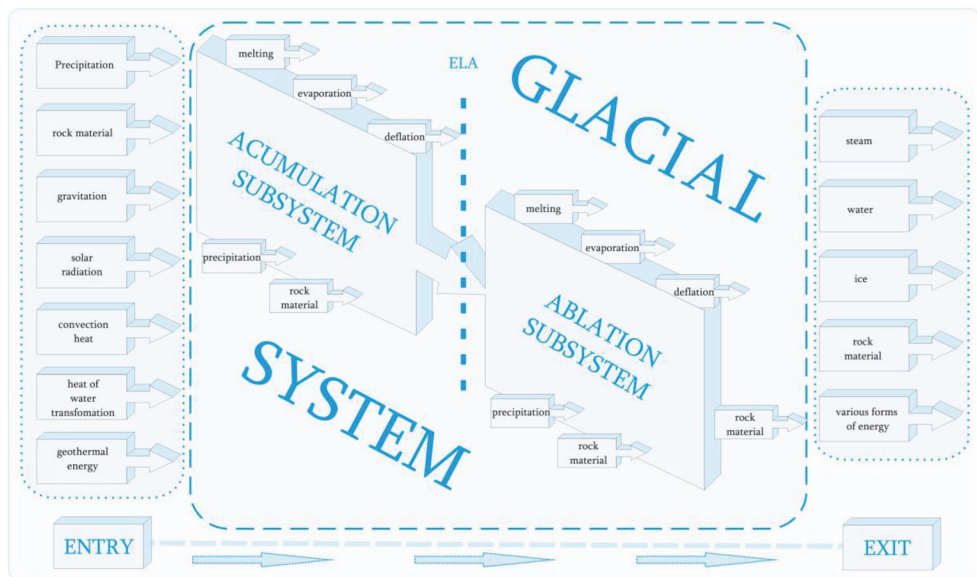
Table 1. Lifespan of selected elements of the cryosphere.



Glaciers develop when snow accumulates over a period of several years, and then gradually transforms into firn (at least 1 year old snow) to finally turn into ice. The ice flows downward due to the force of gravity. Snow accumulation predominantly depends on the climate conditions and topographic characteristics [4, 5, 14, 15]. When the accumulation process (snowfall) prevails over the ablation processes (iceberg calving, surface melting, and runoff, melting under floating ice shelves), glaciers gain mass [4, 5, 14, 15].

An important typical feature of glaciers is the circulation of mass, i.e., ice, snow, water, and mineral matter, as well as the circulation (exchange) of energy manifested in accumulation, the glacier movement, and ablation. The processes are determined by external factors. They also substantially affect the environment, making the glacier a dynamic, open system [16]. The glacier system is fed by and releases various forms of energy and mass, which are subject to further movement and/or transformation inside it. **Figure 2** shows the relations between the entry and exit elements.

The mass movement is determined by the force of gravitation. Energy transformations and movement are accompanied by complex processes within the glacier. As a result of differences in the mass balance, the uniform glacial system is divided into two spatial subsystems, namely the accumulation and ablation system, separated by the equilibrium line [16, 17]. Maintaining balance within the glacial system is only possible when the balance elements (entry and exit elements of the system) are equal, and the mass flow through the equilibrium line is even. Any disturbance in the balance causes a response of the system in the form of feedback loops. An example of such a process is an increase in accumulation, which causes an increased flow of ice



**Figure 2.** Schematic model of the glacial system.

mass through the equilibrium line, contributing to the advance of the glacier terminus, an increase in ablation, and reduction in the lower part of the glacial system.

The dynamic open glacial systems substantially affect climate at the global scale. They are also excellent indicators of climate fluctuations. The response of glaciers to climatic changes varies depending on their morphological features and internal thermal structure [14, 16].

Polythermal glaciers, i.e., glaciers with a complex thermal structure, are particularly good indicators due to their response to changing climate characteristics, as they are developed not only as a result of varied air temperature, but also by variable amount and structure of precipitation. In contrast to glaciers with cold thermal regime, the internal hydrothermal structure of polythermal glaciers is determined not only by solid, but also by liquid precipitation [18].

### 2.3. The beginning of world glacier monitoring

Glacier monitoring has a history dating back to the nineteenth century (Figure 3). The father of glacier monitoring was François-Alphonse Forel, the first scientist to observe changes in Alpine glaciers. The first international initiative emerged during the sixth International

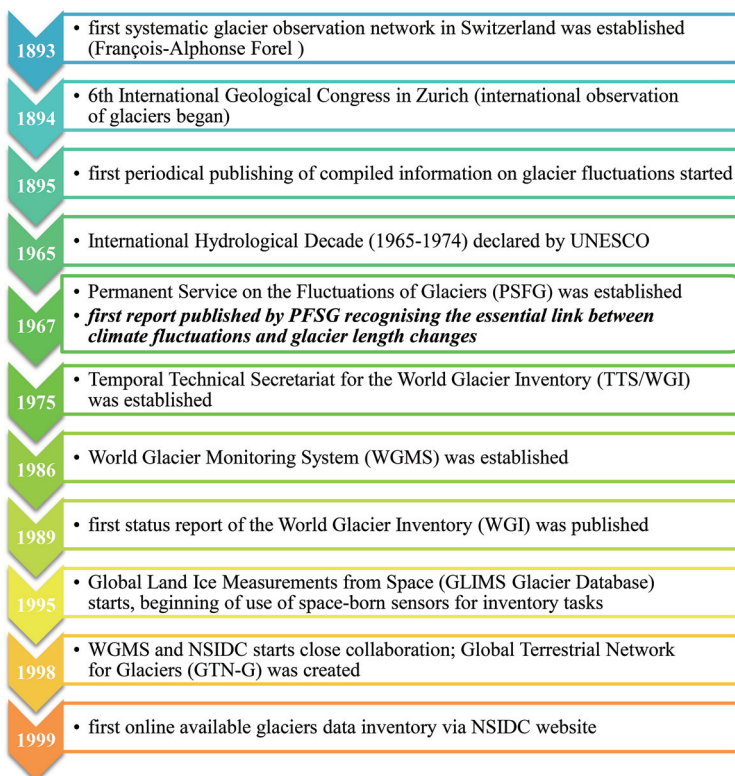


Figure 3. Most important dates in the early history of glacier monitoring.



Geological Congress in Zurich. Since then, scientists have been collecting information on changes in selected glaciers and performing detailed surveys of their tongues on a regular basis. The data were enriched by the indigenous knowledge on earlier glacier stages, provided by the mountain people. At the early stages of the research, it focused on glacier fluctuations, therefore only data on front variations were published. Since 1940, information regarding mass balance has been included in publications. The need for a worldwide inventory of the existing ice and snow masses was recognized just after the declaration of the International Hydrological Decade (1965–1974) by the United Nations Educational, Scientific, and Cultural Organization (UNESCO). This resulted in the establishment, under the auspices of UNESCO, of the first international network called the Permanent Service on the Fluctuations of Glaciers (PSFG). Worldwide glacier monitoring has been rapidly evolving since then, and in 1975, the Temporal Technical Secretariat for the World Glacier Inventory (TTS/WGI) was established. Its role was to collect and periodically publish glacier inventory and fluctuation data. The tasks of TTS/WGI and PSFG were taken over by the World Glacier Monitoring Service (WGMS), established in 1986. The first status report of glaciers inventory, published in 1989, includes information on their geographic location, area, length, orientation, elevation, and classification of morphological type and moraines. The data were mainly based on aerial photographs, maps, and satellite images. Since 1995, when project Global Land Ice Measurements from Space (GLIMS) was launched, the data have also been collected from optical satellite instruments such as the Advanced Spaceborne Thermal Emission and reflection Radiometer (ASTER) [19–21]. The collaboration of WGMS with the US National Snow and Ice Data Center, initiated in 1998, resulted in the first data inventory available online via the website of the National Snow and Ice Data Center (NSIDC) already a year later [20, 22, 23]. The most important dates and events in the early history of worldwide glacier monitoring are provided in **Figure 3**.

#### 2.4. The organization of the glacier monitoring system

The establishment of the Global Terrestrial Observing System (GTOS) in 1996 was a consequence of the Second World Climate Conference held in 1990. The conference called for the establishment of a coordinated monitoring system (**Figure 5**). The Terrestrial Observation Panel for Climate (TOPC) was established within GTOS. The global observing strategy was subsequently designed. It permits introducing all variables essential for the climate (e.g., river discharge, groundwater, lakes, glaciers, and ice caps) related to monitoring systems to the Global Terrestrial Network (GTN). As a result, the Global Terrestrial Network for Glaciers (GTN-G) was established in 1998. GTN-G is responsible for collecting standardized data on the current state of glaciers. Since its establishment, it has been run by WGMS with the assistance of NSIDC and GLIMS. The monitoring system is under the supervision of several worldwide organizations presented in **Figure 4** [22, 24].

#### 2.5. Glacier research projects in Svalbard

Due to the strong response of glaciers to climate change, their great importance for sea-level rise, and impact on the environment, many international research programs and projects have been conducted in the Arctic, including Svalbard. Research projects, unlike monitoring, include innovative testing of new methods and techniques and have a typical duration from



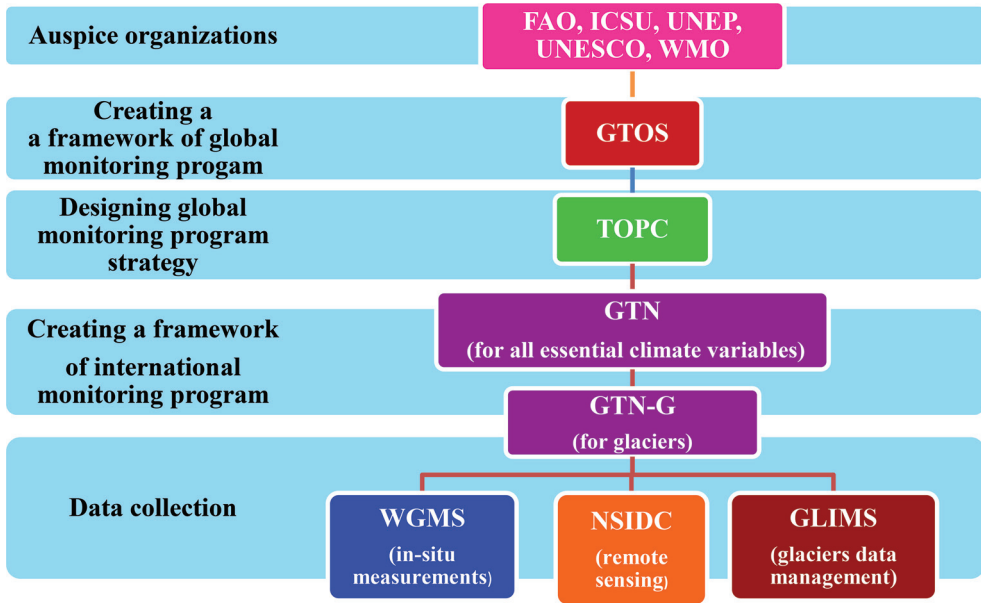


Figure 4. Major international organizations and their role in glacier monitoring.

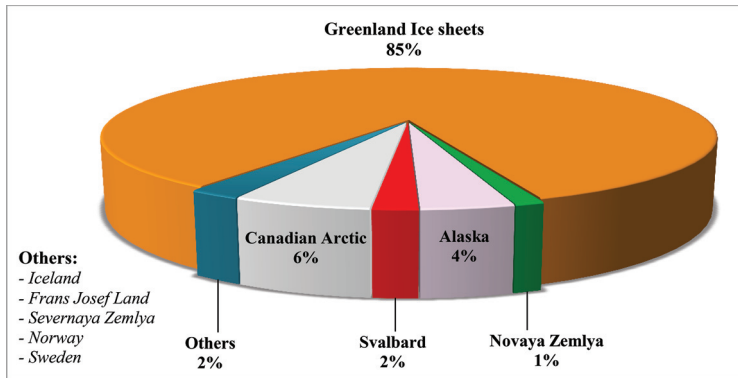


Figure 5. Percent contribution of 10 Arctic regions covered by extensive glaciation [4].

3 to 6 years, and are funded from different sources. Examples of such research projects regarding Svalbard glaciers are listed in **Table 2** [25–28]. A great number of projects is interdisciplinary, concerning both glaciology and glacial hydrology. Some are also related to meteorology (e.g., CRYOMET) and seismology (e.g., SEISMOGLAC). The vast majority of research projects is associated with the response of the cryosphere to global warming and climate change.



| Project (years of implementation)  | Scope of research   | Source of funding |
|--|---|-------------------|
| <b>“GLACIODYN” The dynamic response of Arctic glaciers to global warming (2007–2010)</b>                 | <ol style="list-style-type: none"> <li>1. Current mass budget of each glacier (including calving);</li> <li>2. Subglacial processes (hydrology and sliding interactions);</li> <li>3. New models of calving processes (numerical models including functions of sliding and calving);</li> <li>4. Prediction of glacier response to climate change scenarios.</li> </ol>   | RCN               |
| <b>“SvalGlac” Sensitivity of Svalbard glaciers to climate change</b>                                     | <ol style="list-style-type: none"> <li>1. Measurements of mass budget, glacier flow velocity, glacier thickness and hydrothermal structure, weather;</li> <li>2. Studies on actual glacier topography and shallow ice cores (for the past climate reconstruction).</li> </ol>   | ESF               |
| <b>“Ice2sea” Estimating the future contribution of continental ice to the sea-level rise (2009–2013)</b> | <ol style="list-style-type: none"> <li>1. Studies of key processes in longer-lived elements of the cryosphere (mountain glacier systems, ice caps, ice sheets);</li> <li>2. Improvement of satellite determinations of current changes in continental ice masses;</li> <li>3. Development of a detailed forecast of the contribution of continental ice to the sea-level rise over the next 200 years by means of ice-sheet/glacier models.</li> </ol>                  | ERC               |
| <b>“ICEMASS”ERC advanced grant global glacier mass continuity</b>  | <ol style="list-style-type: none"> <li>1. Data collection and analysis regarding glacier thickness changes, and converting the data to a global glacier mass budget;</li> <li>2. Estimation of the current sea-level contribution from glaciers;</li> <li>3. Studies on glacier mass changes reflecting climate change patterns;</li> <li>4. Examination of the impact of glacier imbalance on river runoff.</li> </ol>   | ERC               |
| <b>“CRYOMET” Bridging models for the terrestrial cryosphere and the atmosphere (2012–2015)</b>           | <ol style="list-style-type: none"> <li>1. Validation of the polar weather research and forecasting model (WRF) land surface scheme;</li> <li>2. Collection of cryosphere data sets constituting variables with Polar WRF;</li> <li>3. Studies on further probabilistic downscaling of snow cover by means of snow distribution models;</li> <li>4. Tests of upscaling schemes for the surface energy balance in polar WRF (cryosphere-atmosphere feedbacks).</li> </ol> | RCN               |
| <b>“SEISMOGLAC”-Seismic monitoring of glacier activity on Svalbard (2012–2015)</b>                       | <ol style="list-style-type: none"> <li>1. Studies on the relation between glacial process and seismicity;</li> <li>2. Finding the source location of ice quakes;</li> <li>3. Use of automatic pattern recognition methods to classify their signals.</li> </ol>   | RCN               |

Abbreviations: RCN: Research Council of Norway, ESF: European Science Foundation, ERC: European Research Council.

**Table 2.** International research projects in Svalbard within the framework of which glaciers are studied.

### 3. Svalbard glaciers and climate warming

Part of the cryosphere of the northern hemisphere categorized as “ice on land” is distributed irregularly in the Arctic. Therefore, glaciers and ice caps are subject to different climatic conditions. In Ref. [5], 10 regions of the Arctic are specified as covered by extensive glaciation. Together they occupy an area of 1,972,600 km<sup>2</sup>. The percent contribution of each of them is shown in **Figure 5**.





Svalbard archipelago is the most glaciated region of the European Arctic. The area of its glaciation (approximately 36.6 km<sup>2</sup>) is substantially higher than that of Norway and Sweden (approximately 3.1 km<sup>2</sup>), Iceland (approximately 10.9 km<sup>2</sup>), Franz Josef Land (approximately 13.7 km<sup>2</sup>), and Novaya Zemlya (approximately 23.6 km<sup>2</sup>).

The response of the Greenland ice sheet to climate change is slower, because more than a half of its surface experiences temperatures well below the freezing point during the entire year. Changes in temperature or precipitation cause a more rapid response in smaller glaciers and ice caps, which are more sensitive [4]. Throughout the Arctic, except for Russian Arctic, the mass balance (difference between annual mass gain and annual mass loss) is only monitored on 27 glaciers. Four of them are located on Svalbard (Midre Lovénbreen, Austre Broggerbreen, Kongsvegen, and Hansbreen) [29].

The Svalbard archipelago includes four main islands (Spitsbergen, Nordaustlandet, Edgeøya, and Barentsøya) and occupies an area of 62,248 km<sup>2</sup>. Approximately, 60% of the Svalbard archipelago is covered with ice. The glacier inventory of Svalbard amounts to 1615 glaciers and ice caps, of which 17 are under permanent or periodic mass balance research.

Sixty percent of Svalbard glaciers are terminating in the sea at calving ice-cliffs. Ref. [7] has emphasized that due to calving, the annual specific mass loss of Svalbard glaciers is much higher than from the Greenland ice sheet and seems to be the highest in the Arctic. Each of the main islands of the archipelago represents a different type of landscape (more detailed information is provided in **Table 3**). On Spitsbergen, the largest island of the archipelago, 90% of glaciers are considered polythermal (subpolar) [8, 30, 31].

Although the dominant component of Spitsbergen landscapes is rugged mountains with glaciers, its eastern part is covered with several large ice caps. Together with ice caps from three other islands, also calving into the sea, they all develop a calving ice front with a total length of approximately 1000 km. The total volume of the ice masses of Svalbard is estimated at 7000 km<sup>3</sup> [7, 32].

### 3.1. Role of glaciers in the Svalbard environment

Glaciers occur in places where climatic and topographic conditions favour snow accumulation. Their role may be considered both at the global scale and at the regional scale, as shown in **Figure 6**.

| Islands                | Landscape                                     | Area of glaciation   |
|------------------------|---|--|
| Spitsbergen            | Steep, rugged mountains                       | ~22,000 km <sup>2</sup> of glaciers<br>~14,600 km <sup>2</sup> of ice caps             |
| Nordaustlandet         | Two largest single ice bodies within Svalbard | ~2450 km <sup>2</sup> (Vestfonna ice cap)<br>~8000 km <sup>2</sup> (Austfonna ice cap) |
| Edgeøya and Barentsøya | Plateau-type terrain                          | ~2800 km <sup>2</sup> of low altitude ice caps   |

**Table 3.** Dominant types of landscapes and extent of glaciation of the main Svalbard archipelago islands [8, 32].



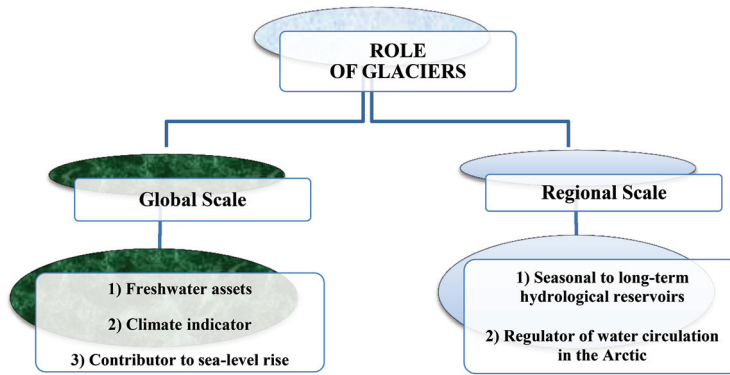


Figure 6. The role of glaciers in the environment [5, 32].

Glaciers adjust their size in response to changes in climate, e.g. in temperature and precipitation. Therefore, they are considered very sensitive climate indicators. Changes in their size or shape may be observed over several decades or even several years. Svalbard glaciers also have a contribution in the sea level rise, estimated at 4% of the total contribution of smaller glaciers and ice caps. The contribution of the archipelago corresponds to the ratio between the glaciated area of Svalbard and the global surface covered by glaciers and ice caps [4, 8].

For the Arctic environment, with a fragile homeostasis, the regional role of glaciers is significant [10, 32]. Glaciers are the most visible component of the Svalbard environment. Due to this, they can also be considered a major geomorphological factor of the entire archipelago [32]. They respond the fastest and strongest to climate changes among all environmental components, and are a major regulator of water circulation in the Arctic [33]. Ref. [32] has emphasised the role of glacier runoff in Svalbard, a factor affecting not only the hydrology of rivers, but also circulation in the neighbouring seas and fjords, due to changes in stratification within the water column. Local climate and biota may also be influenced by changes in the glacial runoff, affecting the sea ice conditions of the archipelago. Even deep-water production close to the shelf of Svalbard may be influenced by a rapid discharge of freshwater from glaciers [32].

#### 4. Glacier water chemistry and the origin of chemical additions

The chemical composition of glacial meltwaters in Svalbard has been subject to increased interest in recent years [34–37]. Waters originating from glaciers affect the quantity and quality of water delivered to the environment in glaciated catchments, which also plays an important role in ice mass dynamics [13]. Furthermore, glaciated catchments regulate the biogeochemical circulation of nutrients, and influence the cryosphere-atmosphere interactions [38].

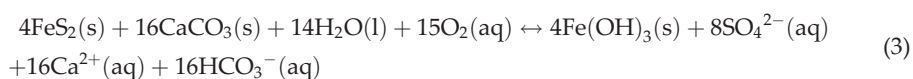
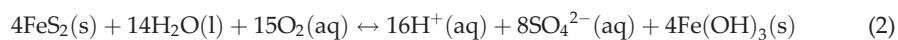
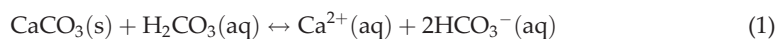
Although the high latitude regions of the Arctic experience very limited human impact and low emission of local origin, they cannot be considered free from pollutants any more. The

long-range atmospheric transport from the regions of Eurasia with higher emissions may influence the Arctic water quality, making atmospheric deposition one of the main factors (alongside rock-water interactions) controlling water chemistry of the polar regions. Due to high rates of chemical weathering and minimal human impact in glaciated areas, they constitute an environment almost ideal for studying water-rock interactions [11–13]. Hydrochemical data on proglacial waters provide explanation of water drainage pathways through glaciers and estimations of chemical weathering rates [34, 39].

Ref. [12] has emphasized the specific conditions of the Arctic environment, such as: “(1) relatively short water-rock contact time, (2) cold temperatures, (3) thin soils, and (4) lack of vegetation,” which reduce the activity of geochemical processes, including chemical weathering. However, the contact of water with eroded glacial debris and the abundance of soluble rocks such as carbonates and sulphides tend to considerably enhance such activity. In addition to the chemical weathering of rocks and the atmospheric deposition, other factors potentially influence dissolved solute concentrations, these are “(1) discharge conditions at the time of sampling, (2) inputs and outputs from the soil exchange pool, (3) uptake of organic nutrients by biomass, and local variations in non-living organic material (humus), and (4) changes in the topography and soil development” [12, 13].

The ionic composition of glacial meltwater varies due to different types of its transit through the glacial system, and the duration of chemical weathering reactions supplying solutes to such waters. The variety of glacial processes, and consequently chemical weathering, is strongly influenced by the thermal regime of glaciers. Meltwater in contact with the bedrock is present in temperate and subpolar glaciers. The acquisition of solute derived from chemical weathering occurs at the glacier bed during the transit of meltwater through two types of drainage systems: distributed and channelised. The distributed drainage involves linked cavities or porous flow through permeable subglacial sediments, and is mainly fed by snowmelt or slow transit of meltwater. This system of drainage is characterised by high water pressure and long residence time. The rock-water contact area is high. The channelised drainage system is fed by ice melt, mixed with waters from the distributed system to produce bulk meltwater. This system rapidly drains high volumes of water from beneath the glacier. The chemical reactions occurring on the water-rock interface in the glacial system depend on the type of drainage and their changeability during the ablation season [13, 40].

The most important mechanism of chemical rock weathering is acid hydrolysis. Ref. [13] has emphasized that dissolved anion signature of the meltwater indicates the source of protons necessary to drive acid hydrolysis reactions. Furthermore, Ref. [13] has listed the sources of protons such as (1) dissociation of atmospheric CO<sub>2</sub> [Eq. (1)], (2) sulphide oxidation [Eq. (2)], and (3) oxidation of pyrite [Eq. (3)]. The latter is often coupled with carbonate dissolution.



The relative proportions of  $\text{HCO}_3^-$  and  $\text{SO}_4^{2-}$  in the bulk outflow reflect the dominance of the major sources of aqueous protons driving subglacial weathering reactions. Ref. [13] has assumed that, when using the C-ratio  $[\text{HCO}_3^-/(\text{HCO}_3^- + \text{SO}_4^{2-})]$ , a value of 1 signifies weathering by carbonation reactions, while a value of 0.5 reflects coupled sulphide oxidation and carbonate dissolution.

#### 4.1. Pollutants examined in the catchments of Svalbard glaciers

Next to the natural chemicals from rock-water contact, human activity also contributes chemicals to Arctic waters, despite the distance of thousands of kilometres between the Arctic and the industrial and agricultural areas. During the last two decades, pollutants continued arriving into the Arctic, and despite their decreasing or steady atmospheric levels [41], their negative impact on the polar environment remains an important concern [42–49].

The Svalbard archipelago is different from the other Arctic regions. Due to its geographical location and specific climate conditions, it is particularly exposed to the accumulation of a wide range of chemical substances recognised as pollutants [9, 10]. Its relatively short distance from continental Europe, the location of the archipelago in the gap between the continents surrounding the Arctic Basin, and its landscape dominated by rugged mountains with glaciers, make it conducive to the accumulation of pollutants on its glaciers. Moreover, ocean and wind currents contribute to the transport of pollutants from lower geographic latitudes. In combination with low temperatures, this results in Svalbard and its glaciers becoming a sink for xenobiotics [50–54]. Although the levels of multiple pollutants such as heavy metals and many POPs contained in various elements of the living and inanimate environment are well known [10], knowledge on the fate of pollutants in Svalbard glaciers is still scarce.

Many scientific studies discuss the issue of the contamination of the Arctic environment. A vast number of publications concern the content of xenobiotics detected both in the living organisms (e.g. [46, 55–59]) and in the inanimate environment [60–64]. In Ref. [10], levels of pollutants present in samples collected in the Svalbard archipelago are discussed in detail. This paper focuses on the literature directly related to the presence of a wide range of chemicals recognised as pollutants in glacial catchments. The majority of research on the chemistry of glacier catchments is performed on Spitsbergen, the largest island of the archipelago (**Figure 7**).

The research site locations are directly related to the occurrence of the warm West Spitsbergen Current, considerably affecting the climate of the western coast of Spitsbergen. The warm waters limit the sea-ice development, which makes this area easier available for research activities. This is evident in the contribution of individual fjords, with the only representant of the eastern side of the island being Woodfjorden. Moreover, due to the cold East Spitsbergen Current, the east coast is dominated by several large ice caps [7, 10, 32].

Three main types of glacial catchments on Svalbard may be distinguished. The first two types involve the glacier terminus ending in the sea. In the first case, the glacier basin covers the coastal valley, and in the second case, the basin reaches into the centre of the island, covering large glaciated valleys. The third type of a glacial catchment is distinguished by the glacier terminus ending on land [78]. The glacier moraine is located in front of the glacier terminus, at



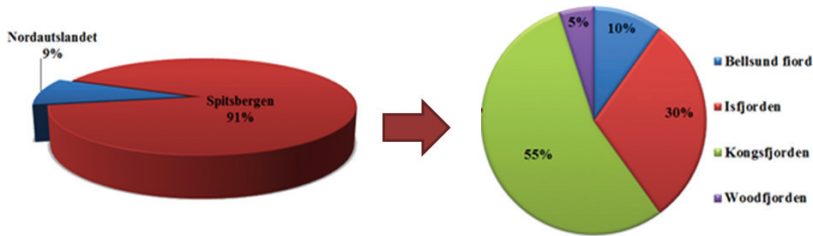


Figure 7. Places of conducting chemical research in glacial catchments in Svalbard, including the contribution of particular fjords of the Spitsbergen island [12, 34, 35, 38, 40, 49, 55, 65–77].

a certain distance from the seashore. Ablation water leaving the glacier flows through the glacier moraine and into the fjord via a number of channels developing a river system between the glacier and the fjord. Various types of surface water samples can be collected and examined depending on the type of catchment. According to the literature, glaciers representing the latter type of glacial catchments are subject to most frequent research activities (Figure 8). The evaluation was based on selected scientific articles, cited in Tables 4, 5 and 6.

A vast majority of publications [12, 34, 40, 49, 75–77] focused on water from glaciers (proglacial, supraglacial, subglacial, and cryoconite waters). However, some include also direct

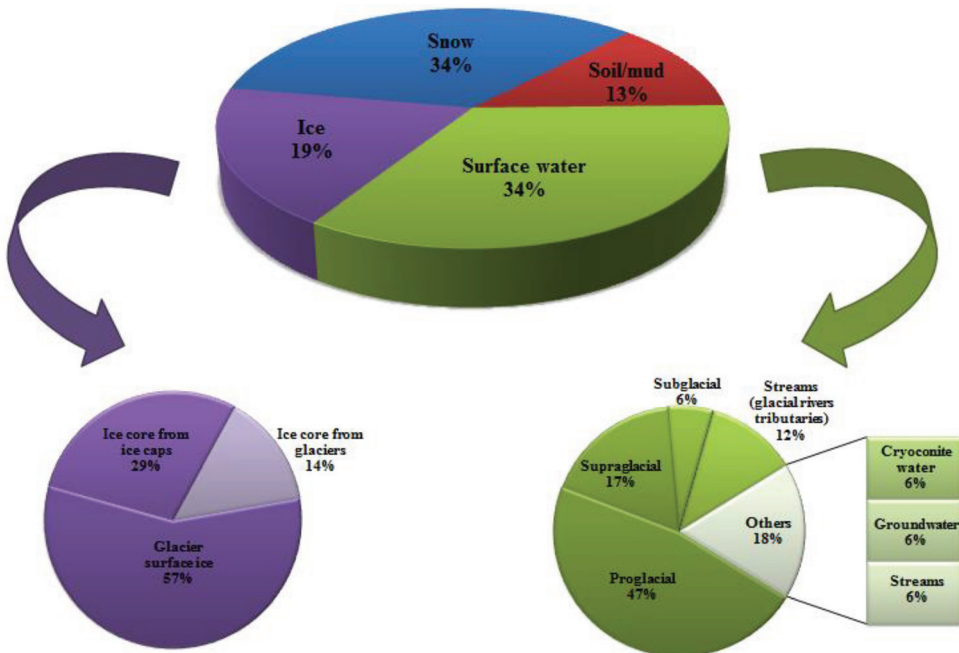


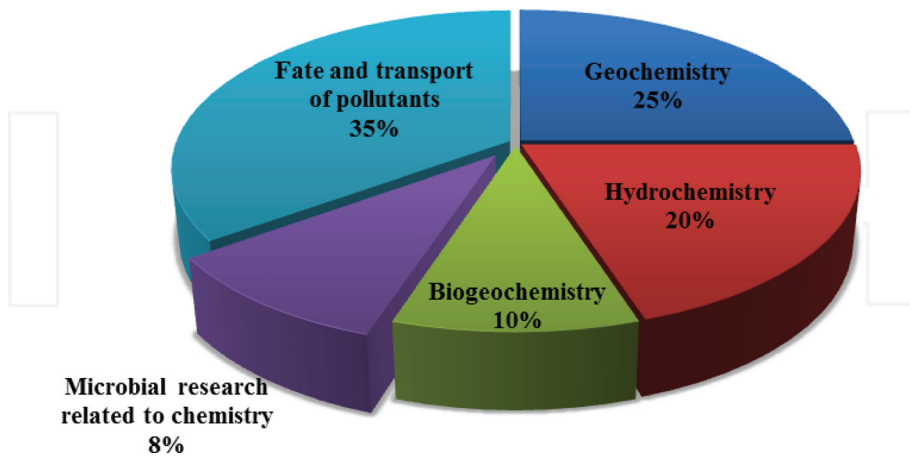
Figure 8. Contribution of different type of samples examined on the Svalbard archipelago [12, 34, 35, 38, 40, 49, 55, 65–77].



tributaries of glacial rivers [12, 76], as well as other streams and groundwaters functioning in glacier basins [12, 38]. A smaller number of studies involves the analysis of ice samples. In prevalence, the examined ice was collected from the surface of glaciers rather than from drilled ice cores, and this sampling strategy may be driven by the predominance of polythermal regime among Spitsbergen glaciers (90%). The percolation of water and chemical substances in this thermal regime disturbs the original depositional sequence of chemical composition, making it difficult to analyze their accumulation in glaciers over time. Therefore, the examined Svalbard ice cores originate usually from ice caps. Only in Ref. [49], authors analyze pollutants in ice cores collected from the polythermal glacier of Longyearbreen. Snow samples for analysis are collected from the surface of glaciers and their surroundings in nearly equal proportion. Substantially, more sediment samples from cryoconite holes [72, 77, 79] on glaciers are subject to research than soil samples collected in glacier catchments.

Projects listed in **Table 2** mainly focus on glaciological investigations [80–84]. Some of them are associated with the impact of climate change on cryosphere components and the modelling of possible cryosphere-climate interactions [8, 85]. Many scientific works also focus on the presence of pollutants such as heavy metals or POPs in biotic samples [50, 55, 61, 86, 87]. The majority of the research is related to biochemistry, and refers to the processes of bioaccumulation and biomagnification of pollutants within the marine or terrestrial food webs. Publications concerning abiotic samples collected from glacier catchments of Svalbard focus on types of research presented in **Figure 9**. The evaluation was based on selected scientific articles cited in **Tables 4, 5** and **6**.

According to the literature review, the majority of conducted research concerns the fate and transport of pollutants in the abiotic environment. These publications mostly refer to levels of selected metals (e.g., Al, Hg) or POPs (e.g., PCN, PCBs, PFOA, PFOS, DDD, DDE, DDT) in snow [49, 67, 69–71] and ice samples [49, 55, 73, 74]. Ref. [49] discusses the effect of pollutants



**Figure 9.** Types of research performed on inanimate samples collected in the Svalbard archipelago [12, 34, 35, 38, 40, 49, 55, 65–77].



present in snow, ice, and surface water samples (i.e., supraglacial lake or river and sea water) collected throughout the glacial catchment, starting from the top of the glacier and ending in the fjord waters. This is the only work providing an insight into the transport of anthropogenic pollutants through almost all of the elements of the glacial catchment. A considerable number of publications focus on the chemical weathering process [12, 34, 35, 38, 75]. Others concern seasonal changes in hydrochemistry [68, 76], or compare the hydrochemistry of inanimate samples collected in different parts of the environment [66, 72]. Such works mainly present results of analysis of inorganic ions (e.g.,  $K^+$ ,  $Na^{2+}$ ,  $Mg^{2+}$ ,  $F^-$ ,  $Cl^-$ ,  $NO_3^-$ ,  $NO_2^-$ ). A smaller number of studies concerns biogeochemistry [40, 65] or microbiology related to the fixation of nitrogen on glaciers or carbon cycle [77, 79].

Since data from long-term chemical monitoring of glaciers are scarce and rarely published in full, we collected here an inventory of shorter published measurement series or important datasets that can be treated as a proxy of the current state of the glacial chemical monitoring in Svalbard. First, we present an overview of the techniques and equipment used for the determination of a wide range of analytes studied in the environmental samples from glacial catchments of the Svalbard Archipelago. We have divided the data into three categories: snow (**Table 4a**), ice (**Table 4b**) and surface water (**Table 4c**). According to the literature review, ion chromatography (IC) is the analytical method that is used most frequently for the determination of not only inorganic ions, but also other pollutants (e.g., methyl-sulfonic acid and glutaric acid). The determination of the concentration of metals in the environment usually involves the methods of flow injection analysis (FIA) or atomic absorption spectroscopy (AAS). The determination of organic pollutants, which are highly detrimental for Arctic biota, is performed by means of gas chromatography (GC), usually coupled with mass spectrometry (MS) in different resolution modes (low resolution, high resolution). Inorganic ions and metals are the most frequently determined analytes in almost all of the elements of glacial catchments (snow, ice, water, soil, and cryoconite). Research involving the determination of persistent organic pollutants (e.g., DDD, DDT, PCBs, PCNs, HCH, HCB) is conducted very rarely in the glacier catchments. These dangerous chemical compounds are usually determined in snow and ice samples (ice cores and surface ice) collected in the glacial catchment, where they reflect contribution of long-range atmospheric transport and their history of accumulation.

Except water samples, other abiotic material has also been investigated in the glacial catchments of Svalbard, especially rock material of different types. For example, cryoconite sediment has been analysed for its nutrient content (for DIN, TIN and TN, using Bran and Luebbe Autoanalyzer 3, [77]) or heavy metal concentration (Fe, Mn, Zn, Pb, Cu, Cd; by voltamperometric and spectrophotometric method, [72]). Similar parameters to water samples were established in soils, especially pH [34, 65], inorganic anions ( $Cl^-$ ,  $NO_3^-$ ,  $SO_4^{2-}$ ,  $HCO_3^-$ ) and cations ( $Na^+$ ,  $K^+$ ,  $Mg^{2+}$ ,  $Ca^{2+}$ ) [34, 65],  $SiO_2$  concentration [34], and organic carbon and nitrogen [65]. The methods used in the mentioned studies matched those used for snow, with the exception of the Fisons NCS analyser application for organic carbon and nitrogen.

In **Tables 5a**, **5b** and **5c**, we present the published chemical concentration data from the samples described in **Tables 4a**, **4b** and **4c**, respectively. Most studies concerned watercourses, and there the highest variability of chemical parameters was found. Ice samples have shown



| Determined compound(s)/parameters   | Analytical method/apparatus  | References                |              |
|---|--|---------------------------|--------------|
| pH  |  | [65]                      |              |
|   | pH meter   | [66]                      |              |
|   | Heito pH meter (Paris)   | [67]                      |              |
|   | Orion SA 250 portable meter with Ross combination electrode                                      | [34]                      |              |
|   | Orion 290a portable pH meter with Ross combination electrode                                     | [68]                      |              |
| EC  | conductivity meter   | [66]                      |              |
| Anions ( $\text{Cl}^-$ , $\text{Br}^-$ , $\text{NO}_3^-$ , $\text{SO}_4^{2-}$ ) | IC   | Dionex ion chromatography | [65]         |
|   |  | DionexR 2100              | [66]         |
|   |  | Dionex DX100              | [40]         |
|   |  | IC, colorimetric method   | [38]         |
|   |  | Dionex ICS 3000           | [67]         |
|   |  | Dionex 4000i              | [34, 68]     |
| $\text{HCO}_3^-$  | Titration (0.01 M HCl)   | [68]                      |              |
|   | Titration (1 mmol HCl)   | [34]                      |              |
|   | Titration ( $10^{-3}$ mol/L $\text{H}_2\text{SO}_4$ )  | [65]                      |              |
|   | Cations ( $\text{Na}^+$ , $\text{NH}_4^+$ , $\text{K}^+$ , $\text{Mg}^{2+}$ , $\text{Ca}^{2+}$ ) | AAS                       | [34, 38, 65] |
| ICP-OES   |  | [66]                      |              |
| FIA   |  | [40]                      |              |
| IC  |  | Dionex ICS-3000           | [67]         |
|   |  | Dionex 4000i              | [68]         |
|   |  | ICS-1100 Dionex           | [49]         |
| Metals  | $\text{Al}_{\text{total}}$   | AAS                       | [65]         |
|   | $\text{Hg}_{\text{total}}$   | CVAFS                     | [67]         |
|   |  | ICP-SFMS                  | [69]         |
|   | $\text{Hg}_{\text{reactive}}$  | ICP-QMS                   | [69]         |
|   | MMHg (monomethylmercury)   | AFS                       | [67]         |
| S   | ICP-OES  | [66]                      |              |
| Si-Si(OH) <sub>4</sub>  | FIA  | [65]                      |              |
| SiO <sub>2</sub>  |  | [34]                      |              |
| Si  |  | [68]                      |              |
| MSA(methyl-sulfonic acid), Glut (glutaric acid)                                 | IC (Dionex ICS 3000)   | [67]                      |              |
|   | GC-MS-EI-SIM   | [70]                      |              |



| Determined compound(s)/parameters  | Analytical method/apparatus | References |
|--|-----------------------------|------------|
| $\Sigma$ PCB9, $\alpha$ -HCH, $\gamma$ -HCH, $\Sigma$ DDT, HCB, chlordane (cis- or trans-) |                             |            |
| $\Sigma$ PCN, $\Sigma$ PCB   | HRGC-LRMS                   | [71]       |
| PFOA, PFOS   | LC-MS/MS                    | [49]       |

**Table 4a.** Literature data on the analytical techniques and equipment used for the determination of a wide range of compounds in the snow samples (snowfall, surface snow, snowpack) collected in the glacial catchments of the Svalbard archipelago.

| Determined compound(s)/parameters  | Analytical method/apparatus   | References  |
|--|---|---|
| pH/EC  | pH/conductometer CPC-411 by Elmetron  | [88]  |
| Anions ( $\text{Cl}^-$ , $\text{NO}_3^-$ , $\text{SO}_4^{2-}$ )  | IC, colorimetric method   | [38]  |
|  | IC (ICS-1100 Dionex)  | [49, 88]  |
|  | IC (ICS-3000Dionex)   |   |
| Cations ( $\text{Na}^+$ , $\text{NH}_4^+$ , $\text{K}^+$ , $\text{Mg}^{2+}$ , $\text{Ca}^{2+}$ )   | AAS   | [38]  |
|  | IC (ICS-1100 Dionex)  | [49, 88]  |
|  | IC (ICS-3000Dionex)   |   |
| Metals   | AAS   | [55]  |
|  | Zn, Mn, Cu, Fe, Ni, Cr, Pb, Cd, Co  | Voltamperometric and spectrophotometric method [72] |
|  | Li, Be, B, Al, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Cd, Cs, Ba, La, Ir, Pb, Th, U | ICP-MS [88]   |
| PFOA, PFOS   | LC-MS/MS  | [49]  |
| Aldrin, Dieldrin, $\alpha$ -HCH, Heptachlor, Heptachlor epoxide, Methoxychlor, Chlorpyrifos, Dacthal, Methyl-parathion                                 | GC-LRMS-EI  | [73]  |
|  | GC-ECD  | [74]  |
| $\gamma$ -HCH, $\alpha$ Endosulfan, $\beta$ Endosulfan, Diazinon, Dimethoate, Disulfoton, Imidan, Terbufos, Alachlor, Pendamethalin, Desethyl atrazine | GC-LRMS-EI  | [73]  |
|  | GC-LRMS-ECNI  | [74]  |
| Endrin-aldehyde  | GC-LRMS-EI  | [73]  |
| Endrin, Endrin-ketone, Cis-nonachlor, Trans-nonachlor, o,p'-DDD, p,p'-DDT (L), p,p'-DDE, $\gamma$ -chlordane, $\alpha$ -chlordane,                     | GC-ECD  | [74]  |
| Endosulfan sulphate, Metolachlor, Trifluralin, Metribuzin  | GC-LRMS-ECNI  | [74]  |
| DOC  | TOC analyser (Shimadzu)   | [88]  |

For acronyms see list in the beginning of the article.

**Table 4b.** Literature data on the analytical techniques and equipment used for the determination of a wide range of compounds in the ice samples (glacier surface, ice cores from glaciers and ice caps) collected on the glaciers of Svalbard.



| Determined compound(s)/parameters  | Analytical method/apparatus                                    | References                |
|--|--|---------------------------|
| pH   | Orion SA 250 portable meter with a Ross combination electrode  | [34]                      |
|  | Jenco pH-meter   | [35]                      |
|  | Orion (Thermo Scientific), WPA (Cambridge, UK) or VWR pH meter | [36]                      |
| EC   | CC-317 conductivity meter                                      | [35]                      |
| Anions ( $\text{Cl}^-$ , $\text{NO}_3^-$ , $\text{PO}_4^{3-}$ , $\text{SO}_4^{2-}$ )             | IC Dionex 4000i  | [75]                      |
|  | Dionex Ion Chromatography                                      | [65]                      |
|  | Dionex DX100   | [40, 36]                  |
|  | IC, colorimetric method  | [38]                      |
|  | Dionex 4000i   | [34]                      |
|  | Metrohm Compact IC 761   | [35, 37]                  |
|  | Dionex DX-120  | [12]                      |
| $\text{HCO}_3^-$   | Dionex ICS-90  | [76, 36]                  |
|  | Dionex 4000i   | [75]                      |
|  | Dionex DX-120  | [12]                      |
|  | Titration ( $10^{-3}$ mol/L $\text{H}_2\text{SO}_4$ )          | [65]                      |
|  | Colorimetric titration   | [38]                      |
|  | Titration (1 mmol HCl)   | [34]                      |
|  | Titration (10 mmol HCl)  | [36]                      |
| $\text{N-NO}_2^-$  | Titration (0.02 M HCl)   | [35]                      |
|  | Titration (Metrohm 702 SM Titrino)                             | [37]                      |
|  | IC Dionex DX-120   | [12]                      |
|  | $\text{N-NO}_3^-$  | Dionex Ion Chromatography |
| Dionex DX-120  |  | [12]                      |
| $\text{N-NH}_4^+$  | Dionex DX-120  | [12]                      |
|  | FIA  | [65]                      |
| Cations ( $\text{Na}^+$ , $\text{NH}_4^+$ , $\text{K}^+$ , $\text{Mg}^{2+}$ , $\text{Ca}^{2+}$ ) | IC Dionex 4000i  | [75]                      |
|  | Dionex ICS-90  | [76, 36]                  |
|  | Metrohm Compact IC 761   | [37]                      |
|  | AAS  | [12, 34–36, 38]           |
| Metals ( $\text{Al}_{\text{total}}$ , Fe, Mn, Zn, Pb, Cu, Cd)                                    | FIA  | [40]                      |
|  | AAS  | [65]                      |
|  | FIA  | [34]                      |
| Si   | Voltamperometric method, spectrophotometric method             | [72]                      |
|  | Colorimetric method (Skalar Autoanalyser)                      | [76]                      |



| Determined compound(s)/parameters | Analytical method/apparatus   | References |
|-----------------------------------|---|------------|
| Si-Si(OH) <sub>4</sub>            | FIA   | [65]       |
| SiO <sub>2</sub>                  | Spectrometry using the method of reduction to molybdenum-blue               | [34]       |
|                                   | Perkin Elmer ICP-OES Plasm 40 spectrometer                                  | [35, 36]   |
| DOC                               | LABTOC Carbon Autoanalyser  | [37]       |
| DOC, DON                          | Shimadzu Total Organic Carbon (TOC)/Total organic nitrogen (TON)-V analyzer | [65]       |
| DIN                               | Bran and Luebbe Autoanalyzer  | [38]       |
| DIC                               | Estimated from charge balances  | [77]       |
| PFOA, PFOS                        | LC-MS/MS  | [76]       |
|                                   |   | [49]       |

For acronyms see list in the beginning of the article.

**Table 4c.** Literature review of the analytical techniques and equipment used for the determination of chemical parameters in the surface water samples (glacial waters, streams, springs, cryoconite water) from glacial catchments of Svalbard.

| Determined compound(s)/parameters | Identified level/range             |                       |                        | References              |
|-----------------------------------|------------------------------------|-----------------------|------------------------|-------------------------|
| pH                                | 4-6.82                             |                       |                        | [34, 65-68]             |
| EC                                | [μS cm <sup>-3</sup> ]<br>6.1-80.4 |                       |                        | [66]                    |
| Anions                            | [μmol L <sup>-1</sup> ]            | [mg L <sup>-1</sup> ] | [μEq L <sup>-1</sup> ] |                         |
| Cl <sup>-</sup>                   | 0.9-553                            | 0.2-20.7              | <LOD-2400              | [34, 38, 40, 49, 65-68] |
| Br <sup>-</sup>                   | <LOD-0.90                          | -                     | -                      | [67]                    |
| NO <sub>3</sub> <sup>-</sup>      | 0.1-3.9                            | 0.01-0.162            | <LOD-7                 | [34, 38, 40, 49, 66-68] |
| SO <sub>4</sub> <sup>2-</sup>     | 0.4-34.5                           | <LOD-2.82             | <LOD-240               | [34, 38, 40, 49, 66-68] |
| HCO <sub>3</sub> <sup>-</sup>     | [μmol L <sup>-1</sup> ]            |                       | [μEq L <sup>-1</sup> ] |                         |
|                                   | 57.1-195                           |                       | 11-900                 | [34, 65, 68]            |
| N-NO <sub>3</sub> <sup>-</sup>    | [mg L <sup>-1</sup> ]              |                       |                        |                         |
|                                   | 0.01-0.02                          |                       |                        | [65]                    |
| Cations                           | N-NH <sub>4</sub> <sup>+</sup>     |                       |                        |                         |
|                                   | 0.06-0.77                          |                       |                        |                         |
|                                   | [μmol L <sup>-1</sup> ]            | [mg L <sup>-1</sup> ] | [μEq L <sup>-1</sup> ] |                         |
| Na <sup>+</sup>                   | 0.8-486                            | 0.12-9.76             | 2-2000                 | [34, 38, 65-68]         |
| NH <sub>4</sub> <sup>+</sup>      | 0.4-5.4                            | <LOD-0.11             | -                      | [38, 40, 49, 67]        |
| K <sup>+</sup>                    | 0.03-11.5                          | <LOD-5.56             | <LOD-96                | [34, 38, 49, 65-68]     |
| Mg <sup>2+</sup>                  | 0.3-47.9                           | <LOD-1.378            | <LOD-200               | [34, 38, 49, 65-68]     |
| Ca <sup>2+</sup>                  | 0.6-15.2                           | 0.04-2.17             | <LOD-110               | [34, 38, 49, 65-68]     |



| Determined compound(s)/parameters |                        | Identified level/range           | References |
|-----------------------------------|------------------------|----------------------------------|------------|
| Si-Si(OH) <sub>4</sub>            |                        | [mg L <sup>-1</sup> ]            |            |
|                                   |                        | 0.03–0.13                        | [65]       |
| SiO <sub>2</sub>                  |                        | 0.0                              | [34]       |
| Si                                |                        | <LOD-1.5 [μmol L <sup>-1</sup> ] | [68]       |
| Metals                            | Al <sub>total</sub>    | 3.78-117 [μg L <sup>-1</sup> ]   | [65]       |
|                                   | Hg <sub>total</sub>    | [ng L <sup>-1</sup> ]            |            |
|                                   |                        | <LOD-59.9                        | [67, 69]   |
|                                   | Hg <sub>reactive</sub> | 2.2–45.3                         | [69]       |
|                                   | MMHg                   | 3–43 [pg L <sup>-1</sup> ]       | [67]       |
| S                                 |                        | 0.17–0.88 [mg L <sup>-1</sup> ]  | [66]       |
| MSA (methyl-sulfonic acid)        |                        | [μmol L <sup>-1</sup> ]          |            |
|                                   |                        | <LOD-1.56                        | [67]       |
| Glut (glutaric acid)              |                        | <LOD-0.07                        |            |
| ΣPCB <sub>9</sub>                 |                        | [pg L <sup>-1</sup> ]            |            |
|                                   |                        | 116–2000                         | [70, 71]   |
| α-HCH                             |                        | <LOD-47.6                        |            |
| γ-HCH                             |                        | 186–3090                         |            |
| ΣDDT                              |                        | 0.391–59.5                       |            |
| HCB                               |                        | 3.10–35.3                        |            |
| ΣPCN                              |                        | 59.0–1100                        | [71]       |
| PFOA                              |                        | 89.5–590.8                       | [49]       |
| PFOS                              |                        | 18.6–133.2                       |            |

**Table 5a.** Literature data on snow samples collected in the glacial catchments of Svalbard.

the pHs closest to neutral and lowest electrical conductivities, and also in terms of inorganic ions their concentration range was smaller than experienced in snow samples (**Table 5b** and **5a**). This reflects the effects of snow accumulation on inorganic chemicals, which are readily removed in meltwater (**Table 5c**) and therefore less of them remains in glacial ice. Conversely, the POPs found in ice were usually occurring at higher concentration than in snow, showing their historical deposition was higher, but also perhaps the ability of the accumulating snowpack to retain them better. An environmental concern are also the concentrations of heavy metals experienced in glacial ice (**Table 5b**), which additionally demonstrate the possibility that glaciers store pollutants of various types.

In **Table 6** we additionally provide the data on other abiotic media except frozen and liquid water, i.e. soil and cryoconite sediment. For cryoconite, it is noteworthy that it may contain



| Determined compound(s)/parameters | Identified level/range   |                          | References   |
|-----------------------------------|--|--------------------------|--------------|
| pH [°]                            | 5.65–7.03  |                          | [88]         |
| SEC [ $\mu\text{S cm}^{-1}$ ]     | 4.50–21.2  |                          |              |
| Anions                            | [ $\mu\text{mol L}^{-1}$ ]   | [ $\text{mg L}^{-1}$ ]   |              |
| Cl <sup>-</sup>                   | 328  | <LOD-1.12                | [38, 49]     |
| NO <sub>3</sub> <sup>-</sup>      | 1.5  | <LOD-0.10                |              |
| SO <sub>4</sub> <sup>2-</sup>     | 19.8   | <LOD-0.27                |              |
| ∑anions                           | F <sup>-</sup> , Cl <sup>-</sup> , NO <sub>2</sub> <sup>-</sup> , Br <sup>-</sup> , NO <sub>3</sub> <sup>-</sup> , PO <sub>4</sub> <sup>3-</sup> , SO <sub>4</sub> <sup>2-</sup> | [ $\text{meq L}^{-1}$ ]  | [88]         |
|                                   |  | 0.022–0.236              |              |
| Cations                           | [ $\mu\text{mol L}^{-1}$ ]   | [ $\text{mg L}^{-1}$ ]   |              |
| Na <sup>+</sup>                   | 199  | <LOD-0.7                 | [38, 49]     |
| NH <sub>4</sub> <sup>+</sup>      | 0.4  | <LOD-0.08                |              |
| K <sup>+</sup>                    | 7.6  | <LOD-0.09                |              |
| Mg <sup>2+</sup>                  | 26.2   | <LOD-0.19                |              |
| Ca <sup>2+</sup>                  | 28.5   | 0.03–0.75                |              |
| ∑cations                          | Na <sup>+</sup> , NH <sub>4</sub> <sup>+</sup> , Li <sup>+</sup> , K <sup>+</sup> , Mg <sup>2+</sup> , Ca <sup>2+</sup>  | [ $\text{meq L}^{-1}$ ]  | [88]         |
|                                   |  | 0.015–0.279              |              |
| Metals                            | [ $\mu\text{g kg}^{-1}$ ]  | [ $\mu\text{g L}^{-1}$ ] | [55, 72, 88] |
| Zn                                | 43.75  | 1–40.91                  | [55, 72, 88] |
| Mn                                | 42.75  | 0.22–5.20                |              |
| Cu                                | 11.25  | 0.27–3.25                |              |
| Fe                                | 2552.50  | 0.10–17.20               |              |
| Ni                                | 7.25   | 0.13–2.34                |              |
| Cr                                | 19.25  | <LOD-0.16                |              |
| Pb                                | 16.75  | 0.02–0.45                |              |
| Cd                                | 4.50   | <LOD-0.10                |              |
| Co                                | 1.50   | <LOD                     |              |
| Be                                | –  | <LOD-0.02                |              |
| B                                 | –  | <LOD-2.31                |              |
| Al                                | –  | <LOD-2.85                |              |
| Se                                | –  | <LOD-0.15                |              |
| Rb                                | –  | <LOD-0.30                |              |
| Sr                                | –  | 0.51–3.89                |              |
| Ba                                | –  | 0.30–3.14                |              |
| U                                 | –  | <LOD-0.02                |              |
| PFOA                              | [ $\text{pg L}^{-1}$ ]   |                          | [49]         |
|                                   |  | 13.5–45.9                |              |



| Determined compound(s)/parameters | Identified level/range |   | References |
|-----------------------------------|------------------------|---|------------|
| PFOS                              | <LOQ-13.5              |   |            |
| DOC                               | [mg L <sup>-1</sup> ]  |   | [88]       |
|                                   | <LOD-0.566             |   |            |
| Pesticides                        | [pg L <sup>-1</sup> ]  | [pg cm <sup>-2</sup> yr <sup>-1</sup> ] | [73, 74]   |
| Aldrin                            | 69,000                 | 30,000                                  |            |
| Dieldrin                          | 7500                   | 54.7                                    |            |
| Endosulfan (α, β)                 | 10,700–19,700          | 2.8–6.8                                 |            |
| Endrin                            | –                      | 16.3                                    |            |
| Endrin-aldehyde                   | 13,600                 | –                                       |            |
| Endrin-ketone                     | –                      | 13.6                                    |            |
| Heptachlor                        | 6500                   | 470                                     |            |
| Heptachlor epoxide                | 32,800                 | 1580                                    |            |
| HCH (α, γ)                        | 1100–7700              | 295–369                                 |            |
| Methoxychlor                      | 4700                   | 19.6                                    |            |
| Chlorpyrifos                      | 16,200                 | 809                                     |            |
| Dacthal                           | 300                    | 12.7                                    |            |
| Diazinon                          | 20,500                 | 1410                                    |            |
| Dimethoate                        | 87000                  | 598                                     |            |
| Disulfoton                        | 6500                   | 447                                     |            |
| Imidan                            | 44,100                 | 3030                                    |            |
| Methylparathion                   | 7400                   | 357                                     |            |
| Terbufos                          | 11,100                 | 530                                     |            |
| Alachlor                          | 1200                   | 57                                      |            |
| Desethyl-atrazine                 | 2100                   | 144                                     |            |
| Metolachlor                       | 9300                   | 450                                     |            |
| Pendimethalin                     | 18,600                 | 890                                     |            |
| Chlordane (α, γ)                  | –                      | 13.39–18.3                              |            |
| DDD(o,p')                         | –                      | 11.5                                    |            |
| DDE (p,p')                        | –                      | 1.14                                    |            |
| DDT (L) (p,p')                    | –                      | 2.93                                    |            |
| Endosulfan sulphate               | –                      | 2.81                                    |            |
| Metribuzin                        | –                      | 1.05                                    |            |
| Nonachlor (trans, cis)            | –                      | 2.28–5.03                               |            |
| Trifluralin                       | –                      | 2.32                                    |            |

**Table 5b.** Literature data on chemical concentrations in ice samples from Svalbard glaciers.



| Determined compound(s)/parameters |                            | Identified level/range                   |                           |                           | References                   |
|-----------------------------------|----------------------------|--|---------------------------|---------------------------|------------------------------|
| pH                                |                            | 4.95–9.74                                |                           |                           | [34–38, 65]                  |
| EC                                |                            | [ $\mu\text{S cm}^{-3}$ ]<br>84.00–188.5 |                           |                           | [35]                         |
| Anions                            | $\text{Cl}^-$              | [ $\mu\text{mol L}^{-1}$ ]               | [ $\text{mg L}^{-1}$ ]    | [ $\mu\text{Eq L}^{-1}$ ] | [12, 34, 35, 37, 38, 65, 76] |
|                                   |                            | 58–464                                   | 0.41–36                   | 4–991                     |                              |
|                                   | $\text{NO}_3^-$            | 0.1–34.7                                 | 0.4–2.2                   | 0.56–9.0                  | [34, 35, 38, 40, 76]         |
|                                   | $\text{PO}_4^{3-}$         | –  | <LOD-1.0                  | –                         | [12]                         |
|                                   | $\text{SO}_4^{2-}$         | 12–217.8                                 | 0.73–920.0                | 1–27,400                  | [12, 34–38, 65, 75, 76]      |
| $\text{HCO}_3^-$                  | [ $\mu\text{mol L}^{-1}$ ] |  | [ $\mu\text{Eq L}^{-1}$ ] | [12, 34–38, 65, 75]       |                              |
|                                   |                            | 4.65–3198                                | <LOD-7600                 |                           |                              |
| $\text{N-NO}_2^-$                 |                            | [ $\text{mg L}^{-1}$ ]                   |                           |                           | [12]                         |
|                                   |                            | <LOD-4.90                                |                           |                           |                              |
| $\text{N-NO}_3^-$                 |                            |  |                           |                           | [12, 65]                     |
|                                   |                            | 0.01–50.70                               |                           |                           |                              |
| $\text{N-NH}_4^+$                 |                            |  |                           |                           | [12, 65]                     |
|                                   |                            | <LOD-19.50                               |                           |                           |                              |
| Cations                           | $\text{Na}^+$              | [ $\mu\text{mol L}^{-1}$ ]               | [ $\text{mg L}^{-1}$ ]    | [ $\mu\text{Eq L}^{-1}$ ] | [12, 34–38, 65, 76]          |
|                                   |                            | 79–513                                   | 0.39–35.1                 | 4–833                     |                              |
|                                   | $\text{NH}_4^+$            | 0.1–6                                    | –                         | –                         | [38, 40]                     |
|                                   | $\text{K}^+$               | 8–26                                     | 0.22–5.5                  | <LOD-37                   | [12, 34, 35, 37, 38, 65, 76] |
|                                   | $\text{Mg}^{2+}$           | 92–633                                   | 0.18–75.3                 | <LOD-12,300               | [12, 34–38, 65, 75, 76]      |
|                                   | $\text{Ca}^{2+}$           | 249–1072                                 | 0.54–33,300               | 9–18,700                  | [12, 34–38, 65, 75, 76]      |
| Metals                            | $\text{Al}_{\text{total}}$ | [ $\text{mg L}^{-1}$ ]                   |                           |                           | [65, 72]                     |
|                                   |                            | 1.9–275.0                                |                           |                           |                              |
|                                   | Fe                         | <0.010–0.300                             |                           |                           |                              |
|                                   | Mn                         | <0.050                                   |                           |                           |                              |
|                                   | Zn                         | <0.001–0.010                             |                           |                           |                              |
|                                   | Pb                         | <0.001–0.010                             |                           |                           |                              |
|                                   | Cu                         | <0.001                                   |                           |                           |                              |
|                                   | Cd                         | <0.001                                   |                           |                           |                              |
|                                   | Si                         | [ $\text{mg L}^{-1}$ ]                   |                           |                           | [76]                         |
|                                   |                            | 0.46–2.31                                |                           |                           |                              |
| $\text{Si-Si(OH)}_4$              |                            | 0.01–0.63                                |                           | [65]                      |                              |
| $\text{SiO}_2$                    | [ $\mu\text{mol L}^{-1}$ ] | [ $\text{mg L}^{-1}$ ]                   | [ $\mu\text{Eq L}^{-1}$ ] | [34–37]                   |                              |
|                                   | 2-22                       | 0.120–0.780                              | 2–34                      |                           |                              |
| DIC                               |                            |  |                           |                           | [76]                         |
|                                   |                            | 15.3–851.3                               |                           |                           |                              |
| DOC                               |                            |  |                           |                           | [38, 65]                     |
|                                   |                            | 0.31–2.17                                |                           |                           |                              |
|                                   |                            | [ $\mu\text{mol L}^{-1}$ ]               |                           |                           |                              |

| Determined compound(s)/parameters | Identified level/range                | References |
|-----------------------------------|---------------------------------------|------------|
|                                   | 165–426                               |            |
| DON                               | <7–27                                 | [38]       |
| DIN                               | <LOD–132.5 [ $\mu\text{g N L}^{-1}$ ] | [77]       |
| PFOA                              | [ $\text{pg L}^{-1}$ ]                | [49]       |
|                                   | 95.7–639                              |            |
| PFOS                              | <LOQ–967                              |            |
|                                   | –                                     |            |
| TIN                               | <LOD–18.2                             |            |
| TN                                | 2200–3800                             |            |

**Table 5c.** Literature overview of chemical concentrations in surface water samples from the glacial catchments of Svalbard.

marked amounts of both harmful heavy metals and life-supporting nutrients. In respect to soils, it can be highlighted that their ionic components may be at lower concentrations than those encountered in the riverine waters flowing out of glacial catchments, especially the fast-flowing, sediment-rich proglacial rivers (**Table 5c**).

| Type of abiotic sample | Determined compound(s)/parameters | Identified level/range     | References                |                           |          |
|------------------------|-----------------------------------|----------------------------|---------------------------|---------------------------|----------|
| Soil                   | pH                                | 7.38–8.79                  | [34, 65]                  |                           |          |
|                        | Anions                            | $\text{Cl}^-$              | [ $\mu\text{Eq L}^{-1}$ ] | [34]                      |          |
|                        |                                   |                            | 120                       |                           |          |
|                        |                                   | $\text{NO}_3^-$            | 19                        |                           |          |
|                        |                                   | $\text{SO}_4^{2-}$         | 240                       |                           |          |
|                        | $\text{HCO}_3^-$                  |                            | 4100                      | [34]                      |          |
|                        | Cations                           | $\text{Na}^+$              | [ $\text{mmol kg}^{-1}$ ] | [ $\mu\text{Eq L}^{-1}$ ] | [34, 65] |
|                        |                                   |                            | 0.12–1.72                 | 180                       |          |
|                        |                                   | $\text{K}^+$               | 1.74–4.04                 | 31                        |          |
|                        |                                   | $\text{Mg}^{2+}$           | 4.11–23.4                 | 1700                      |          |
|                        |                                   | $\text{Ca}^{2+}$           | 63.2–528                  | 2700                      |          |
|                        |                                   | Organic carbon             |                           | [%]                       | [65]     |
|                        |                                   |                            | 1.28–6.05                 |                           |          |
| N                      | 0.04–0.16                         |                            | [65]                      |                           |          |
|                        | $\text{SiO}_2$                    | 3.3 [ $\text{mg L}^{-1}$ ] | [34]                      |                           |          |
| Cryoconite (sediment)  | Metals                            | Fe                         | [ $\text{g kg}^{-1}$ ]    | [72]                      |          |
|                        |                                   |                            | 31.9                      |                           |          |





| Type of abiotic sample | Determined compound(s)/parameters | Identified level/range     | References |
|------------------------|-----------------------------------|----------------------------|------------|
|                        | Mn                                | 0.11                       |            |
|                        | Zn                                | 0.08                       |            |
|                        | Pb                                | 0.19                       |            |
|                        | Cu                                | –                          |            |
|                        | Cd                                | –                          |            |
|                        | DIN                               | [ $\mu\text{g N g}^{-1}$ ] | [77]       |
|                        | TIN                               | <LOD-18.2                  |            |
|                        | TN                                | 2200–3800                  |            |

**Table 6.** Literature data on sediment samples (soil, cryoconite) collected in the glacial catchments of Svalbard.

## 5. Summary

The results of research presented in the reviewed literature do not answer all questions arising in the context of the current global warming. The role of glaciers as contributors to the sea level rise is widely discussed by scientists, and extensively described in the latest IPCC report. However, the role of the changing glaciers and glacial waters, particularly for the biota of the polar environment, frequently does not receive enough attention. Considering the presence of contaminants such as POPs in many abiotic elements of the glacial catchment (e.g., snow, ice, surface water), it seems necessary to ask questions about the way and pace of the release of these highly toxic contaminants from the rapidly melting Arctic glaciers, as well as about the potential impact of those on the polar wildlife. Further research should address these questions, in order to help protect the highly sensitive environment of this area. Especially, a more detailed approach to the transport, deposition, and redistribution or transformation of pollutants in the glacial catchments is required, as opposed to the focus on the presence of pollutants in the environment only. However, without a stronger basis in chemical monitoring, there is frequently too little data to draw more global conclusions about the fate of chemicals in Svalbard glaciers.

## Acknowledgements

K. Koziol acknowledges National Science Centre in Poland (NCN) funding, grant no. 2012/05/N/ST10/02848. The publication has been (partially) financed from the funds of the Leading National Research Centre (KNOW) received by the Centre for Polar Studies of the University of Silesia, Poland.

## List of acronyms

|                     |   |
|---------------------|---|
| <b>AAS</b>          | Atomic Absorption Spectroscopy  |
| <b>ACIA</b>         | Arctic Climate Impact Assessment  |
| <b>AFS</b>          | Atomic Fluorescence Spectrometry  |
| <b>ASTER</b>        | Advanced Spaceborne Thermal Emission and reflection Radiometer  |
| <b>CVAFS</b>        | Cold Vapour Atomic Fluorescence Spectroscopy  |
| <b>DDD</b>          | Dichlorodipenyldichloroethane   |
| <b>DDE</b>          | Dichlorodipenyldichloroethylene   |
| <b>DDT</b>          | Dichlorodipenyltrichloroethane  |
| <b>DIC</b>          | Dissolved Inorganic Carbon  |
| <b>DIN</b>          | Dissolved Inorganic Nitrogen  |
| <b>DOC</b>          | Dissolved Organic Carbon  |
| <b>DON</b>          | Dissolved Organic Nitrogen  |
| <b>EC</b>           | Electrochemical Conductivity  |
| <b>ECV</b>          | Essential Climate Variables   |
| <b>ERC</b>          | European Research Council   |
| <b>ESF</b>          | European Science Foundation   |
| <b>FAO</b>          | Food and Agriculture Organization   |
| <b>FIA</b>          | Flow Injection Analysis   |
| <b>GC-ECD</b>       | Gas Chromatography with Electron Capture Detection  |
| <b>GC-LRMS-ECNI</b> | Gas Chromatography Coupled to Low Resolution Mass Spectrometry in Electron Capture Negative Ionization Mode |
| <b>GC-LRMS-EI</b>   | Gas Chromatography Coupled to Mass Spectrometry with Low Resolution in Electron Ionization Mode             |
| <b>GC-MS-EI-SIM</b> | Gas Chromatography Coupled to Mass Spectrometry in Electronic Ionization Mode with Selected-Ion Monitoring  |
| <b>GLIMS</b>        | Global Land Ice Measurements from Space   |
| <b>GLS</b>          | Global Land Surface   |
| <b>GOA</b>          | Global Ocean Area   |
| <b>GTN</b>          | Global Terrestrial Network  |



|                  |  |
|------------------|--|
| <b>GTN-G</b>     | Global Terrestrial Network for Glaciers  |
| <b>GTOS</b>      | Global Terrestrial Observing System  |
| <b>HCB</b>       | Hexachlorobenzene  |
| <b>HCH</b>       | Hexachlorocyclohexane  |
| <b>HRGC-LRMS</b> | High-Resolution Gas Chromatography Coupled with Low Resolution Mass Spectrometry |
| <b>IC</b>        | Ion Chromatography   |
| <b>ICP-OES</b>   | Inductively Coupled Plasma Optical Emission Spectrometry                         |
| <b>ICP-SFMS</b>  | Inductively Coupled Plasma-Sector Field Mass Spectrometry                        |
| <b>ICP-QMS</b>   | Inductively Coupled Plasma-Quadrupole Mass Spectrometry                          |
| <b>ICSU</b>      | International Council for Science  |
| <b>IPCC</b>      | Intergovernmental Panel on Climate Change  |
| <b>LC-MS/MS</b>  | Liquid Chromatography with Tandem Mass Spectrometry                              |
| <b>LOD</b>       | Limit Of Detection   |
| <b>LOQ</b>       | Limit Of Quantitation  |
| <b>LRAT</b>      | Long Range Atmospheric Transport   |
| <b>NSIDC</b>     | National Snow and Ice Data Center  |
| <b>PCB</b>       | Polychlorinated Biphenyls  |
| <b>PCN</b>       | Polychlorinated Naphthalene  |
| <b>PFOA</b>      | Perfluorooctanoate   |
| <b>PFOS</b>      | Perfluorooctane sulfonate  |
| <b>POP</b>       | Persistent Organic Pollutants  |
| <b>PSFG</b>      | Permanent Service on the Fluctuations of Glaciers                                |
| <b>RCN</b>       | Research Council of Norway   |
| <b>TIN</b>       | Total Inorganic Nitrogen   |
| <b>TN</b>        | Total Nitrogen;  |
| <b>TOC</b>       | Total Organic Carbon;  |
| <b>TON</b>       | Total Organic Nitrogen;  |
| <b>TOPC</b>      | Terrestrial Observation Panel for Climate;                                       |



|                |   |
|----------------|---|
| <b>TTS/WGI</b> | Temporal Technical Secretariat for the World Glacier Inventory;   |
| <b>UNEP</b>    | United Nations Environment Programme;                             |
| <b>UNESCO</b>  | United Nations Educational, Scientific and Cultural Organization; |
| <b>WGMS</b>    | World Glacier Monitoring Service;                                 |
| <b>WMO</b>     | World Meteorological Organization.                                |

## Author details

Sara Lehmann-Konera<sup>1</sup>, Marek Ruman<sup>2,3\*</sup>, Krystyna Kozioł<sup>1</sup>, Grzegorz Gajek<sup>4</sup> and Żaneta Polkowska<sup>1\*</sup>

\*Address all correspondence to: marek.ruman@us.edu.pl; zanpolko@pg.gda.pl

1 Department of Analytical Chemistry, Faculty of Chemistry, Gdansk University of Technology, Gdansk, Poland

2 Faculty of Earth Sciences, University of Silesia, Sosnowiec, Poland

3 Centre for Polar Studies, Leading National Research Centre (KNOW), Sosnowiec, Poland

4 Department of Geology and Lithosphere Protection, Faculty of Earth Sciences and Spatial Management, Maria Curie-Skłodowska University in Lublin, Lublin, Poland

## References

- [1] Bogdal C, Schmid P, Zennegg M, Anselmetti FS, Scheringer M, Hungerbühler K. Blast from the past: Melting glaciers as a relevant source for persistent organic pollutants. *Environmental Science & Technology*. 2009;**43**:8173–8177
- [2] Grannas AM, Bogdal C, Hageman KJ, Halsall C, Harner T, Hung H, Kallenborn R, Klán P, Klánová J, Macdonald RW, Meyer T, Wania F. The role of the global cryosphere in the fate of organic contaminants. *Atmospheric Chemistry and Physics*. 2013;**13**:3271–3305
- [3] Hodson AJ. Understanding the dynamics of black carbon and associated contaminants in glacial systems. *WIREs Water*. 2014;**1**:141–149. DOI: 10.1002/wat2.1016
- [4] ACIA. Arctic Climate Impact Assessment. Cambridge University Press. Cambridge: 2005. p. 1042. <http://www.acia.uaf.edu> (19.07.2014): 183–242
- [5] IPCC 2013, Vaughan DG, Comiso JC, Allison I, Carrasco J, Kaser G, Mote P, et al. Observations: cryosphere. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, et al, editors. *Climate Change 2013: The Physical Science Basis. Contribution of working group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate*



Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2013

- [6] Jansson P, Hock R, Schneider T. The concept of glacier storage: A review. *Journal of Hydrology*. 2003;**282**(1):116–129
- [7] Błaszczyk M, Jania JA, Hagen JO. Tidewater glaciers of Svalbard: Recent changes and estimates of calving fluxes. *Polish Polar Research*. 2009;**30**(2):85–142
- [8] Nuth C, Moholdt G, Kohler J, Hagen JO and Kääb A. Svalbard glacier elevation changes and contribution to sea level rise. *Journal of Geophysical Research*. 2010;**115**:F01008. DOI: 10.1029/2008JF001223
- [9] Ruman M, Kozak K, Lehmann S, Koziół K, Polkowska Ż. Pollutants present in different components of the Svalbard archipelago environment. *Ecological Chemistry and Engineering S*. 2012;**19**(4):571–584
- [10] Kozak K, Polkowska Ż, Ruman M, Koziół K, Namieśnik J. Analytical studies on the environmental state of the Svalbard Archipelago provide a critical source of information about anthropogenic global impact. *TrAC Trends in Analytical Chemistry*. 2013;**50**:107–126
- [11] Jiao L, Zheng GJ, Minh TB, Richardson B, Chen L, Zhang Y, et al. Persistent toxic substances in remote lake and coastal sediments from Svalbard, Norwegian Arctic: Levels, sources and fluxes. *Environmental Pollution*. 2009;**157**:1342–1351
- [12] Dragon K, Marciniak M. Chemical composition of groundwater and surface water in the Arctic environment (Petuniabukta region, central Spitsbergen). *Journal of Hydrology*. 2010;**386**(1):160–172
- [13] Brown GH. Glacier meltwater hydrochemistry. *Applied Geochemistry*. 2002;**17**(7):855–883
- [14] Cuffey K, Paterson WSB. *The Physics of Glaciers*. 4th ed. Academic Press; San Diego, United States: 2010
- [15] Irvine Flynn TDL, Hodson AJ, Mooram BJ, Vatne G, Hubbard AL. Polythermal glacier hydrology: A review. *Reviews of Geophysics*. 2011;**49**(4):RG4002. DOI: 10.1029/2010RG000350
- [16] Jania J. *Glaciologia. Nauka o Lodowcach*. Warszawa: PWN. 1993. p. 358
- [17] Sugden DE, John BS. *Glaciers and Landscape. A Geomorphological Approach*. London: Edward Arnold. 1976. p. 376
- [18] Głowacki P. Rola procesów fizyczno-chemicznych w kształtowaniu struktury wewnętrznej i obiegu masy lodowców Spitsbergenu. *Publications of the Institute of Geophysics. Polish Academy of Sciences*. 2007;**M-30**(400):147
- [19] Kääb A, Huggel C, Paul F, Wessels R, Raup B, Kieffer H, Kargel J. Glacier monitoring from ASTER imagery: Accuracy and applications. In *Proceedings of EARSeL-LISSIG-Workshop Observing our Cryosphere from Space*. 2002;**2**: 43–53
- [20] Roer I. Global glacier changes: Facts and figures. In: Zemp M, van Woerden J, editors. *UNEP/Earthprint*; 2008



- [21] GLIMS Information from: <http://www.glims.org/> [date:19.08.2014]
- [22] Zemp M. The monitoring of glaciers at local, mountain, and global scale. Geographisches Institut der Universität Zürich. 2012;**65**
- [23] Kargel JS. Global land ice measurements from space. In: Leonard GJ, Bishop MP, Käab A, Raup BH, editors. Heidelberg: Springer; 2013. ISBN 978-3-540-79818-1 (eBook)
- [24] GTN-G Information. Available from: <http://www.gtn-g.org/> [Accessed date August 19, 2014]
- [25] UIO Information. Available from: <http://www.mn.uio.no> [Accessed date August 19, 2014]
- [26] ICE2SEA Information. Available from: <http://www.ice2sea.eu> [Accessed date August 19, 2014]
- [27] SVALGLAC Information. Available from: <http://svalglac.eu> [Accessed date August 19, 2014]
- [28] GLACIODYN Information. Available from: <http://www.unis.no/> [Accessed date August 19, 2014]
- [29] Sharp M, Wolken G, Geail ML, Burgess D, Cogley JG, Arendt A, Wouters B. Mountain Glaciers and Ice Caps (Outside Greenland)[in Arctic Report Card 2013], [ftp://ftp.oar.noaa.gov/arctic/documents/ArcticReportCard\\_full\\_report2013.pdf](ftp://ftp.oar.noaa.gov/arctic/documents/ArcticReportCard_full_report2013.pdf) [date: 19.08.2014], p. 108.
- [30] Hagen JO, Liestøl O, Roland E, Jørgensen T. Glacier atlas of Svalbard and Jan Mayen. Norsk Polarinstitut Meddelelser; 1993. p. 129
- [31] Ziaja W, Skiba S. [ed.] Structure and functioning of the Sorkapland natural environment [in Polish: Struktura i funkcjonowanie środowiska przyrodniczego Sorkaplandu]. Kraków: UJ; 2002.
- [32] Hagen JO, Kohler J, Melvold K, Winther JG. Glaciers in Svalbard: Mass balance, runoff and freshwater flux. Polar Research. 2003;**22**(2):145–159
- [33] Głowacki P. The mass balance of Hans glacier in the light of cryochemical investigation. In: P Głowacki, editor. Pol Polar Stud 1997. 24th Polar Symposium, Warszawa, 1997. Warszawa: Institute of Geophysics of the Polish Academy of Sciences; 1997. pp. 75–79
- [34] Hodson A, Tranter M, Gurnell A, Clark M, Hagen JO. The hydrochemistry of Bayelva, a high Arctic proglacial stream in Svalbard. Journal of Hydrology. 2002;**257**:91–114
- [35] Krawczyk WE, Lefauconnier B, Petterson LE. Chemical denudation rates in the Bayelva Catchment, Svalbard, in the Fall of 2000. Physics and Chemistry of the Earth Parts A/B/C. 2003;**28**(28):1257–1271
- [36] Nowak A, Hodson A. Changes in meltwater chemistry over a 20-year period following a thermal regime switch from polythermal to cold-based glaciation at Austre Brøggerbreen, Svalbard. Polar Research. 2014;**33**: 1-19. Article number: 22779. DOI: 10.3402/polar.v33.22779
- [37] Stachnik Ł, Majchrowska E, Yde JC, Nawrot AP, Cichała-Kamrowska K, Ignatiuk D, Piechota A. Chemical denudation and the role of sulfide oxidation at Werenskioldbreen, Svalbard. Journal of Hydrology. 2016;**538**:177–193



- [38] Tye AM, Heaton THE. Chemical and isotopic characteristics of weathering and nitrogen release in non-glacial drainage waters on Arctic tundra. *Geochimica et Cosmochimica Acta*. 2007;**71**:4188–4205
- [39] Stachnik Ł, Yde JC, Kondracka M, Ignatiuk D, Grzesik M. Glacier naled evolution and relation to the subglacial drainage system based on water chemistry and GPR surveys (Werenskioldbreen, SW Svalbard). *Annals of Glaciology*. 2016;**57**:1–12
- [40] Wynn PM, Hodson AJ, Heaton THE, Chenery SR. Nitrate production beneath a high Arctic glacier, Svalbard. *Chemical Geology*. 2007;**244**:88–102
- [41] AMAP 2016. AMAP Assessment 2015: Temporal Trends in Persistent Organic Pollutants in the Arctic. Oslo; pp. i-71
- [42] Wang-Andersen G, Utne Skaare J, Prestrud P, Steinnes E. Levels and congener pattern of PCBs in arctic fox (*Alopex lagopus*) in Svalbard. *Environmental Pollution*. 1993;**82**(3):269–275
- [43] Bernhoff A, Wiig Ø, Skaare JU. Organochlorines in polar bears (*Ursus maritimus*) at Svalbard. *Environmental Pollution*. 1997;**95**(2):159–175
- [44] Kleivane L, Severinsen T, Skaare JU. Biological transport and mammal to mammal transfer of organochlorines in Arctic fauna. *Marine Environmental Research*. 2000;**49**(4):343–357
- [45] Henriksen EO, Wiig Ø, Skaare JU, Gabrielsen GW, Derocher AE. Monitoring PCBs in polar bears: Lessons learned from Svalbard. *Journal of Environmental Monitoring*. 2001;**3**(5):493–498
- [46] Fuglei E, Bustnes JO, Hop H, Mørk T, Björnfoth H, Van Bavel B. Environmental contaminants in arctic foxes (*Alopex lagopus*) in Svalbard: Relationships with feeding ecology and body condition. *Environmental Pollution*. 2007;**146**(1):128–138
- [47] Routti H, Letcher RJ, Chu S, Van Bavel B, Gabrielsen GW. Polybrominated diphenyl ethers and their hydroxylated analogues in ringed seals (*Phoca hispida*) from Svalbard and the Baltic Sea. *Environmental Science & Technology*. 2009;**43**(10):3494–3499
- [48] Letcher RJ, Bustnes JO, Dietz R, Jenssen BM, Jørgensen EH, et al. Exposure and effects assessment of persistent organohalogen contaminants in arctic wildlife and fish. *Science of the Total Environment*. 2010;**408**(15):2995–3043
- [49] Kwok KY, Yamazaki E, Yamashita N, Sachi Taniyasu S, Murphy MB. Transport of perfluoroalkyl substances (PFAS) from an arctic glacier to downstream locations: Implications for sources. *Science of the Total Environment*. 2013;**447**:46–55
- [50] Hallanger IG, Ruus A, Herzke D, Warner NA, Evenset A, et al. Influence of season, location, and feeding strategy on bioaccumulation of halogenated organic contaminants in Arctic marine zooplankton. *Environmental Toxicology and Chemistry*. 2011;**30**(1):77–87
- [51] Vallack HW, Bakker DJ, Brandt I, Broström-Lundén E, Brouwer A. Controlling persistent organic pollutants—What next? *Environmental Toxicology and Pharmacology*. 1998;**6**(3):143–175



- [52] Lohmann R, Breivik K, Dachs J, Muir D. Global fate of POPs: Current and future research directions. *Environmental Pollution*. 2007;**150**(1):150–165
- [53] Macdonald RW, Barrie LA, Bidleman TF, Diamond ML, Gregor DJ. Contaminants in the Canadian Arctic: 5 years of progress in understanding sources, occurrence and pathways. *Science of the Total Environment*. 2000;**254**(2):93–234
- [54] Wania F, Mackay D. The evolution of mass balance models of persistent organic pollutant fate in the environment. *Environmental Pollution*. 1999;**100**(1):223–240
- [55] Drbal K, Elster J, Komarek J. Heavy metals in water, ice and biological material from Spitsbergen, Svalbard. *Polar Research*. 1992;**11**(2):99–101
- [56] Wang Z, Ma X, Na G, Lin Z, Ding Q, Yao Z. Correlations between physicochemical properties of PAHs and their distribution in soil, moss and reindeer dung at Ny-Ålesund of the Arctic. *Environmental Pollution*. 2009;**157**(11):3132–3136
- [57] Hoekstra PF, Braune BM, O'Hara TM, Elkin B, Solomon KR, Muir DCG. Organochlorine contaminant and stable isotope profiles in Arctic fox (*Alopex lagopus*) from the Alaskan and Canadian Arctic. *Environmental Pollution*. 2003;**122**(3):423–433
- [58] Gabrielsen GW. Levels and effects of persistent organic pollutants in arctic animals. In *Arctic Alpine Ecosystems and People in a Changing Environment*. Berlin Heidelberg; Springer; 2007. pp. 377–412
- [59] Bang K, Jenssen BM, Lydersen C, Skåre JU. Organochlorine burdens in blood of ringed and bearded seals from north-western Svalbard. *Chemosphere*. 2001;**44**(2):193–203
- [60] Weber J, Halsall CJ, Muir D, Teixeira C, Small J, et al. Endosulfan, a global pesticide: A review of its fate in the environment and occurrence in the Arctic. *Science of the Total Environment*. 2010;**408**(15):2966–2984
- [61] Bidleman TF, Helm PA, Braune BM, Gabrielsen GW. Polychlorinated naphthalenes in polar environments – A review. *Science of the Total Environment*. 2010;**408**(15):2919–2935
- [62] Wong F, Jantunen LM, Pucko M, Papakyriakou T, Staebler RM, Stern GA, Bidleman TF. Air-water exchange of anthropogenic and natural organohalogens on International Polar Year (IPY) expeditions in the Canadian Arctic. *Environmental Science & Technology*. 2010;**45**(3):876–881
- [63] Kallenborn R, Christensen G, Evenset A, Schlabach M, Stohl A. Atmospheric transport of persistent organic pollutants (POPs) to Bjørnøya (Bear island). *Journal of Environmental Monitoring*. 2007;**9**(10):1082–1091
- [64] Hung H, Kallenborn R, Breivik K, Su Y, Brorström-Lundén E, et al. Atmospheric monitoring of organic pollutants in the Arctic under the Arctic Monitoring and Assessment Programme (AMAP): 1993–2006. *Science of the Total Environment*. 2010;**408**(15):2854–2873
- [65] Stutter MI, Billett MF. Biogeochemical controls on streamwater and soil solution chemistry in a High Arctic environment. *Geoderma*. 2003;**113**(1):127–146





- [66] De Caritat P, Hall G, Gislason S, Belsey W, Braun M. Chemical composition of arctic snow: Concentration levels and regional distribution of major elements. *Science of the Total Environment*. 2005;**336**(1):183–199
- [67] Larose C, Dommergue A, De Angelis M, Cossa D, Averty B, et al. Springtime changes in snow chemistry lead to new insights into mercury methylation in the Arctic. *Geochimica et Cosmochimica Acta*. 2010;**74**(22):6263–6275
- [68] Hodgkins R, Tranter M. Solute in High Arctic glacier snow cover and its impact on runoff chemistry. *Annals of Glaciology*. 1998;**26**:156–160
- [69] Ferrara CP, Padova C, Fain X, Gauchard PA, Dommergue A, et al. Atmospheric mercury depletion event study in Ny-Alesund (Svalbard) in spring 2005. Deposition and transformation of Hg in surface snow during springtime. *Science of the Total Environment*. 2008;**397**(1):167–177
- [70] Herbert BMJ, Halsall CJ, Villa S, Jones K C, Kallenborn R. Rapid changes in PCB and OC pesticide concentrations in Arctic snow. *Environmental Science & Technology*. 2005a;**39**(9):2998–3005
- [71] Herbert BMJ, Halsall CJ, Villa S, Fitzpatrick L, Jones KC, et al. Polychlorinated naphthalenes in air and snow in the Norwegian Arctic: A local source or an Eastern Arctic phenomenon? *Science of the Total Environment*. 2005b;**342**(1):145–160
- [72] Chmiel S, Reszka M, Rysiak A. Heavy metals and radioactivity in environmental samples of the Scott Glacier region on Spitsbergen in summer 2005. *Quaestiones Geographicae* 28A/1. Poznań: Adam Mickiewicz University Press; 2009. pp. 23–29. ISBN 978-83-232-2128-9
- [73] Hermanson MH, Isaksson E, Teixeira C, Muir DC, Compher KM, et al. Current-use and legacy pesticide history in the Austfonna ice cap, Svalbard, Norway. *Environmental Science & Technology*. 2005;**39**(21):8163–8169
- [74] Ruggirello RM, Hermanson MH, Isaksson E, Teixeira C, Forsström S, et al. Current use and legacy pesticide deposition to ice caps on Svalbard, Norway. *Journal of Geophysical Research Atmospheres*. 2010;**115**(D18):1–11. Article number: D18308
- [75] Wadham JL, Cooper RJ, Tranter M, Bottrell S. Evidence for widespread anoxia in the proglacial zone of an Arctic glacier. *Chemical Geology*. 2007;**243**(1):1–15
- [76] Rutter N, Hodson A, Irvine-Fynn T, Solås MK. Hydrology and hydrochemistry of a deglaciating high-Arctic catchment, Svalbard. *Journal of Hydrology*. 2011;**410**(1):39–50
- [77] Telling J, Anesio AM, Tranter M, Irvine-Fynn T, Hodson A, et al. Nitrogen fixation on Arctic glaciers, Svalbard. *Journal of Geophysical Research Biogeosciences*. 2011;**116**:1–8; Article number: G03039
- [78] Pulina M, Burzyk M. Fuglebekken catchment [in Polish]. In: *Glaciological workshops 2004; Polish Geomorphologists Association, Sosnowiec-Poznań-Longyearbyen*. 2004;**VI**:58–62



- [79] Stibal M, Tranter M. Laboratory investigation of inorganic carbon uptake by cryoconite debris from Werenskioldbreen, Svalbard. *Journal of Geophysical Research*. 2007;**112**:9; G04S33. DOI: 10.1029/2007JG000429
- [80] Taurisano A, Schuler TV, Hagen JO, Eiken T, Loe E, Melvold K, Kohler J. The distribution of snow accumulation across the Austfonna ice cap, Svalbard: Direct measurements and modelling. *Polar Research*. 2007;**26**(1):7–13
- [81] Kääb A. Glacier volume changes using ASTER satellite stereo and ICESat GLAS laser altimetry. A test study on edgeoya, eastern svalbard. In: Paper presented at IEEE International Geoscience and Remote Sensing Symposium (IGARSS); Jul 23–27; Barcelona, Spain. IEEE-Instrumentation Electrical Electronics Engineers Inc; 2008
- [82] Rolstad C, Norland R. Ground-based interferometric radar for velocity and calving-rate measurements of the tidewater glacier at Kronebreen, Svalbard. *Annals of Glaciology*. 2009;**50**:47–54
- [83] Sund M, Eiken T, Hagen JO, Kääb A. Svalbard surge dynamics derived from geometric changes. *Annals of Glaciology*. 2009;**50**(52):50–60
- [84] Moholdt G, Hagen JO, Eiken T, Schuler TV. Geometric changes and mass balance of the Austfonna ice cap, Svalbard. *The Cryosphere*. 2010;**4**:21–34. DOI: 10.5194/tc-4-21-2010
- [85] Schuler TV, Loe E, Taurisano A, Eiken T, Hagen JO, Kohler J. Calibrating a surface mass-balance model for Austfonna ice cap, Svalbard. *Annals of Glaciology*. 2007;**46**(1):241–248
- [86] Norheim G, Kjos-Hanssen B. Persistent chlorinated hydrocarbons and mercury in birds caught off the west coast of Spitsbergen. *Environmental Pollution Series A*. 1984;**33**(2):143–152
- [87] Vieweg I, Hop H, Brey T, Huber S, Ambrose Jr WG, Locke VWL, Gabrielsen GW. Persistent organic pollutants in four bivalve species from Svalbard waters. *Environmental Pollution*. 2012;**161**:134–142
- [88] Lehmann S, Gajek G, Chmiel S, Polkowska Ż. Do morphometric parameters and geological conditions determine chemistry of glacier surface ice? Spatial distribution of contaminants present in the surface ice of Spitsbergen glaciers (European Arctic). *Environmental Science and Pollution Research*. 2016;**23**(23):23385–23405

