POLAR ECOLOGY OF SVALBARD
Textbook

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Content

Preface

The Czech Republic (formerly Czechoslovakia) has been conducting research on Svalbard for approximately 40 years. Over the last ten years, it has acquired permanent premises at the Julio Payer's house in Longyearbyen, the Nostoc field station and the RV Clione for the purpose of this research.

This enabled the development of good relations between Norwegian and Czech polar academic environments and institutions. The same Norwegian institutions contributed professional content as part of Arctic festivals in the Czech Republic in 2019 and 2020/21. Through the EEA and Norway Funds, we were able to contribute to the implementation of some activities, such as the publication of this book that you are now holding in your hands.

As the Norwegian ambassador to the Czech Republic from 2018 to 2022, I was delighted by the great interest of the Czech public in the polar region and the specific conditions that prevail there. Today, climate change and its consequences are a central topic of research. For Norway, it is important that researchers from other countries take part in developing knowledge and understanding of what is happening to the climate, and thus to animal and plant life in the Arctic.

The Arctic – and Antarctica – has a central place in Norwegian history. The mapping of unknown areas and the exploitation of their natural resources form important chapters in the story of Norway and the building of national identity. The life work of Fridtjof Nansen and Roald Amundsen continues in the form of current research - both in Tromsø and Svalbard, where we have enabled other countries to conduct research, both in Longyearbyen and Ny-Ålesund. The story of Svalbard is also the story of the transition from coal mining to research. All Norwegian coal mining in Svalbard has now ended, with the exception of Mine 7, which supplies the Longyearbyen power plant. Mine 7 is scheduled to close in September 2023.

Thanks to the Treaty on Svalbard from 1920, the archipelago became part of Norway (Treaty recognizing the sovereignty of Norway over the Archipelago of Spitsbergen). However, the treaty gives citizens and companies of all contracting parties the right to reside and operate on Svalbard as defined in the treaty, including conducting research. Norway attaches great importance to this treaty and makes sure that it is properly observed.

This book gives a broad picture of research activities in the archipelago. It discusses its nature, animal life and, last but not least, the consequences of climate change. The book also shows us how vast our knowledge is now thanks to the efforts of our researchers.

H.E. Robert Kvile

Ambassador of Norwegian Kingdom in Czech Republic

Introduction

Josef Elster and Oleg Ditrich

The first mention of the archipelago can be found in Icelandic annals from 1194 and here is also mentioned for the first time Svalbard, a name that is valid to this day. For a long period from that date, however, there is no mention of this Arctic Archipelago until the voyage of discovery of the Dutch navigator Willem Barents in 1596 (Fig. 1.0).

Fig. 1.0: Mercator Hondius Map of the Arctic (First Map of the North Pole) (https://commons.wikimedia.org/wiki/File:1606_Mercator_Hondius_Map_of_the_Arctic_%28First_Map_of_the_North_Pole%29_-_Geographicus_-_NorthPole-mercator-1606.jpg)

The purpose of the trip was both to find the Northeast Sea Route and to map this hitherto unknown part of the Arctic. Svalbard or Spitsbergen, as W. Barents named the archipelago, is an archipelago in the Arctic Ocean north of the European mainland. It is a group of islands scattered between 74° and 81° north latitude and between 10° and 34° east longitude. At the same time, it is the northernmost part of the Kingdom of Norway. Strictly speaking, Western

Spitsbergen is only the name of the largest island in the west of the archipelago, but the designation of the entire archipelago by this name is widespread, albeit inaccurate. Under the Spitsbergen Agreement of 9 February 1920, the archipelago is under the direct sovereignty of Norway and, according to the Act of 17 June 1925, also part of the Kingdom of Norway.

After the first voyage of discovery of W. Barents, whaling fever broke out in this part of the Arctic region, and throughout the 17th century, English and Dutch whaling ships sailed there and decimated marine mammals in a relatively short period. Whaling fever lasted until 1710. In addition to hunting, however, these expeditions also significantly contributed to the mapping of the entire area. To this day, we can find remnants of whaling activities from that time in a number of locations. In the period between 1773 and 1839, the presence of Norwegian hunters and trappers on Svalbard increased, but only after 1858 began interest in scientific exploration of the archipelago, including mapping the area, measuring climatic parameters, describing geological development, and related biological research. This pioneering discovery of Svalbard was followed in the 19th and 20th centuries by interest in economic use, including the continuation of hunting and fishing use of the land, mining of mineral resources and finally the development of tourism (Fig.2.0).

Fig.2.0: Geographical map of Svalbard

(https://commons.wikimedia.org/wiki/File:Topographic_map_of_Svalbard.svg, Creative Commons Attribution-Share Alike 4.0 International).

History of Czech (Czechoslovak) scientific activities in Svalbard

The first Czech scientist at Svalbard was probably the physicist Professor František Běhounek. On Umberto Nobile's airship Italia, he was the first Czech to fly over the North Pole. The subsequent shipwreck during the return of the airship, several weeks stay on the ice floe and rescue by the Soviet icebreaker Krasin, he described in the book Castaways on the Ice Floe (1928).

Before World War II, the Czech botanist Professor Emil Hadač worked in Svalbard. Hadač's book Svalbard – Cold Coast (1946) also comes from this period. Hadač later participated in several Czechoslovak scientific expeditions organized by the Slovak Academy of Sciences. In the eighties of the last century, physical geographers from Masaryk University also organized several expeditions and their work was published in the book Brázdil et al. 1988. The same group later founded the Czech Scientific Antarctic Infrastructure "J. G. Mendel Station" on James Ross Island.

The main task of the expedition of the Czechoslovak Academy of Sciences in cooperation with Krátký film Praha in 1988 under the leadership of Prof. Jiří Komárek was the shooting of the films "On the Edge of Life" and "Man and Svalbard" near the Russian mining towns of Barentsburg and Pyramiden. In the 80s, expeditions were also organized by Czech speleologists (SPELEO, Josef Řehák, Semily), who in cooperation with Polish colleagues studied glacial systems in the southwestern part of Svalbard.

The golden period of Czech Arctic research occurred after the Velvet Revolution in November 1989. Several projects sponsored by Czech and foreign grant agencies took place in the western part of the archipelago (Ny-Ålesund) and in cooperation with groups in the vicinity of the Polish station in Hornsund. Most of these projects were focused on studying the ecological role of cyanobacteria and algae in Arctic ecosystems, including microbial primary succession after deglaciation and the study of subglacial systems. Selected projects were carried out in cooperation with SPELEO of Josef Řehák, Semily.

On the basis of the above-mentioned Czech scientific expeditions, the Norwegian Polar Institute (NPI) invited Czech scientists to long-term cooperation. In preparation for the program of the International Polar Year, NPI organized a seminar on the topic of Biological and climatic diversity of Svalbard. At this seminar we presented previous Czech research at Svalbard and NPI recommended the involvement of Czech experts especially in the fields of microbial and plant ecology - ecophysiology and climatology. At the same time, it was proposed that the Czech Republic rent or renovate a terrain cottage in the central part of Svalbard (in the area of Isfjorden Bay). Based on this information, we prepared a project proposal for the program of the Ministry of Education, Youth and Sports (MEYS) "Biological and climatic diversity of the central part of the Arctic archipelago of Svalbard" (INGO LA 341) in 2006. The project was supported and with the support of this project we modified two iron containers in 2007 (one accommodation for six people and one storage for the zodiac and a small workshop), which were then transported to Pyramiden (Fig.3a.0 and 3b.0). At the same time, an automatic climate station was installed on the adjacent site (Fig. 3c.0).

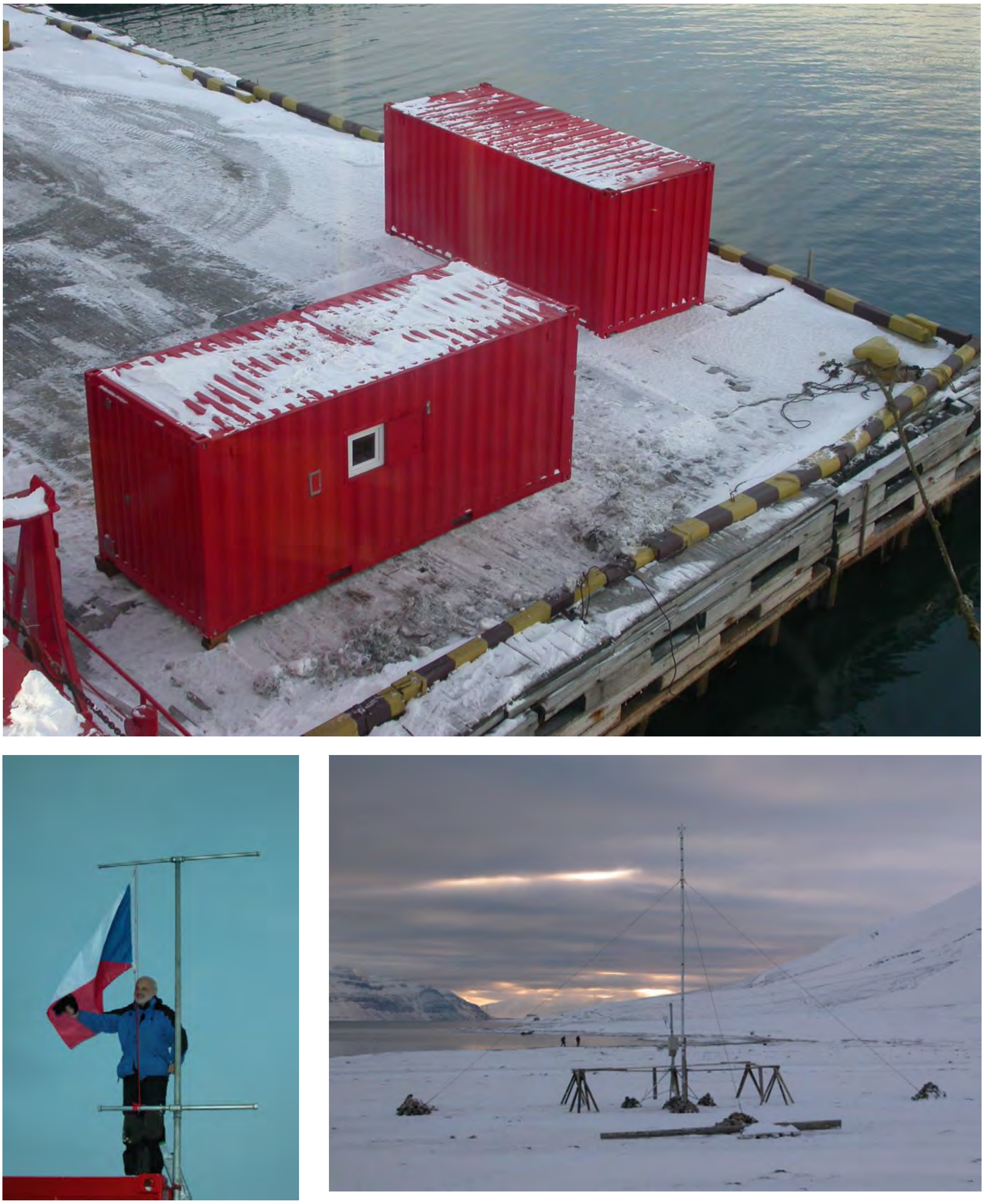

Fig.3.0: (a) 2 containers – technical and accommodation – were transported to the pier in Pyramiden; (b) thus began the official Czech presence and began scientific research on the Arctic archipelago of Svalbard; (c) an automatic meteorological station was established in Petuniabukta Bay (also Petunia) (CPE Archive).

Following the logistical possibilities of the container station, a contract was prepared between the University of South Bohemia (USB) and Arktikugol for the use of their hut (Fig.4.0).The preparation of the Russian-Czech treaty was also approved by the office of the governor of Svalbard in Longyearbyen. At the same time, the USB received permission from the Governor's Office of Svalbard to conduct long-term ecological research in this area. Safety at work (defense against polar bears) was provided by the USB by contract with the University Centre Svalbard (UNIS).

Fig.4.0: Russian hunting lodge in Petuniabukta Bay (CPE archive).

During the project (2007 – 2010) a study of the terrestrial ecosystem was carried out in terms of microbial (cyanobacteria and algae) and plant diversity (bryophytes and vascular plants) and productivity. At the same time, climatic and microclimatic factors influencing diversity and productivity were measured at selected locations. This study has a Czech tradition in the Polar Regions, especially in cooperation with botanists from the Faculty of Science of the USB and the Institute of Botany of the Academy of Sciences of the Czech Republic and climatologists from the Institute of Geography of the Faculty of Science of Masaryk University. Marine biota was studied on the adjacent sea shelf, the diversity of animals across the system was described, including possible phylogenetic relationships of selected groups. The complexity of the ecosystem was assessed based on fish parasites and their life cycles. Some selected groups of organisms (cyanobacteria, algae and parasites of fish and their intermediate hosts) have also been studied at the molecular level. The results of this first project were published in a special issue of the Polish scientific journal Elster, J., Rachlewicz, G. (eds.) 2012, Polish Polar Research.

Czech Arctic Research Infrastructure "Josef Svoboda Station" (CARI – JSS) on Svalbard

During the project completed in 2010, we intensively prepared the conditions for long-term research in Svalbard. From the experience of using iron containers and a Russian hunting lodge, it became clear that it was necessary to prepare conditions - to establish laboratories with basic equipment, increase the possibility of transport, expand the network of automatic climate stations, acquire your own equipment and ensure the safety of work on Svalbard, etc. It was necessary to gradually incorporate Czech Arctic research into existing international projects and international institutions coordinating Arctic research. In 2009, the MEYS of the Czech Republic invited us to prepare an infrastructure project. After a series of meetings, a project proposal for the construction and operation of the Czech Arctic Research Infrastructure (2011 – 2015 Project CzechPolar – Czech Polar Stations: Construction and operation expense, MEYS – LM2010009). Since the start of regular scientific expeditions, all scientific, pedagogical and operational activities have been recorded on the website of the Centre of Polar Ecology – CPE, FS, USB). The Czech Arctic Research Infrastructure (CARI) was named after Josef Svoboda, Ph.D., a political prisoner from the fifties of the last century, professor emeritus of the University of Toronto and doctor honoris causa of Masaryk University in Brno. In 1968 Josef Svoboda immigrated to Canada, where he completed a bachelor's degree in plant physiology and a postgraduate degree in arctic ecology. Since 1970 he has participated in annual Arctic expeditions, and since 1975 he has organized them himself as an assistant professor at the University of Toronto.

The Josef Svoboda station (JSS) in Svalbard consists of several facilities located in the central part of the island of West Spitsbergen and a separate building at the FS USB in České Budějovice, where the CPE is located. The CPE is a scientific workplace that aims to conduct and support research and teaching in polar ecology at the FS USB in České Budějovice. It is housed in a separate building with four fully equipped laboratories including a molecular laboratory, a lecture room for 30 people, a refrigerated room for cultivation and simulation of low temperatures in the Arctic, facilities for sterile work including DNA isolation and amplification, and measurement of photosynthesis in experimentally manipulative conditions (Fig. 5.0). Another part of the infrastructure is the Payer House, the main base in Longyearbyen, the starting point for all parts of the infrastructure in Svalbard, accommodation capacity of 10 people with kitchen and sanitary facilities, two fully equipped scientific laboratories, warehouses, workshop and technical facilities to support all parts of the infrastructure (Fig.6.0). The field station Nostoc (Fig.7.0) is located 60 km northeast of Longyearbyen. It consists of 4 containers, which are connected by a central tent (2x accommodation container, kitchen, field laboratory). There is accommodation for up to 12 people, with technical facilities (generators, basic workshop). 6 km from the station, in the settlement of Pyramiden, there are two more containers (set up at the beginning of the first project), which serve as a warehouse and an emergency overnight shelter. Another essential part of the infrastructure is the research vessel (RV) "Clione", a motor sailer with a length of 15 m with three cabins, a galley and a saloon and storage facilities (Fig.8.0) Depending on the cruise area, the RV can carry up to 12 people.

Fig. 5.0: CPE building of the FS USB - CARI - in České Budějovice (CPE arc hive)

Fig. 6.0: Julius Payer's house - research station in Longyearbyen, CARI JSS on Svalbard (CPE archive).

Fig.7.0: Nostoc field station in Petuniabukta Bay, CARI JSS on Svalbard (CPE archive).

Fig.8.0: Research motor sailer Clione (CPE archive).

The equipment on Svalbard also includes four rubber boats (Fig.9.0), two off-road vehicles, safety equipment – protection against polar bears (weapons, signal pistols, signalling movement at the station's borders) and communication equipment for field work (satellite phones and walkie-talkies). Several instruments are deployed around the station for long-term monitoring of the main environmental parameters. Laboratories are equipped with other instruments such as microscopes, magnifying glasses, sterilization units, sterile boxes, fluorometers, etc. Field laboratories are equipped for the initial processing of patterns and their preparation for transport to the Czech Republic.

Fig. 9.0: Rubber boats, CARI JSS on Svalbard (CPE archive).

Since 2010, interdisciplinary Czech Arctic research in Svalbard has been carried out with the support of infrastructure projects, in the period from 2010 to 2015, the CzechPolar Project – Czech Polar Station: Construction and Operating Costs, the MEYS – LM2010009 and in the period from 2016 to 2019 the follow-up project CzechPolarII – Czech Polar Infrastructure, MEYS – LM2015078. Reports from individual scientific projects are published annually on the website of the CPE. This website also provides summaries of all scientific results. The range of scientific disciplines represented by domestic and foreign institutions and the period during which the infrastructure is used for research has been greatly expanding during the period from 2010 to 2019. In the first years, the station had about 30 employees in the summer, currently the station is open all year round with summer and winter projects and the station has up to 170 employees a year at different times. The technical support, including occupational safety support, provided to individual projects has also increased considerably.

Last but not least, the activities of the CARI JSS in Svalbard help to promote Czech science and culture abroad. In 2018, we co-organized with the Ministry of Foreign Affairs and UNIS a scientific and cultural festival to mark the 100th anniversary of the establishment of Czechoslovakia, the 30th anniversary of the establishment of the Czech Republic and the 10th anniversary of the establishment of the CARI JSS (Fig.10.0). In 2019, with the support of the Norway Grants, the Czech version of the Arctic Festival took place, which we co-organized with the support of the Norway Grants with the Ministry of Foreign Affairs and Norwegian and Nordic partners in Prague and other cities across the Czech Republic. At the same time, the CARI JSS serves as an "embassy" of Czech science and culture in the Arctic.

Fig.10.0: Poster informing about the 2019 Arctic Festival (Arctic Festival Archive).

Polar ecology courses

This textbook does not cover the whole wide spectrum of polar ecology; nor was that the aim of the decision to create it. Members of the team of authors participated in polar ecology courses that have been taking place since 2010 in the Isfjord area, along with the gradual building of the Czech polar infrastructure. During these courses, we found out that Svalbard, a logistically very easily accessible area (especially for the inhabitants of European countries) provides a plethora of examples on which most of the important laws of polar ecology can be demonstrated and that it is figuratively speaking a very illustrative textbook of this very interesting field. During the fieldwork and at the research station, we obtained extensive material, which we then used for presentations in the theoretical parts of the course, and very often we based our presentations on the preparation of this book. We are aware that these facts give rise to a certain apparent imbalance of the individual chapters. Where we can rely on our own observations and results, the text goes into greater detail; elsewhere it is brief and refers mainly to the published results of other teams. In our opinion, however, the chance that some interesting fact will spark interest in polar ecology is preferable to the effort to cover the entire breadth of the field evenly. Where possible, we use photographic documentation created during field expeditions. These were events paid for from grant funds and, according to prior agreement, their participants provided photos for use by the entire CPE. In many cases, we mention the CPE archive as a source of photographic documentation. During the field courses, we have verified that observation directly in the field is not only of interest to motivated students, but also to colleagues, specialists in other fields and even laymen who have a deep interest in what is happening in nature. Therefore, we tried to prepare the textbook so that it would serve not only as an aid for a specialized course, but also as a source of information for experts in various fields and inquisitive laymen. We hope that this textbook will put a stone in the mosaic of knowledge about the ecology of the Polar Regions and that it will contribute to polar literacy.

1. Svalbard, Arctic Science Laboratory

Josef Elster

The Arctic is the northern polar region bounded by an isotherm of about 10° C in the warmest month. It includes the Arctic Ocean and parts of the northern coasts of Europe, Asia and North America. About half of Norway's territory lies in the Arctic region. The two continental parts of Norway, Troms and Finnmark, are located in the northernmost part of the Scandinavian Peninsula, and the Svalbard archipelago, including Bear Island and Jan Mayen Island, is part of the Arctic region of Norway. Approximately 0.5 million people live here. This part of Norway is very important for the Kingdom of Norway and for the whole of the European continent for economic reasons. There are large reserves of oil and natural gas, an area suitable for sea transport and fishing. Together with tourism, these are the fastest growing economic activities in Norway. Norway and the whole of Europe, including the non-Arctic part, need young people educated in the polar sciences to participate in the development of their nation-states and the Arctic. With the economic development of the Arctic part of Europe, and with climate change affecting the whole of Europe and specifically its Arctic part, it is necessary to invest in research and education to create educational potential to address the global challenges of climate change accompanied by Arctic economic development. The cooperation of the University of South Bohemia with academic institutions in Norway, which focus on Arctic science, is an example of good cooperation and participation of a non-Arctic country from Central Europe in solving the global problems of our planet.

Fig.1.1: Logo of the Norwegian Polar Institute (NPI).

On March 7, 1928, **the Norwegian Polar Institute (NPI),** originally called Norway's Svalbard and Arctic Ocean Research Survey, Norges Svalbard and Ishavs-undersøkelser, was founded. It is a government scientific institution directly managed by the Ministry of the Environment and climate of Norway (Ministry of Climate and Environment).

The main mission of this institute is to conduct scientific research in a wide range of scientific disciplines including physical geography, such as cartography, climatology, geology, glaciology, including environmental monitoring, and life sciences covering molecular diversity and the evolution of polar ecosystems and the response of communities, populations and individual organisms to changes in the Arctic and Antarctic environments.

From 1909, the Kingdom of Norway began to significantly sponsor regular scientific expeditions to Svalbard, thus creating the conditions for the establishment of the international treaty "Svalbard Treaty 1920". Czechoslovakia acceded to the Svalbard Treaty by a special law in October 31, 1932. Based on this treaty and its entry into force in 1925, the Norwegian Parliament significantly increased funding for Svalbard research. After World War II, on March 1, 1948, the Norwegian Parliament elevated the importance of the NPI, especially with the aim of becoming one of the leading institutions in European Arctic research. Since 1968, with the launch of the scientific town of Ny-Ålesund, (Fig.2.1) Scientific stations of 10 countries: Italy 1997, Holland 1995, China 2004, UK 1991, France 1963, South Korea 2002, India 2008, Japan 1990, Germany 1991, Norway 1988), this proposition to be the leading institution in Arctic research came to a reality.

Fig.2.1: Ny-Ålesund is the northernmost municipality in the world, founded in 1916 by the Kings Bay Kull Company of Ålesund. Coal mining ceased after a mining disaster in 1962, and Ny-Ålesund became the starting point for polar expeditions, such as Roald Amundsen's Norge airship trip to the North Pole in 1926. Today it provides facilities for research institutions from a number of countries (CPE Archive).

In 1993, the NPI was relocated from Oslo to Tromsø. This move was also linked to the introduction of a number of new research directions. At present, the NPI focuses mainly on climate change research, as well as research and protection of the cultural heritage of Svalbard and Jan Mayen. Last but not least, the NPI acts as a worldwide centre for coordinating Svalbard research.

Longyearbyen Fig.3.1), Svalbard's administrative centre, is another Svalbard research center, home to the **Svalbard University Center** (UNIS), the Norwegian Polar Institute (NPI) and the **EISCAT Svalbard Radar** - European Incoherent Scatter Scientific Association, which measures fluctuations in electromagnetic atmospheric waves using installed radars. This institution, which operates this technical facility, is an international institution with several member countries (China, Finland, Japan, Sweden and the United Kingdom).

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Fig.3.1: (a) Longyearbyen; (b) UNIS (CPE Archives).

Another important scientific infrastructure in Longyearbyen is the **Svalbard Satellite Station** (Svalbard satelittstasjon in Norwegian) or SvalSat, located on the Platåberget plateau above Svalbard Airport. It is a station managed by the Norwegian Satellite Service (Kongsberg Satellite Services - KSAT) and the Norwegian Air Defence and the Norwegian Space Institute (Kongsberg Defense & Aerospace and the Norwegian Space Centre - NSC). The station is used to control satellite traffic in low orbit and is composed of more than a hundred parabolic antennas. The station is one of the largest centres for satellite traffic control on Earth. It provides services to a wide range of customers, such as the European Organization for Meteorological Satellites. Another important institution conducting long-term scientific research focused on permafrost is the **Centre for Permafrost, University of Copenhagen** (Centre for Permafrost - CENPERM), which has a workplace in Adventdalen. In addition to the science station in Adventdalen, the university operates several similar stations in Greenland and northern Sweden. The main goal of their research is long-term monitoring of permafrost behaviour in the Arctic region.

Finally, Longyearbyen also houses the **Czech Arctic Scientific Infrastructure "Josef Svoboda Station", the house of Julius Payer**, and is the home port of the research **motor-sailer Clione** (see in the introductory chapter).

Other science centres are the Russian city of **Barentsburg**, home to the Russian coal company Trust Arktikugol, where the Russian Academy of Sciences, the Russian Federal Hydrometeorological and Roshydromet - the Institute for Environmental Monitoring run their research programs.

Grumant, a subsidiary of the Arktikugol Trust, also manages the mining town of Pyramiden (Fig.4.1), which was closed in 1998. Currently, there are only a few employees of the mining company in the city, who provide tourist traffic and city administration. The city is used as a museum, a tourist attraction, where tourists get acquainted with the life of Soviet miners in the conditions of the high Arctic. The city of Pyramiden also houses Czech containers that we installed on the city's pier in 2007 and then moved ashore (see more information in the introductory chapter).

Fig.4.1: Pyramiden (CPE archive).

The Polish Academy of Sciences established its **Hornsund** scientific station in 1957, where long-term scientific programs and monitoring of a number of ecological parameters take place. The station in Hornsund, which is open all year round, was followed by smaller scientific bases from several Polish universities. In the past, we had the opportunity to work in some of these stations. The **Petuniabukta** station, founded and managed by Adam Mickiewicz University in Poznań, is located just a few meters from our Nostoc field station. We have had very good cooperation with colleagues from this university for several years (Fig.5.1).

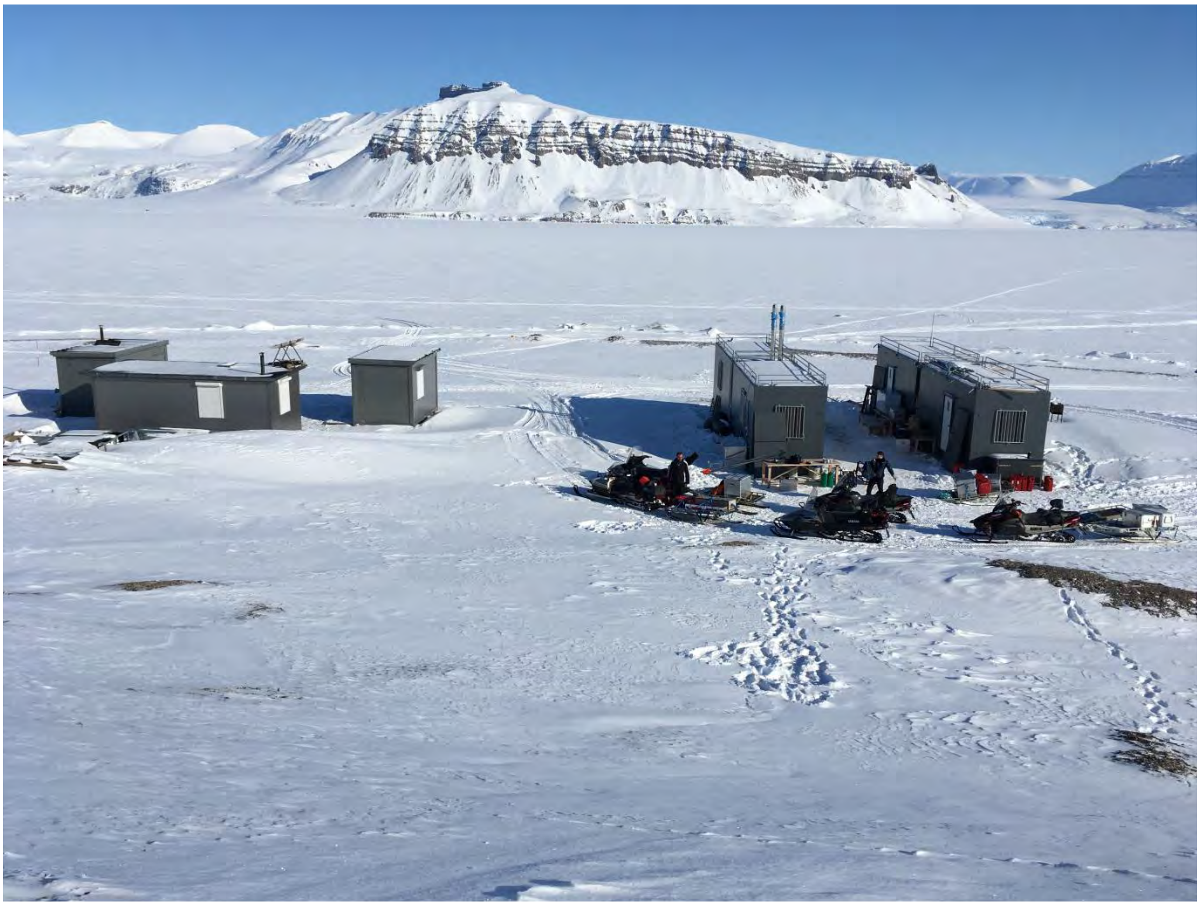

Fig.5.1: In parallel with the construction of our Nostoc station, colleagues from Adam Mickiewicz University in Poznań built their own station, which is adjacent to ours: (a) view of Petuniabukta Bay with Nostoc station (right) and Poznań University station (left); (b) Nostoc station (left) and University of Poznań station (right; CPE Archive).

Another well-known university scientific base is the **Kaffiøyr**a station of Toruń University of Nikolaos Copernicus, which is located on the northwest coast of the Earth Oscar II.

Another seasonal Polish base is the **Stanislaw Baranowski Station (Fig.6.1)** (operated by the University of Wroclaw, which is located not far from the main station Hornsund in the Land of Wedel-Jarlsberg. Czech glacier speleologists have been working at this station for a long time.

Fig. 6.1: (a) Stanislaw Baranowski station of the University of Wrocław, also used by (b) Czech glacial speleologists (Elster).

The Polish Polar Consortium coordinates scientific and logistical activities, including ensuring the regular supply of all Polish stations in Svalbard. The Czech Arctic infrastructure uses this service and annually uses the Polish ship Horizont to transport cargo to Svalbard.

SVALBARD
SCIENCE
FORUM

Fig.7.1: Logo of the Svalbard Scientific Forum (SSF).

The **Svalbard Science Forum** (SSF - https://www.forskningsradet.no/en/svalbard-science-forum/) coordinates and records all scientific activities taking place in the archipelago and its wider surroundings.

Each year, with the help of the mandatory project database "Research in Svalbard" (RiS), it registers more than 3,600 projects from 30 countries. With the help of this open record, SSF coordinates cooperation and data sharing between scientific teams, thus ensuring a higher quality of the obtained results, creating conditions for mutual information and minimizing the environmental footprint arising from the management of individual projects. At the same time, it prevents overlapping of individual projects and contributes to general information about research directions, researchers and their institutions. The SSF is directly governed by the Norwegian Scientific Council, which, with the help of this institution, generalizes the data obtained, both within Svalbard and the entire Arctic and on a global scale.

Fig.8.1: Logo of the Svalbard Integrated Arctic Observation System (SIOS).

Another important international science initiative, also set up by the Norwegian Scientific Council, is the **Svalbard Integrated Arctic Earth Observing System** (SIOS), (https://sios-svalbard.org). The SIOS is a monitoring system launched in 2010 to assess changes in the Svalbard ecosystem and its wider environment over long time series. At the same time, SIOS aims to respond to the development of the Svalbard and Arctic ecosystem in the long term and to modify and develop the monitoring system. 23 institutions from 9 countries participate in this observation system. The USB Polar Ecology Center has observer status in this organization. On the basis of annual reports and databases, which SIOS continuously develops, a complete assessment of the environmental status of the archipelago and its wider surroundings, especially in terms of the effects of climate change on the long-term interactions between individual ecosystem components, including the biosphere, geosphere, atmosphere, cryosphere and hydrosphere. These results are then passed on to the political institutions within the Kingdom of Norway, the European Union and the national governments concerned.

Several other Norwegian scientific institutions operate in Svalbard in cooperation with NPI, UNIS, SSF and SIOS. In this list, we name only a few that are most important in addressing environmental issues in the Arctic. The **Norwegian Institute for Nature Research** (NINA) specializes in research on the interactions between human settlements, natural resources and biodiversity. The institute's offices are scattered throughout Norway, including the Arctic region. The **Norwegian Institute for Atmospheric Research** (NILU) is another very important institution that is intensively involved in the research of atmospheric processes, especially in connection with the ongoing climate change in the continental part of Norway and in the Barents Sea, including Svalbard. The **Center for International Climate and Environmental Research** (CICERO) also focuses on climate change research. Another important scientific institution contributing to Arctic research is the **Nansen Environmental and Remote Sensing Center,** which combines research in the fields of physical geography and political science. Lastly, another very important and very unique Norwegian institution dealing exclusively with the polar regions is the **Norwegian Scientific Academy for Polar Research**, which was founded in 2008 and is housed in the UNIS building in Longyearbyen.

Norway also has a number of agreements creating the conditions for international cooperation in research and education in the Arctic (EU, USA, Canada, Russian Federation, Japan, China, South Korea, India, etc.), under which various countries conduct their scientific activities in the Norwegian Arctic region. Norway is an active member of the **Arctic Council** and chaired this international Arctic community from 2007 to 2009. Norway has also, for example, initiated the first international agreement between Arctic Council member states to protect the marine ecosystem from pollution from oil production. The Arctic Council Secretariat is located in

Tromsø. Norway is also a member of the **International Arctic Science Committee** and has chaired this scientific society for several periods. Norway is also very active in creating a political system in integrating the indigenous people of northern Scandinavia into the democratic political system of Norway. Around 50 to 80 thousand indigenous people, who declare their Saami nationality, live In Norway, Sweden, Finland and Russia. Since 1989, the Saami have had their own parliament, based in Norway, which serves as an advisory body to the Norwegian state administration.

Fig.9.1: Logo of the International Consortium of Terrestrial Arctic Research and Monitoring (INTERACT).

International Consortium of Terrestrial Research and Monitoring of the Arctic "International Network for Terrestrial Research and Monitoring in the Arctic - Interact I, II, III". INTERACT is a long-term infrastructure project supported by the European Union. It currently brings together 88 field science stations in the Arctic (European, Russian, USA, Canada, Greenland, Iceland, the Faroe Islands and the Scottish and Alpine Science Stations in the Alpine temperate regions of the Northern Hemisphere). INTERACT offers a wide range of international scientific projects (Transnational Access Program). The main task of the project is to create conditions for long-term study of the effects of climate change on the Arctic ecosystem, and on the reconstruction and prediction of its development.

Since the beginning of regular scientific and educational projects of the CPE FS USB and the establishment of the CARI JSS in Svalbard, all activities are interconnected and linked mainly to Norwegian institutions integrated into international Arctic research and education cooperation.

2. Arctic university education

Josef Elster and Harald Ellingsen

The Arctic countries (Canada, the Kingdom of Denmark, the Faroe Islands, Finland, Greenland, Iceland, the Kingdom of Norway, the Russian Federation, the Kingdom of Sweden and the United States of America) offer higher education in Arctic sciences. Some non-Arctic states, including the Czech Republic, have also begun to support Arctic-based higher education at their universities. In the Czech Republic, this higher education is provided by the the CARI JSS in Svalbard, which is operated by the CPE, **FS**, USB, (more details below). Educational and scientific institutions that deal with education in the Arctic sciences are associated and coordinated by an international consortium of the Arctic University (University of the Arctic - https://www.uarctic.org). In 1997, the Arctic Council (https://arctic-council.org/en) initiated the creation of this educational consortium of Arctic universities. At present, this consortium brings together 217 educational and scientific institutions from all over the world, including the CPE, FS, USB.

The Kingdom of Norway operates five universities (Bergen, Oslo, Trondheim, Tromsø and Stavanger) dedicated to the education of Arctic scientists. As in the Czech Republic, higher education is divided into three consecutive degrees, a three-year - bachelor's, two-year - master's and three-year – doctoral (in the Czech Republic there is a four-year – doctoral). Studying at Norwegian universities is free, with the operation of the universities paid for by the Ministry of Education and Science. At the same time, this ministry lists the possibilities for obtaining a study scholarship. The Kingdom of Norway operates.

The University Centre at Svalbard in Longyearbyen (Universitetssenteret på Svalbard AS; UNIS). This is the northernmost university institution in Norway and the world, focusing on Arctic education and research. It was founded by the Norwegian Ministry of Education and Research in 1993. UNIS is governed by the Board of Directors of four scientific universities, and thus has the status of a faculty at these four scientific universities (Oslo, Bergen, Trondheim and Tromsø). In terms of scientific quality, these four Arctic research universities have been evaluated as the best scientific and educational institutions in Norway.

The University of Oslo is the oldest (more than 200 years) and the most prestigious university in Norway and one of the leading European universities (similar to Charles University in Prague, the Czech Republic). The university's current research is focused on three key areas - life sciences, energy and Nordic studies. **The University of Bergen** (Bergen University) focuses on marine research, climate and energy research, and global change research**. The Norwegian University of Science and Technology** (UTNU) focuses on interdisciplinary scientific and technological studies.

UArctic

Fig.1.2: Logo of the Arctic University (UArctic).

Finally, **the Arctic University of Norway**, UiT, The Arctic University of Norway, is the third largest and northernmost university in Norway and at the same time the northernmost university in the world. Due to the location of the University of the Arctic, which is surrounded by Arctic nature, with its significant Arctic manifestations, great distance from civilization centres, multicultural society is one of the most important global research and university education centres in the Arctic. The University of Tromsø offers higher education in these scientific fields; medical and social, biological and environmental, educational and humanitarian, technical and economic, law, tourism, sport and art. The university's research focuses mainly on the fields of polar science, climate change, Arctic indigenous peoples, political science, medical biology, astrophysics, oceanology and marine biology (bioprospection), linguistics and computer science.

The "ARCTOS network" program is hosted by the Faculty of Life Sciences, Fisheries and Economics UiT in connection with the Norwegian Polar Institute. The university also hosts the "Fram Centre" (FRAM - High North Research Centre for Climate and the Environment). Every year, the Centre organizes international conferences "Arctic Frontiers", which are attended by politicians and businessmen to discuss Arctic issues. The Secretariat of the "Arctic Council" is located in this centre. About 15,500 students study at the University, 10% of which are international and the university employs 3,300 teachers, of which 20% are foreign teachers and researchers at nine faculties, focusing mainly on Arctic studies. About 20% of the courses at all levels are in English.

UNIS
The University Centre in Svalbard

Fig. 2.2: Logo of the University Centre Svalbard in Longyearbyen (UNIS).

The University Centre at Svalbard in Longyearbyen (Universitetssenteret på Svalbard AS; UNIS) is an Arctic university institution focused on education and research in the following disciplines: Arctic Biology, Geology, Geophysics and Technology for bachelor's, master's and doctoral degrees. The language of instruction at UNIS is English, the ratio of foreign and domestic students is about 50: 50%, with foreign students representing 43 countries. About 800 students at all levels study at UNIS, with 12 professors, 15 associate professors, 36 external professors and 160 external teachers. Research and education at UNIS is based on broad international cooperation with the support of a large number of Norwegian and foreign projects. UNIS is led by a number of scientific projects involving mainly doctoral and master's students, including students from the USB and other Czech universities.

UNIS is not an independent educational organisation. Separately, it does not offer the completion of education at a certain level, but only individual courses. For this reason, international students who are supported by one of the international study projects (Erasmus+ / Nordlys / Nordplus) must also be students of one of the named Norwegian universities.

Fields of study and research at UNIS.

Arctic biology

Despite the harsh natural conditions of Svalbard, a very wide range of organisms live here, from the simplest microorganisms to vascular plants, to a wide range of mammal and bird species. Such a wide range of organisms are studied by scientists and students at all possible levels, from the study of molecular taxonomy and diversity focused on the origin and speed of adaptive abilities of individual species to ecological links between individual organisms and physiological principles of adaptation to changing natural environments. Research and teaching take place in field and laboratory exercises, as well as in lectures and seminars. In Arctic Biology, UNIS offers 16 bachelor's, 16 master's and 16 doctoral courses.

Arctic Geology

The geological history of Svalbard is very diverse from the Precambrian to the Cenozoic and the local landscape offers unique opportunities to study the development of the Arctic landscape, especially in the last glacial period of the Quaternary (Pleistocene and Holocene). In this long time sequence, it is possible to study the development of the landscape as influenced by tectonic, glacial, periglacial, fluvial and sedimentary processes. In Arctic Geology, UNIS offers 7 courses for bachelor's, 25 for master's and 17 for doctoral studies.

Arctic Geophysics

Thanks to Svalbard's geographical location and the logistical background provided by UNIS, geophysical research and education has endless possibilities, from studying the deepest parts of the Arctic Ocean to the upper edge of the Earth's atmosphere. In Arctic Geophysics, UNIS offers 15 bachelor's, 9 master's and 8 doctoral courses.

Arctic technology

In the Arctic there is a large number and great diversity of possibilities, both in terms of mineral resources and biotechnologically interesting organisms, which offer the possibility of practical use. The development of technologies to exploit these potential opportunities is one of the most important directions in contemporary Arctic science. Incorporating this line of research is an important part of higher education at the University of Longyearbyen. In Arctic Technology, UNIS offers 2 bachelor's and 3 master's and doctoral courses.

Financial demands for studies

Although higher education is free of charge at Norwegian universities, potential applicants must have to pay for some accommodation - study costs. The monthly subsistence costs in Longyearbyen, including accommodation and meals, amount to around NOK 10,000 (Norwegian kroner). Other smaller fees are for some field courses, using specialized facilities. These fees, including health insurance, can total around 3,000 -NOK per month.

The natural conditions of Svalbard, together with the support of the Kingdom of Norway, make it possible to develop unique conditions for higher education and research at a broad international level and at the same time at a very high-quality level. Another no less important function of the UNIS is to create conditions for education and research in terms of logistics and occupational safety. In addition to a high standard of education, research and logistical support for these activities, this institution also has an undeniable social role within the local community of Longyearbyen, where it represents Norwegian Arctic policy. All these activities bring a great educational and research benefit, which is primarily focused on the processes associated with climate change and the long-term sustainability of Arctic development, including technological innovation.

Czech educational system of Arctic ecology

Jihočeská univerzita
v Českých Budějovicích
University of South Bohemia
in České Budějovice

Fig. 3.2: Logo of the University of South Bohemia in České Budějovice (USB).

University of South Bohemia
in České Budějovice
Faculty
of Science

Fig. 4.2: Logo of the Faculty of Science of the University of South Bohemia in České Budějovice (FS USB).

The University of South Bohemia (USB) is a public university. It consists of eight faculties, which cover a wide range of disciplines from the humanities, economics and pedagogy to fisheries and agriculture. The university focuses on high-quality research and all eight faculties are accredited to educate students up to the doctoral level. It currently has more than 13,000 students, more than 600 of whom are studying for a Ph.D. program. More than 800 faculty university staff provide education at the university. The Faculty of Science, which is a medium-sized faculty with strong research support, participates in the different projects. The quality of research at the Faculty of Science is further enhanced by close cooperation with the institutes of the Academy of Sciences of the Czech Republic, which are located either directly on the premises or in the vicinity. International cooperation at the faculty is maintained at the level of laboratory cooperation, with many contacts throughout the EU and European non-EU countries, Japan and the USA. The faculty operates field research stations in Papua New Guinea and Svalbard. The Faculty of Science offers undergraduate and postgraduate studies in biology, chemistry, physics and mathematics with a strong emphasis on independent research. The faculty has long had good success in securing funding from various grants, both nationally and internationally.

Josef Svoboda Station
University of South Bohemia
in České Budějovice

Fig. 5.2: Logo of the Centre for Polar Ecology of the Faculty of Science of the University of South Bohemia in České Budějovice (CPE, FS USB).

Part of the FS USB is also the already mentioned Centre for Polar Ecology, whose main goal is to provide regular and long-term ecological research in the Arctic and university teaching of the Polar Ecology Course and related topics, which focus on extreme Arctic environmental biology, including microbiology-phycology, botany, zoology-parasitology, physiology and molecular biology. In addition to this basic course, CPE FS USB staff offer several specialized courses, which, however, take place irregularly and their organization depends on financial support.

During the first project solved by the staff of the USB, the Botanical Institute of the Academy of Sciences of the Czech Republic in Třebon and the Masaryk University in Brno, entitled "Biological and climatic diversity of the central part of the Arctic Archipelago of Svalbard", which ended in 2010, we intensively prepared the conditions for long-term research and Arctic higher education. From the experience with the use of iron containers and the Russian hut (see the introductory chapter) it became clear that it is necessary to prepare the conditions for more efficient and technically and technologically better equipped research, i.e., to establish laboratories with basic equipment, increase transport capacity, expand the network of automatic climate stations, purchase own equipment and ensure work safety in Svalbard. At the same time, it was necessary to gradually include Czech Arctic research in international projects and international institutions coordinating Arctic research. During the period of infrastructure support, an overview of all resolved projects was published annually on the website of the CPE FS USB, together with a list of published works in which CPE PřF JU students participated, among others. At the same time, already during the first year of solving the infrastructure project, we started regularly organizing the Polar Ecology Course with the support of the aforementioned project.

The course supported by the Ministry of Education, Youth and Sports of the Czech Republic was open to students of science-oriented universities in the Czech Republic. The fields of non-living nature (climatology, glaciology, geology, geomorphology, hydrology and limnology) were led by experts from Masaryk University (MU) and Charles University (CHU), and the fields of living nature (microbiology, algology, botany, plant physiology, zoology and parasitology) were in turn responsible for the staff of the FS USB. The two-semester Polar Ecology Course consisted of a one-week lecture camp in České Budějovice, where individual lecturers and students prepared specific field scientific projects for each student in addition to teaching. After this preparation, the students and their trainers left for 2 weeks in Svalbard, where their field part of the course took place. After returning from Svalbard, students and supervisors had 2 months to analyse samples and prepare data and measurements. In October, there was a weekend training session, during which the students presented their results and wrote the final test.

In 2012, in addition to the infrastructure project, we also received a project for the creation of education in the field of polar ecology, including support for the above-mentioned course organization in the period from 2012 to 2014 (the project was entitled "Establishment of a work team and conditions for education in the field of polar ecology and life in extreme environments”, No. CZ.1.07 / 2.2.00 / 28.0190 and was financed from the European Social Fund and the state budget of the Czech Republic). This project enabled, for example, the organization of Polar Ecology student conferences and the preparation of an educational film. In 2015, the Polar Ecology Course was supported by Norwegian Funds projects with the names "Inanimate Nature – MU in Brno" and "Living Nature - USB in České Budějovice". Both parts of the course took place in close cooperation with UNIS, whose students the course was open to (Fig.6.2 and 7.2.

Fig.6.2: A student observes with a simple microscope the alga *Prasiola* sp., which she specializes in in her studies (CPE Archive).

Fig. 7.2: (a) Students in field work; (b) participants of the Polar Ecology Course (CPE Archive).

In 2016, the first year of the Winter Arctic Ecology Course took place (within the projects "Inanimate nature – MU" and "Alive nature – USB” (Fig. 8.2) and two courses took place in the summer of the same year – the biological part of the Polar Ecology Course and the Course for the Ministry of the Environment of the Czech Republic (ME CR); all courses were supported by Norwegian Fund projects. In the years 2018 and 2019, summer courses of polar ecology - living nature for students of FS USB took place, which were sponsored by the faculty.

Fig. 8.2: Participants of the Winter Polar Ecology Course common to USB and UNIS students (CPE Archive).

3. Geographic location of Svalbard, ocean currents and sea ice

Zbyněk Engel

Location

The Svalbard archipelago ("the land with the cold shores"), the Norwegian territory in the Arctic, includes islands located between 10° and 35° east longitude and 74° and 81° north latitude (Fig.1.3). The island territory is part of the northern polar region (Arctic), geographically defined by the Arctic Circle (66° 33′ 49′ ′ north latitude). As a result of the location of the archipelago beyond the Arctic Circle, the islands alternate between polar day and polar night i.e., the parts of the year during which the Sun remains for at least one day above and below the horizon, respectively. The length of the polar day lasts ranges from 99 to 144 days between the southern and northern border of the archipelago, respectively, while the length of the polar nights varies between 84 and 128 days. In the administrative centre of Longyearbyen (78° 13′ N, 15° 37′ E), the polar night begins after sunset on October 26 or 27 and lasts until February 14 or 15, when the Sun rises and remains above the horizon for 22 minutes. Polar summer lasts from April 19–20 to August 23–24, with the Sun culminating at 35.2° above the horizon at the summer solstice, which occurs on June 20 or 21.

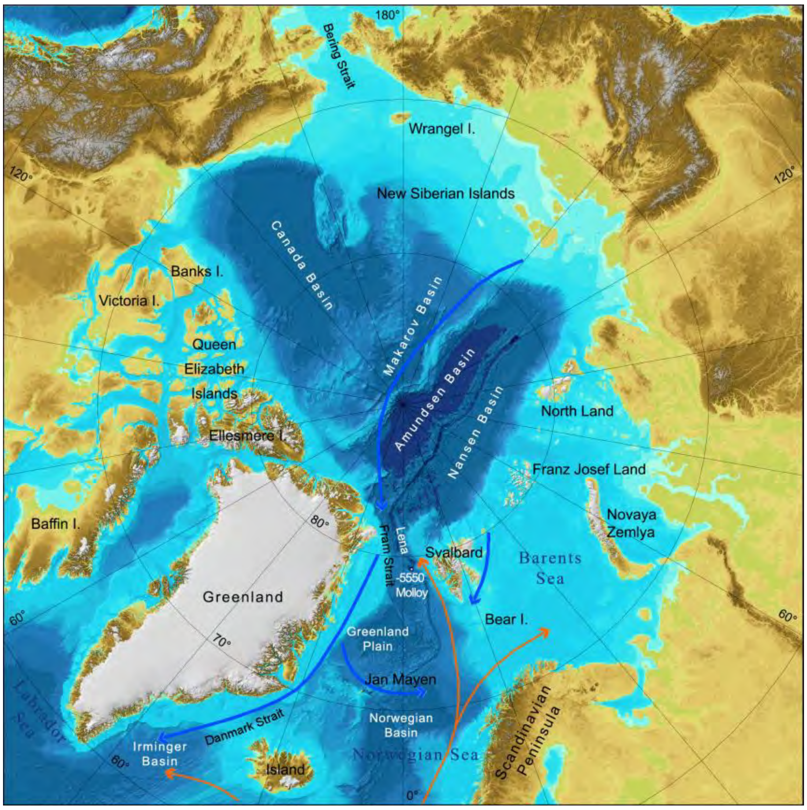

Fig 1.3: A map of the Arctic with the main directions of surface sea currents in the Svalbard region (Jakobsson et al. 2012).

The southernmost of the Svalbard islands, Bear Island (Bjørnøya, 74° 20–30′ N, 18° 45′ to 19° 16′ E), lies in the western part of the Barents Sea (Fig. 1.3)), approximately 420 km north from the Scandinavian coast and less than 240 km south of West Spitsbergen, the largest island of the archipelago. The north-western part of the archipelago (Amsterdam Island) is 440 km from the north-eastern tip of Greenland, and White Island (Kvitøya) on the eastern edge of the territory is only 220 km from the western islands of Franz Josef Land. Ross Island, the northernmost of the Svalbard islands (80° 49′ 44.4″ N), lies closer to the North Pole (1024 km) than to Nordkapp in Scandinavia (1084 km). The largest island is West Spitsbergen (37,673 km^2), which represents more than half of the area of the archipelago (61,022 km^2). The large islands also include Nordaustlandet (14,443 km^2), Edgeøya (5074 km^2), Barentsøya (1288 km^2), Kvitøya (682 km^2) and Prins Karls Forland (615 km^2). All other islands are smaller than 200 km^2. The main residential centre of the archipelago is Longyearbyen on the southern coast of Isfjorden in the central part of Western Spitsbergen.

The surface of the islands is predominantly mountainous (the summit of Newtontoppen in the north-eastern part of West Spitsbergen is 1717 m above sea level) and considerably rugged, which is a consequence of the lithological variability and glacial action. Extensive glaciation covered almost the entire archipelago during the glacial stages, except for the highest peaks and a small part of the north-western coast of Spitsbergen. Glaciers reshaped the surface topography into a rugged alpine relief with morphologically distinct peaks, sharp rock ridges, and deep troughs. Glacial erosion also affected the recently deglaciated parts of the islands, which are dominated by large fjords (Wijdefjord and Isfjord exceed 100 km in length) with steep walls and flat floors. In current conditions, these are mainly modelled by periglacial and slope processes, but on the bottom of deglaciated valleys and coastal plains (strandflaten), the morphological action of water courses is also important. The deglaciated area occupies approximately 45% of the surface of the archipelago /Fig.2.3) and will continue to increase due to the rapid retreat of the glaciers, which are not in equilibrium with the current climatic conditions. Climate change also accelerates the degradation of permafrost, increases the area affected by seasonal melting and thickness of the active layer.

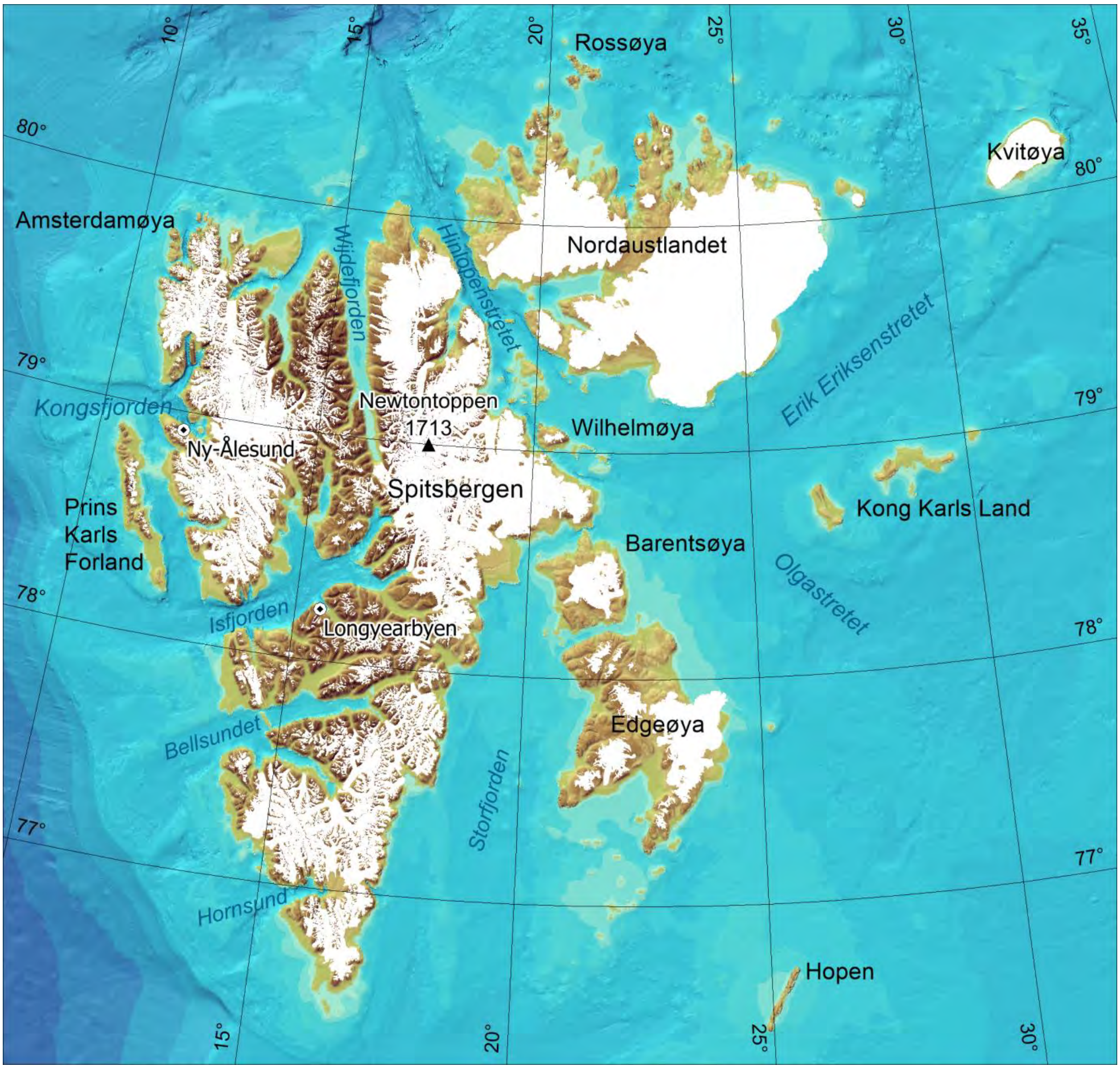

Fig. 2.3: Topographic map of Western Spitsbergen and adjacent parts of the Svalbard archipelago (Jakobsson et al. 2012; RGI Consortium 2017).

The archipelago is located in the north-western section of the continental shelf of Eurasia, whose northern edge in the Barents Sea extends up to a distance of 1,500 km from the coast of the continent, making it the most extensive shelf of current continents. North of the shelf edge is the 3000–4000 m deep Nansen ocean basin, which is separated by the 1800 km long mid-ocean Gakkel ridge from the deeper (>4000 m) Amundsen basin. The north-western edge of the Barents Sea shelf in the Fram Strait between Spitsbergen and Greenland falls in the narrow Lena tectonic depression, the only connection between the deep waters of the Arctic Ocean and the world ocean. In the middle part of the strait, 160 km west of the coast of Spitsbergen, there is the Molloy Basin (-5550 m), which is the deepest place in the Arctic Ocean. The Molloy Basin borders the Hovgård Sill to the south, whose southern slope faces the Boreas Plain. Together with the Greenland Plain, it is part of the submarine edge of the North American lithosphere between Greenland, the island of Jan Mayen and the mid-oceanic ridge bordering the west coast of Spitsbergen. The Norwegian Basin located to the south is already part of the

Eurasian lithosphere and, together with the Greenland Plain, belong to the main source regions of the deep circulation of the world ocean.

Surface and deep ocean currents

Svalbard is located between the Greenland Sea, which washes the western coast of the archipelago, and the Arctic Ocean, whose peripheral cold waters, driven by easterly winds, flow along the eastern and northern coasts of the archipelago. The surface waters (down to a depth of 1,000 m) of the Atlantic Ocean are brought from lower latitudes by the North Atlantic Current and Norway Current, from which the North Cape Current separates north of the Scandinavian Peninsula and heads into the Barents Sea .. The western branch of the North Atlantic Current heads further north via the Spitsbergen Current, which flows along the west coast of the archipelago as the West Spitsbergen Current. The warm North Atlantic Current is the cause of the mild climatic conditions of the western part of Spitsbergen, and its strengthening during the 20th century led to prominent changes in the natural environment on the island. The West Spitsbergen Current converges with cold Arctic water at the southern edge of the archipelago, where it merges with the East Spitsbergen (or Bear Island) Current, and northwest of Spitsbergen, where the relatively warm and salty water from the Atlantic mixes with the surface water of the Arctic Ocean. Arctic water flows through the Fram Strait into the northern part of the Greenland Sea, from where it heads as the East Greenland Current towards Iceland and the Denmark Strait further south, strengthened by the warm Irminger Current.

Relatively warm (~8 °C) and salty (>35.2 ‰) water, carried by the Spitsbergen Current to the western part of the Svalbard archipelago, is entrained by the cyclonic flow in the North Atlantic (Icelandic) low pressure area into a swirling motion around the Norwegian and Greenland Seas. The circulation movement is also enhanced by submarine ridges in the area of Jan Mayen Island and the Denmark Strait, which form an obstacle for the southward flow and divert part of the water to the east. The water circulating around the Greenland and Norwegian Seas gradually cools, and because the Arctic air masses are also extremely dry (a result of water vapour freezing in the cold air), the water evaporates and the salt content of the sea increases. The inflow of water from the Arctic Ocean, which is very salty as a result of the seasonal formation of sea ice, also contributes to the rise in salinity (the release of salts during the freezing of ice crystals leads to an increase in the salinity of the surrounding unfrozen water). As a result of low temperatures and increasing salt content, the density of water in the Norwegian and Greenland Seas increases and begins to sink to the bottom of the ocean basin pushing less salty and warmer water upwards (thermohaline circulation). Vertical movements of seawater drive the deep circulation, which, unlike the wind-driven surface sea currents, is conditioned by differences in seawater density.

The subarctic region of the ocean between Greenland, Iceland, the Scandinavian Peninsula and the Svalbard archipelago is one of the most important areas of deep-water formation. Greenland, Labrador, Weddell and Ross Seas, together with the Labrador Sea, are considered to be main source regions for the deep-sea circulation. Cold and salty water (<0 °C, 34.9 ‰) drains through the Denmark Strait and across the Faroe-Iceland Ridge into the Irminger and Iceland basins and further south across the Atlantic Ocean floor to the mid-latitudes of the Southern Hemisphere (45–60°), where it is distributed into the Indian and Pacific oceans by a strong westerly current. In the zone of the Antarctic Circumpolar Current, there are also upward movements of deep water, which subsequently becomes part of the surface sea circulation through the cold Peru (Humboldt), Benguela, and West Australian currents. One of the strongest surface currents is the Gulf Stream, which brings water from the central part of the Atlantic Ocean back to the Norwegian and Greenland Seas, where the global circulation of deep and bottom water masses initiates.

The system of ocean currents fundamentally affects the exchange of heat on the earth's surface. Water has a greater specific heat capacity (4181.8 $J \cdot kg^{-1} \cdot K^{-1}$ at 20 °C) and an order of magnitude higher thermal conductivity (0.55–0.61 $W \cdot m^{-1} \cdot K^{-1}$) than air (1000 $J \cdot kg^{-1} \cdot K^{-1}$ or 0.026 $W \cdot m^{-1} \cdot K^{-1}$), and is therefore significantly more effective in the transport of heat from the equatorial zone to regions with a negative energy balance at higher latitudes. The horizontal transport of heat through surface ocean currents, combined with vertical thermohaline circulation and deep-sea transport, is therefore referred to as the global conveyor belt. Its effect is indicated by surface seawater temperatures that are approximately 5°C higher in the Greenland Sea than in comparable latitudes of the Pacific Ocean. Similarly, the surface water temperatures in the source areas of deep-sea water formation are up to 10 °C higher. The heat transferred from the equatorial zone by the Gulf, North Atlantic, Norway, Spitsbergen and finally the West Spitsbergen currents also affects the climatic conditions of Svalbard, which are warmer, wetter and generally milder compared to other areas at the same latitude. The limited duration of sea ice, which locks in the coast for only a few days to weeks during February and March, also contributes to favourable climate conditions on the islands.

Sea ice

Ice forms in seawater when the surface temperature drops to about -1.8 °C and ice crystals of 3–4 mm in size grow on the surface. In calm conditions, the crystals form a continuous thin sheet of transparent ice (nilas), which becomes thicker as the ice further freezes (congelation growth) on the bottom of the ice. The congelation ice has a columnar structure and a smooth lower surface. Its thickness does not exceed 1 m in the fjords of Svalbard. In the open sea, the ice crystals freeze together in the form of circular patches (pancake ice), the edges of which are strengthened due to mutual contacts. The circular formations grow larger, slide over each other, and freeze together, which leads to the formation of a continuous layer of sea ice. First-year ice has an irregular surface and may reach a thickness of 1.5 to 2m. While the majority of the first-year ice melts during the summer, the remaining ice after the end of the seasonal melt begins to strengthen again and becomes part of the multiyear ice. Second-year ice is up to three meters thick and is significantly stronger than seasonal ice.

On the northern islands of Svalbard, sea ice appears during November, while the expansion of ice around the coast of Spitsbergen usually occurs in February. The maximum extent of sea ice occurs mostly in March or April (Fig. 3.3), but extensive sea ice may also surround the archipelago in the following months. The continuous ice around the islands breaks up during a few initial days of the polar summer, but it often persists in narrow fjords and straits until May. A large number of ice fragments released from the Arctic Sea ice during the summer drift on the northern coast of the Svalbard Islands and into the Fram Strait. The Fram Strait is the most important transport route for sea ice, the average annual amount of which in the period 1935–2014 corresponded to 880,000 km^2. In addition to sea ice, the coastal areas of Svalbard also contain a number of icebergs detached from floating glaciers or ice shelves. Their amount increases in the summer months when the intensity of disintegration of glacier termini (calving) increases due to the enhanced action of storm waves and sea swell.

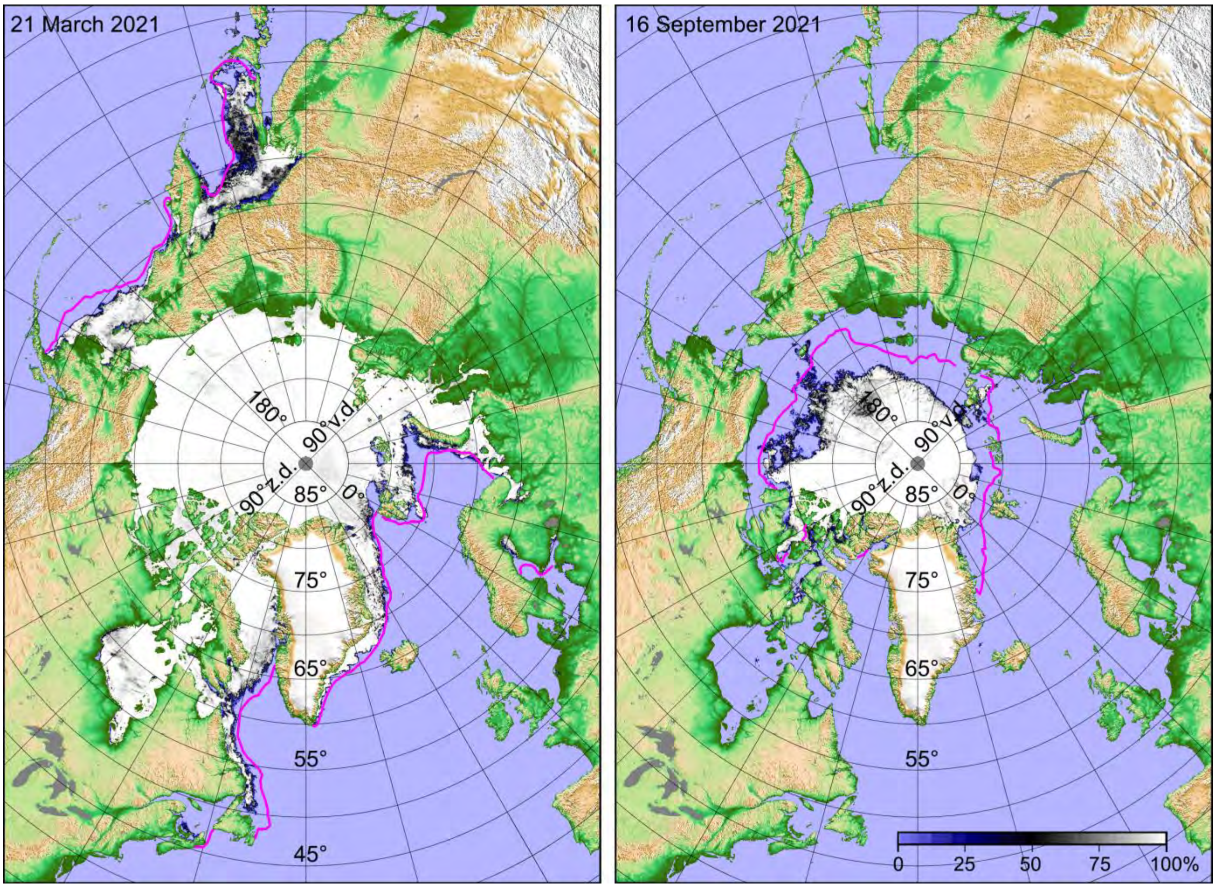

Fig. 3.3: Sea ice extent in the northern polar region during the period of maximum (March) and minimum (September) annual extent of sea ice. The purple line delimits the mean extent of sea ice from 1981 to 2010, the grayscale shows the extent of sea surface ice coverage (Melsheimer et Spreen 2021; NSIDC 2021).

The amount of ice transported through the Fram Strait fluctuates considerably from year to year, but it did not show a statistically significant trend until 2006. Since then, the amount of ice drifting into the Greenland Sea has increased and, in some years, exceeded a total of 1 million km^2. Between 1990 and 2012, the average age of the ice decreased from three to two years, and its thickness also decreased. The observed changes correspond to the main trends in the development of ice, i.e., the reduction of the extent, thickness, and the proportion of multi-year ice (Fig. 3.3). An analysis of the development of Arctic Sea ice since 1850 revealed a decrease in extent during the 1920s to 1940s and a gradually increasing loss since the late 1960s (Fig. 4.3). While in the first period the changes were observed only in the summer season, in recent decades the trends are also visible in other parts of the year. The main reason is the increased flow in the northern part of the Atlantic Ocean and the transfer of heat from mid-latitudes to Arctic waters, which also contributes to the thinning of sea ice and a decrease in its average age. Multiyear ice made up 80% of the Arctic sea ice in the 1990s but decreased to a fifth in the last decade.

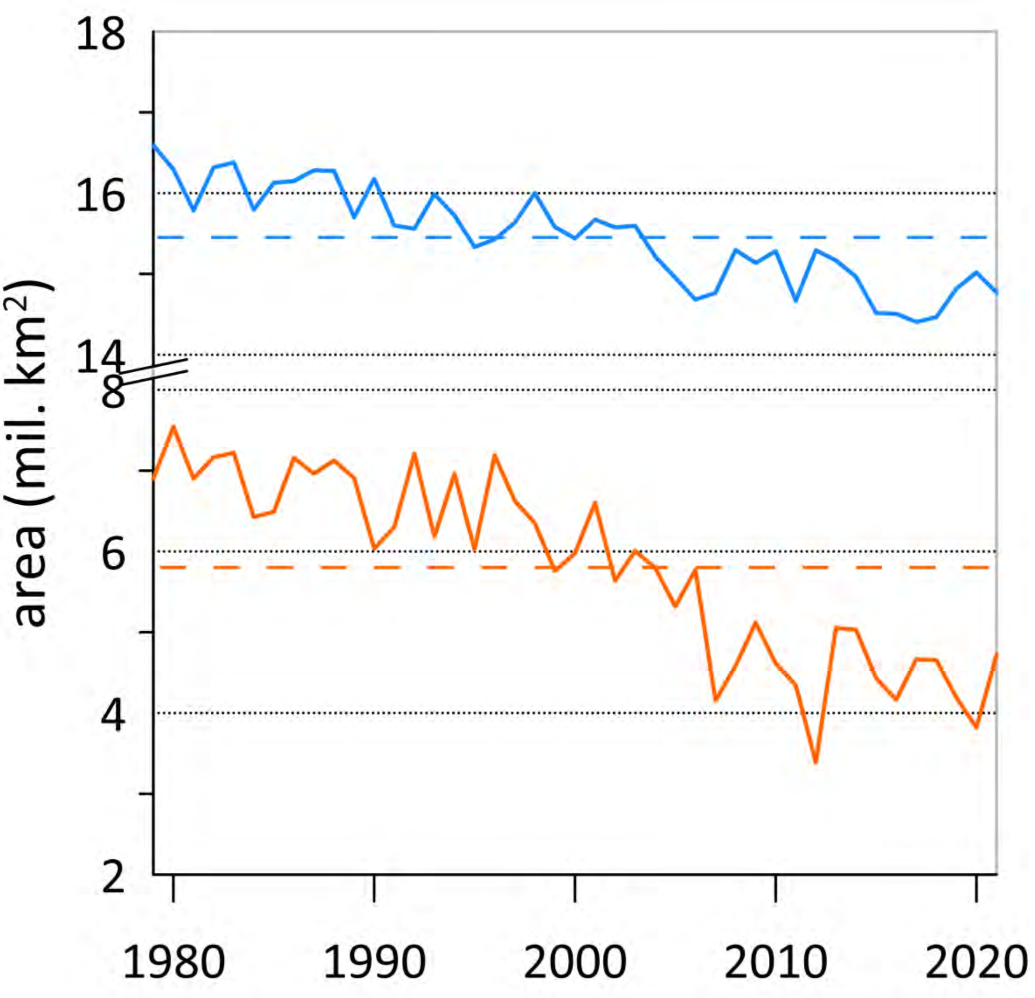

Fig. 4.3: Evolution of the maximum (blue line) and minimum (orange line) annual values of the Arctic Sea ice extent. The dashed lines show the average maximum and minimum value for the period 1979 to 2021 (NSIDC 2021).

Shrinking sea ice increases evaporation and the transfer of heat to the atmosphere, leading to enhanced cloud formation, intense cyclonic activity, and higher precipitation totals in the Arctic. Changing sea ice also affects the Arctic and North Atlantic Oscillations, which modulate climate conditions across the North Atlantic region, including Europe. From a global perspective, the most important consequence of the loss of sea ice is the reduction in surface reflectivity (albedo) in the Arctic. While the albedo of sea ice varies between 0.5 and 0.9 depending on its age and physical properties, the ocean surface reaches an average value of 0.06. The order-of-magnitude difference in the amount of reflected energy means more efficient absorption of heat by the Arctic Ocean, accompanied by more intense melting of shrinking sea ice and floating ice sheets. The positive feedback amplifies the impact of climate change in the Arctic (a phenomenon called Arctic amplification) and affects the circulation processes in the Arctic Ocean, which have an impact on the world ocean and the global climate system.

4. Geological and paleoecological evolution of Svalbard

Martin Hanáček and Alexandra Bernardová

Svalbard is a geological puzzle. It consists of several parts that have always been spatially unrelated. These parts are called provinces or terranes and are in contact along strike slip faults. The oldest rocks (1.8 billion years old) build the north-eastern part of the archipelago. Separate provinces were parts of different areas of eastern and north-eastern Greenland (the Laurentia continents). The southwestern province was part of the continent Baltica (the Precambrian core of Europe (Harland 1997, Wala et al. 2021).

In the Neoproterozoic (youngest Precambrian, 1 billion to 539 million years ago), Laurentia and Baltica were parts of the supercontinent Rodinia. Rodinia connected the Precambrian centres (so-called cratons) of all the continents. It extended from the equator to about the 60th latitude of the southern and northern hemispheres. Around 700-600 million years ago, Rodinia broke into individual continents. A new supercontinent, Gondwana, formed from most of the continents in the southern hemisphere. The continents Baltica, Laurentia and Siberia remained separate (Smelror a Petrov 2018).

During the Neoproterozoic, most of the continents were covered by glaciers. That was a global glaciation under "Snowball Earth" conditions. Glaciation also affected the equatorial continents, including Laurentia and the Baltica. Neoproterozoic glacial diamictites occur in Prins Karls Forland, Oscar II Land, Wedel Jarlsberg Land and Nordaustlandet. In Nordaustlandet, they are from the so-called Marinoan glaciation, which took place about 630 million years ago (Halverson et al. 2004). After the end of the Neoproterozoic global glaciation, the Svalbard provinces developed as parts of the Laurentia and Baltica continental shelves. They were flooded by the sea, whose layers preserved Cambrian, Ordovician and Silurian fauna (trilobites, brachiopods, graptolites, and others). These faunas have been found around Hornsund and in Ny-Friesland (Laurentian part of Svalbard, Harland 1997).

From the end of the Silurian to the beginning of the Carboniferous was the most dynamic period of Svalbard's geological history. Laurentia and Baltica merged into one supercontinent, Laurussia. The continental collision was the result of the subduction of the oceanic crust that initially separated the continental crust blocks (continents). During the continental collision, rocks on the margins of Laurentia and Baltica were folded and moved over each other in the form of nappes. The thickness of the continental crust grew. Parts of the continental crust were pulled deep below the Earth's surface. Here, the metamorphism of the crustal rocks took place.

Some of the crust melted. Magma was formed and from it various igneous rocks. A long mountain range was formed in the line of the continental collision.

The folding, metamorphism and magmatism associated with the collision of these continents and the formation of the mountains are called the Caledonian orogeny. The central part of the mountain range ran through the western part of the Scandinavian Peninsula (the Baltica margin) and the eastern part of Greenland (the Laurentia margin). The Svalbard provinces lay directly in the line of the continental collision and within the Caledonian mountain range. Wrinkling and metamorphosis mainly affected sedimentary rocks from earlier periods. Complexes of metamorphic schists, quartzites and marbles were formed. However, some sediments were not metamorphosed. In Nordaustlandet and Olav V Land, there are both granites and basal intrusive rocks (Winsnes 1988, Harland 1997).

After the collision, the continents did not stop. Baltica began to move along the edge of Laurentia. The edges of both continents were deforming, and segments of continental crust were breaking off. These segments remained clamped in the collision zone of the continents and moved with the continents. Displacements occurred along the strike-slip faults. The displacement of one segment along another segment spatially converged the initially individual Svalbard geological provinces. By the Caledonian conjunction of the originally separate provinces, Svalbard began to exist geologically as a single unit (Harland 1997), but not geographically, as the merged provinces also remained part of the Greenland margin. Greenland and Svalbard have been part of the Laurussia margin since the end of the Caledonian orogeny. The whole continent was at the equator (Cocks at Torsvik 2011). Since the Devonian, Svalbard has moved north from the equator to its present position on the margin of North America and later Eurasia.

The Caledonian orogen was rapidly eroding. The intermontane and foreland basins were filled with thick, red and brown eroded material (gravel, sand, silt clay). In geological terminology, the reddish brown deposits formed by the erosion of the Caledonian orogen are called Old Red Sandstone. One intermontane basin of these sediments was also formed in Svalbard. It is found in Andrée Land, Dickson Land and James I Land. Its margin starts west of the town of Pyramiden (Bertildalen, Munindalen). The basin was formed at the Silurian-Devonian boundary and sedimentation in the basin lasted until the end of the Devonian (Piepjohn et Dallmann 2014). The sedimentary fill consists of conglomerates, sandstones, siltstones and mudstones. They were formed in an environment of alluvial fans, braided rivers, meandering rivers, lakes and brackish lagoons.

The aquatic environment was inhabited by a diversified fish fauna of the Agnatha (Heterostracans, Osteostracans) and Gnathostomata (Placodermi, Acanthodii, Crossopterigii) groups. The land was colonised by psylophytes (Harland 1997). In the Upper Devonian (Famennian stage 380 million years ago), one of the oldest forests on Earth formed on Svalbard (Berry et Marshall, 2015). The tree layer was represented by *Protolepidodendropsis*, progymnosperms of the genera *Svalbardia* and *Enigmophyton*, and tree ferns (*Caulopteris*). The tree ferns and horsetails represented the herb layer (Harland 1997).. Trees reached a maximum height of 4 m and formed dense stands in the moist soil of the marsh and river plain. Fossils of the Upper Devonian forest were found in Munindalen, west of Pyramiden. Some tree-like *Lycopsids* have even been preserved in living positions (Fig.1.4).

Fig.1.4: Tree-lycophyte *Protolepidodendropsis pulchra*) trunks preserved in Old Red conglomerates in a living position. These were one of the oldest forests on Earth (Upper Devonian-Frasnian). Munindalen. (Hanáček).

In the early Carboniferous, Svalbard was affected by the Ellesmere Orogeny, caused by the collision of the Alaskan-Chukchi microcontinent with the northern margin of Laurussia (Cocks et Torsvik 2011). The Ellesmerian orogeny deformed the sedimentary fill of the Devonian intermontane basin. Shifts along horizontal faults also predisposed the relief of Svalbard until the end of the Palaeozoic (Harland 1997). This relief consisted of horst-like elevations (uplands, hills) and elongated basins (lowlands).

At the beginning of the Carboniferous, a collision occurred between Laurussia and Gondwana. The merging of the two supercontinents created Pangea. The collision zone of the continents was on the opposite side of Laurussia, so Svalbard was not affected. What changed for Svalbard was that it no longer lay on the northern edge of Laurussia, but on the northern edge of the Laurussia part of Pangea, in the subtropical zone.

In the Early Carboniferous (Mississippian), the northern edge of Pangaea remained in the humid tropical zone. The lowlands were covered with forests of tree-like pteridospermatophytes (Fig. 2.4). They grew on the floodplain around meandering rivers. High groundwater levels, flooding, and a warm humid climate predisposed the formation of swamps and peat bogs. In these, dead plant biomass did not decompose. Peat was formed, which transformed into black coal during the following geological periods. Mississippian sediments with hard coal seams occur west of Petuniabukta (Scheibner et al. 2012). Hard coal was mined at the Soviet/Russian town of Pyramiden in the second half of the 20th century.

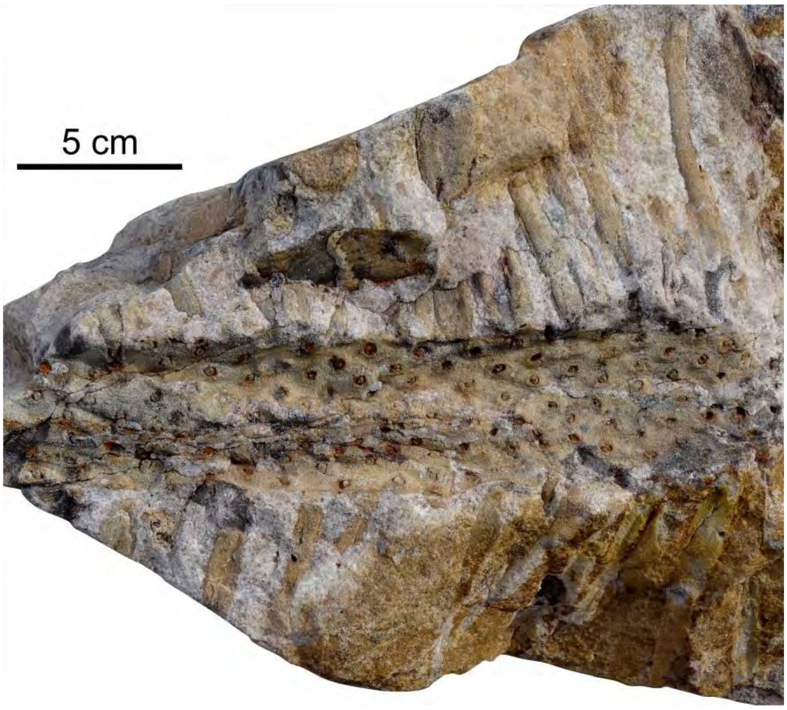

Fig. 2.4: Rhizophorus of arborescent lycophyte of the genus *Stigmaria* in sandstone, Carboniferous-Mississippian. Clast from Svenbreen moraine (Hanáček).

Pangea shifted northwards during the Carboniferous, resulting in a transition from a tropical humid to a subtropical semi-arid climate at the northern edge of the supercontinent, including Svalbard, in the Late Carboniferous (Pennsylvanian).

The environment changed to semi-deserts with ephemeral lakes. Along the seacoast, sebkhas with fluctuating saltwater levels were formed. Evaporation in the sebkhas caused the deposition of monomineralic gypsum layers. The foothills of the uplands were lined with alluvial cones whose clastic material was originally formed on the tops of the uplands by mechanical weathering in the arid climate. Ephemeral streams then washed this material to the foothills (Dallmann: Litostratigraphic Lexicon). Layers of black coal and the first Carboniferous semi-deserts are exposed in the massif between Pyramiden Mt. and Birger Johnsonfjellet between Svenbreen and Hørbyebreen.

At the Carboniferous/Permian boundary, a shallow, bright sea flooded the northern edge of Pangaea. It contained the typical biota of the late Palaeozoic. Organic calcareous accretions (biostromes, bioherms) were mainly built up by Bryozoa-Cryptostomata, Algae, Anthozoa, and Crinoidea (Fig. 3.4)

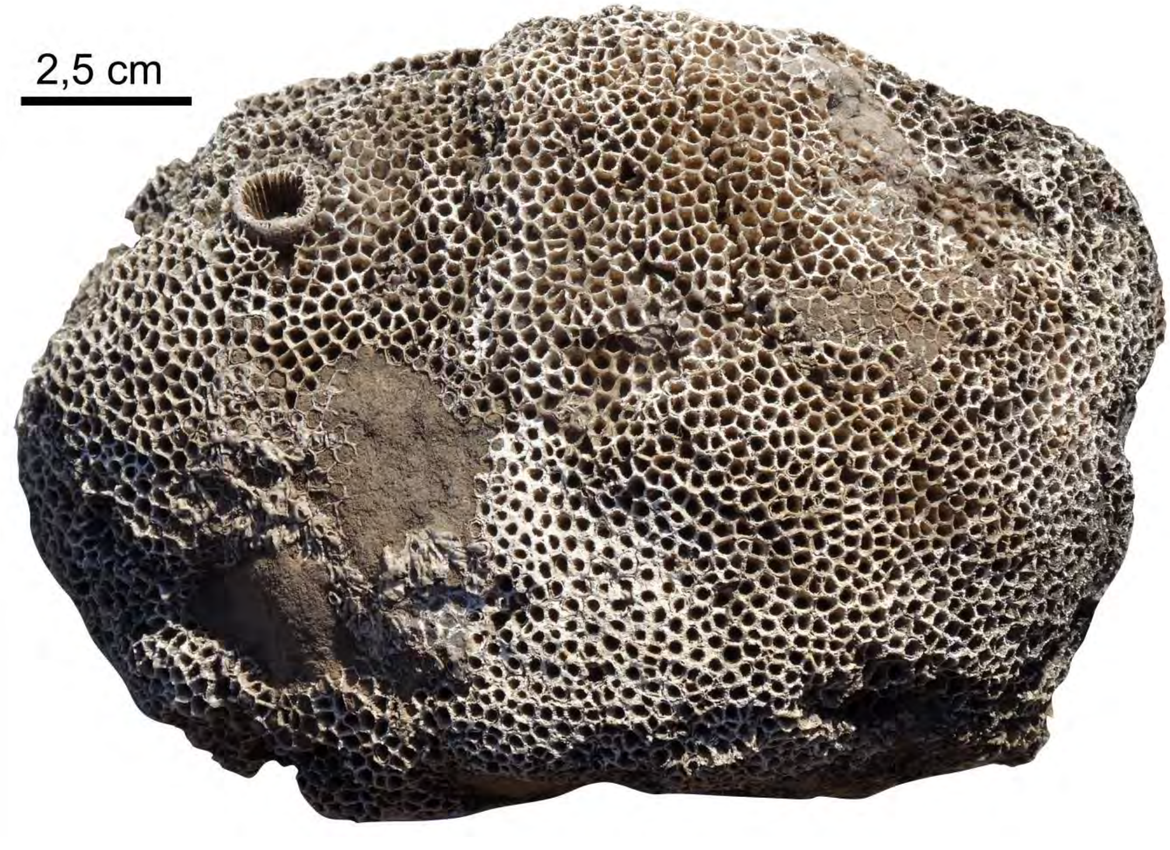

Fig. 3.4: Loaf-shaped colony of tabular anthozoan with one solitary Rugosa corallite. Carboniferous – Permian (Moscovian – Sakmarian). Odindalen (Hanáček).

The sessile benthos also contained abundant brachiopods and macroscopic foraminifera (fusulinids). The sea level fluctuated as a result of glacieustatic changes. Terrestrial glaciations formed and disappeared in the southern hemisphere (the Gondwanan part of Pangea). Glacial growth caused a fall in sea level, while deglaciation in turn caused a sea level rise. As the sea level dropped, the sea at the northern edge of Pangea became shallow and changed into sebkhas with evaporites. With rising sea levels, the sea deepened, and limestones were deposited on the sea floor. At the end of the Permian, the glaciostatic regime ended. The glaciers in the southern hemisphere definitively melted Resulting in the sea extensively flooding the northern edge of Pangaea (Smelror et al. 2009). to a depth of probably 200 m. Fine silt (future shale) was deposited on the bottom. The thick strata of the Carboniferous-Permian Sea form impressive profiles in Billefjorden and Sassenfjorden (Dallmann et al. 2004). The horizontal layering of the strata over a large area (like a lying book) evokes the idea of a flat shelf edge in northern Pangea (Fig. 4.4).

Fig. 4.4: Formation of gypsum, anhydrite, limestone, dolomite and shales. Horizontally and laterally permanent strata of the Carboniferous (Pennsylvanian) - Permian (Guadalupian) marine shelf of northern Pangaea. Formation thickness 650 m. Templet plateau (Hanáček).

The first continental rift valleys (so-called grabens) were formed already at the beginning of the Mesozoic. These constituted the first phase of the break-up of Pangea. A major continental rift opened in the Triassic in the caledonites line between Greenland and the Scandinavian Peninsula. Svalbard was located within this rift. The bottom of the rift consisted of terrestrial plains and a narrow sea bay (Smelror et al. 2009). Sea levels rose globally at the end of the Jurassic (Tithonian, 150-145 million years ago). The Barents Basin became the bottom of a shelf sea up to 200 m deep. Dark claystone on the bottom of this sea was deposited, which preserved abundant shells of nektonic organisms - ammonites (Cephalopoda) and giant predatory aquatic reptiles (Pliosaurs, Plesiosaurs). In the Lower Cretaceous (Barremian, Albian stages, 130-99 million years ago), the sea receded from most of the Barents Basin. It was replaced by coastal marshes, where coal was formed. The flora included Ginkgo digitata. Traces of dinosaurs are known from the Cretaceous sediments of Svalbard (Smelror et al. 2009, Dallmann: Litostratigraphic Lexicon).

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At the same time as the Atlantic was opening, the basins of the future Arctic Ocean were also opening. The extension of the continental crust and the transition to oceanic crust allowed basal magma to penetrate the crust. This magma then solidified as veins and sills of basalt (e.g. Høgskulefjellet and Gåsoyane at the mouth of the Billefjorden to Isfjorden, Fig. 5.4).

Fig. 5.4: Dolerite veins (Volcanic sill, Lower Cretaceous). Gåsøyane. (Hanáček)

A very interesting period in the history of terrestrial ecosystems is the turn of the Paleocene and Eocene 59-50 million years ago (the Paleocene-Eocene temperature maximum and the subsequent Early Eocene temperature optimum). During this time, forest zones extended from the equator to the polar latitudes of both the northern and southern hemispheres. There was a polar broadleaf deciduous forest in the Arctic. The considerable latitudinal range of the warm zones was made possible by the configuration of the land, seas and oceans. By the beginning of the Paleogene, all the major continental parts of the disintegrated Pangaea were separated by seas. These seas were oriented in a meridional direction (e.g. the Turgai Sea along the Ural Mountains). Warm tropical water circulated through these seas, both warming and moistening the polar regions. Fifty-six million years ago, Svalbard had a forest composed of large-leaved deciduous trees (*Rarytkinia, Trochodendroides, Ulmus, Aesculus, Betula, Alnus*) and conifers of the Cupressaceae family (*Metasequoia, Taxodium, Glyptostrobus*) (Budantsev et Golovneva 2009, Kvaček 2010).. The herbaceous floor was represented by ferns (Osmunda) and up to 30 cm tall horsetail *Equisetum arcticum*. According to the flora, palaeontologists estimated Svalbard's climatic conditions in the Eocene as follows: average annual temperature +11,6 °C (summer: +18,7 °C, winter +4,5 °C, no frost), precipitation to 1531 mm/year (Clifton 2012). In the Eocene, Svalbard was almost at its present-day northern latitude of 75°. Therefore, the Eocene Forest existed under conditions of alternating polar day and night. Leaf fall occurred at the beginning of the polar night, as evidenced by the taphonomy of fossil leaves: leaves on layered sediment surfaces are often complete and piled on top of each other like forest litter at the bottom of water pools (Fig. 6.4). The polar broadleaf deciduous forest of warm and moist conditions is unique in the geological history of ecosystems.

Fig. 6.4: Forest litter on sandstone surface strata. Eocene. Longyearbreen supraglacial debris. (Hanáček)

In the Paleogene, Svalbard went through the last orogeny, the so-called Eurekan Orogeny (Gion et al. 2017). It was related to the ocean floor spreading in the Atlantic Ocean. The new ocean floor was pushing Greenland north-eastwards. In the process, the northern margins of Greenland, including the western half of Svalbard, were deformed. Impressive thrusts and folds were formed in the rocks (Fig. 7.4)

Fig. 7.4: Oiginally horizontal layers from the Younger Palaeozoic deformed by the Eurekan orogeny in the Palaeogene to form a mound. Gizehfjellet a Sfinksen Mts. (Hanáček)

At the turn of the Paleogene and Neogene, the expansion of the ocean floor of the North Atlantic and Eurasian Basin of the Arctic Ocean advanced. The expanding oceans finally tore Eurasia and North America apart. Svalbard became the edge of the Eurasian continental plate. The onset of a long-term cold polar climate and the formation of permafrost and glaciation are fundamental to the current landscape of Svalbard. The extent of glaciation varies considerably depending on glacial/interglacial cycles. This cyclicity is due to changes in the shape of the Earth's orbit around the Sun (eccentricity) from elliptical to circular and vice versa (cycles lasting about 96 000 years), changes in the tilt of the Earth's axis (cycles lasting about 41 000 years) and the precession of the Earth's axis (cycles lasting about 26 000 years). These are called Milankovitch cycles after their discoverer Milutin Milankovich (1879-1958). However, the astronomical causes of the glacial/interglacial cycles would not be apparent without the appropriate configuration of the land and oceans. During the Cenozoic, Eurasia and North America moved towards higher latitudes. The North Polar region is, therefore, covered mainly by land, which is a basic predisposition for the formation of glaciers. At the same time, in the mid to equatorial latitudes, the Alpine-Himalayan orogeny (mountain belts from the Iberian Peninsula to the peninsula of the West Indies) continues, as does the orogeny uplifting the Cordilleras and the Andes. An increasing area of mountain ranges is rising above the snow line. A significant event has been the shift of Antarctica across the southern hemisphere. Antarctica separated from India and Australia during the Cretaceous-Paleogene and moved to the South

Pole. Around Antarctica, an isolated atmospheric and oceanic circulation developed (the Antarctic Circumpolar Current), which permanently cooled the continent.

Land configuration in both hemispheres and mountain growth caused the first mountain glaciers to form in the Transantarctic Mountains 58 million years ago in the Palaeocene (Davies et al. 2012). In the Arctic, the oldest Cenozoic glaciers formed in northeast Greenland and Nordaustlandet (northeast Svalbard) in the Eocene 42-40 million years ago. The presence of glaciers is proved by clasts from drifting icebergs (dropstones) in Eocene marine sediments. (Tripati et al. 2008). That suggests that the first glaciers appeared on Svalbard less than 10 million years after the Early Eocene Thermal Optima when there were deciduous broadleaf forests. In the Eocene, 37-34 million years ago, Antarctica was already covered by a continuous ice sheet. Rising glaciers caused a global decline in ocean levels and the emergence of shelves, promoting a continental climate and cooling in the polar regions. In the Miocene, 15–13 million years ago, the connection between North and South America (the Panama Isthmus) developed. The new land barrier interrupted the equatorial flow of seawater and turned the Atlantic Sea currents towards the Arctic. The Gulf Stream, North Atlantic Current and its branches (Norwegian Current, West Spitsbergen Current) were formed, bringing precipitation to the cooling Arctic. At the end of the Pliocene, about 2.75-2.5 million years ago, continuous glaciation appeared in the Canadian and Eurasian Arctic and northern Greenland. Under these conditions, the Milankovitch cycles could begin to manifest, and the glacial/interglacial cycle that continues nowadays began.

We do not have much information about the older Quaternary glaciations of Svalbard because younger glaciers have destroyed the evidence. A well-documented period is the Last Glacial Maximum (LGM), which peaked on Svalbard 20-19 000 years ago. Svalbard lay on the edge of the Barents Sea Ice Sheet, which was connected to the Fennoscandian Ice Sheet and the British-Irish Ice Sheet to form the European Ice Sheet Complex (Greenwood et al. 2021). The Svalbard glaciers reached an average thickness of 800 m with a maximum of 2000 m and covered the entire archipelago except for the highest nunataks (Landvik et al. 2003). They remodelled older river valleys into huge U-shaped valleys, in which they moved as terrestrial ice streams. The most important ice streams were the ice streams in Hinlopen, Isfjorden, Van Mijenfjorden, Honsund and Kongsfjorden. Most of the ice streams moved into the Atlantic basin, reaching the edge of the Eurasian shelf west of Svalbard. The ice stream in Isforden was formed by joining its tributaries in Nordfjorden, Billefjorden and Sassenfjorden. In the Billefjorden area, the main glacier was Nordenskiöldbreen, which led through the Adolfbukta into Billefjorden. The coalescent glaciers at Petuniabukta and Mimerbukta were tributaries of Nordenskiölbreen. This is evidenced by the erratic boulders (glacially transported boulders of rocks exotic to their underlying bedrock) found on the southern coast of Adolfbukta and especially along the eastern coast of Billefjorden. The erratic boulders come from the bedrock below Nordenskiöldbreen and Lomonosovfonna.

The ice sheet's retreat began in the highest mountain areas of Svalbard and on the edge of the Atlantic shelf (mountain peaks of northwest Spitsbergen were already deglaciated 26-16 000 years ago). The Atlantic shelf glacier disappeared between 20-14 000 years ago. The glacial retreat was followed by the very rapid disintegration of the glaciers in the Atlantic-facing fjords. In Isfjorden, for example, glacier break-up lasted only about 1 500 years (about 12 500-11 000 years ago). In contrast, the glaciation of the Barents Sea shelf receded much more slowly. The ice-sheet glaciostatically loaded Svalbard. Deglaciation was followed by a rapid marine transgression, flooding the U-shaped valleys, which became fjords (Ingólfsson et Landvik 2013).

The newly emerged marine environment was rapidly colonised by fauna (Fig. 8.4).

Fig. 8.4: *Mya truncata* shell (27x19 mm) in beach sediments of a marine terrace 53 m a.s.l. Holocene-Preboreal, 11 200–11 400 BP (C-14 dating). Bertildalen. (Hanáček)

The relieved archipelago then began to rise. Relics of the original coastline have been preserved as marine terraces consisting of deltaic and beach sands, and gravel. The highest Svalbard marine terrace is 96 m above the present sea level, which corresponds to the postglacial uplift of the archipelago. In Billejforden, the most elevated terraces lie about 65 m above the current sea level. Between the highest terraces and the coastline lie several lower terrace levels, which correlate with the gradual retreat of the sea. The present-day coastline is only the youngest phase of Svalbard's postglacial glaciostatic uplift process. As the uplift continues, rock erosion and sediment transport from the land to the marine fjords accelerate. Sediments fill the fjords, and the sea recedes. An example of the steady retreat of the shoreline is the shallow Petuniabukta, which is intensively filled with sediments from the surrounding glacial and non-glacial rivers.

Extensive deglaciation and the emergence of archipelago following glacioisostatic uplift have resulted in large areas of exposed substrate. This provided the space for the beginning of the development of the present-day Svalbard flora, which was probably established at the beginning of the Holocene. Paleoecological records suggest that vegetation colonisation began very soon after the glacial retreat or after the terraces were raised above sea level by surface uplift (before 12 000 years ago), see (Fig. 9.4). The vegetation as we know it now dates from the Tertiary (3 million years ago). Subsequent Ice Age plants survived either in previous Arctic biomes in areas that were not glaciated, mountainous areas of the Subarctic, or nunataks. The influx of diaspores during the Holocene was (and still is) constant. The success of a species' establishment is primarily determined by its ability to establish itself in a new location and build a permanent population. Genetic studies suggest that the main source of diaspores which established in Svalbard is primarily from the Russian region.

Fig. 9.4: Pre-Little Ice Age (LIA) soil developed on the surface of till from the Last Glacial Maximum (LGM) and covered by marine clays (near the subsurface grey horizon on soil top). The clay horizon indicates sea transgression caused by LIA-glacioisostasy depression. Brucebyen. (Bernardová)

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The favourable climatic conditions of the early Holocene (before 11 700 – ca. 8 200 years ago) allowed the establishment of a wide range of species, not excluding thermophilic species (Birks 1991). The species spectrum of (higher) plants was broad, indicating a variety of environments for the establishment of the first colonisers. A common characteristic of species in the early stages of colonisation is the ability to transport over long distances. These species tend to have tiny seeds and are wind- or self-pollinated. Records also document the presence of species of debris slopes, snowfields, or species typical of Arctic deserts.

The fossil record also contains thermophilous species (e.g., *Betula nana*, *Salix herbacea*), whose occurrence is currently very sporadic and restricted to the warmest sites. However, the humid climate favoured mainly humidophilous species. The higher abundance of such species documented in the palaeoecological record is probably also because they more easily overcame the long migration on timber from large rivers in Siberia.

The Middle Holocene period (before 8 200 - ca. 4 200 years ago) was characterised by a drier climate. Amongst the vegetation recorded, moist snow bed communities dominated and were later replaced by communities of semi-arid heathland. Communities with *Cassiope tertagona*, which requires milder winters and a developed soil profile, were present towards the end of the middle Holocene. However, its later onset may also be since its refugia after the last glaciation were far from the Svalbard Archipelago, probably as far as the Bering Strait. After deglaciation, it gradually spread across the Arctic to Svalbard (Eidesen et al. 2003).

In the late Holocene (last 4 200 years), the vegetation stabilised into its present form. An interesting phenomenon is a decrease in species richness compared to the early Holocene recorded in palaeoecological records. This is explained by the fact that the de-glaciation of the archipelago and the exposure of the substrate enabled colonisation by new species; however, climate change and interspecific competition have selected the species spectrum in its present form.

Cooler but still wet conditions favoured a higher abundance of species from the more cold-adapted snow bed communities. The consistent occurrence of taxa requiring dry environments as well as thermophilic species in the fossil record illustrates the diverse mosaic of ecological habitats in the late Holocene and the associated plant communities (Birks 1991, Voldstadt 2018).

In the Holocene, several glacial oscillations occurred called the Neoglacial. The last period of glacial advance up to several km into the foreland was the Little Ice Age (LIA), which peaked around 1900. From this date onwards, the glaciers have retreated. The general retreat was interrupted by rapid episodic advances for some glaciers, followed by a resting state and ice-decay (surge glaciers, Lønne 2016).. This is evidenced, for example, by the discovery of preserved tundra communities among the till layers – eg. in the foreland of the Werenskiold Glacier.

Glacial advance and subsequent deglaciation are the main factors forming the present glacial landscape, which is the focus of much modern natural history research. Glaciers in Svalbard have a predominantly polythermal basal regime: the thick upper part of the glacier tongue has a warm/wet base (liquid water occurs at the contact between the glacier and the base), and the peripheral zone has a cold/dry base (the glacier is frozen to the base, Hambrey et al. 2012).

Warm base conditions allow glacial erosion of hard bedrock. This forms Roches moutonnée - hills of hard rocks with a gentle and a steep side (Fig.10.4).

Fig. 10.4: Roches moutonnée in Adolfbutka (Nordenskiöldbreen forefield) (Hanáček)

The gently sloping side was exposed to the advancing glacier and has been intensively abraded by it. The steep side was protected from the glacier's onslaught. The gently sloping side is therefore smooth and striated. The opposite side is rough because the blocks were only broken off from this side, but there was no smoothing. The Roche moutonnées may occur as isolated (e.g. in front of the Svenbreen) or form continuous areas (Nordenskiöldbreen northern forefield). On plateaus, subglacial till is deposited beneath warm-based glaciers. In the terrain, they appear as fluted moraines. These are sedimentary plateaus (subglacial till plains) with large boulders and long and narrow sedimentary ridges. Boulders were dragged along the glacier base and were lodged in the basement. Sedimentary ridges were formed behind the boulders in the direction of glacier advance. Fluted moraines build the southern forefield and part of the northern forefield of Nordenskiöldbreen (Fig. 11.4)

Fig. 11.4: A subglacial till plateau with erratic boulders and sedimentary ridges (fluted moraine). Nordenskiöldbreen, southern forefield. (Hanáček)

Most of the area of post-LIA foreland glaciers is ice-cored moraines (Fig. 12.4).

Fig. 12.4: Degraded ice-cored moraines in the Bertilbreen terminoglacial zone. (Hanáček)

The moraines have an ice core due to a cold regime based on polythermal glaciers. The glacier snout is frozen to the bedrock and blocks the mobile part of the glacier with a warm base in the upper part of the valley. The pressure of the warm-based part of the glacier deforms the frozen glacier snout by folding and thrusting. A deformed glacier snout consists of slabs of clean ice, dirty ice and subglacial debris. During the degradation of a glacier front, sedimentary material, especially when present in significant volume, prevents the glacier from melting. When the glacier disappears, debris thrusted into the glacier is released by melting ice. The resulting landscape comprises hummocks and ridges with ice cores and debris mantles (moraine-mound complexes, ice-cored moraines or debris-covered glaciers (Hambrey et al. 1997). This landscape covers most of the post-LIA glacier forefield (for example, Hørbyebreen and Svenbreen (Fig. 13.4).

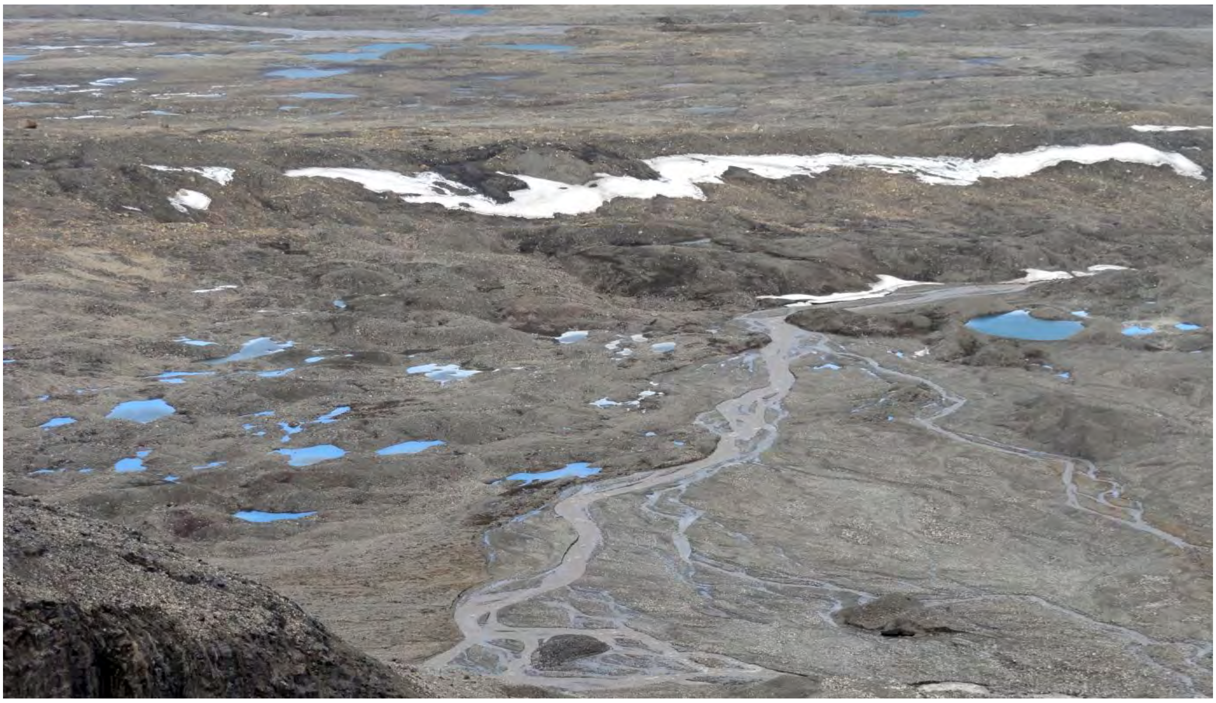


Fig. 13.4: The complex of hummocky moraines with kettle lakes dissected by an outwash sandur. The LIA proglacial zone of Svenbreen and Hørbyebreen (Hanáček).

Active moraine-mound complexes have a dynamic relief through down wasting (melting from the surface of the hummock to the base) and back wasting of the hummocky slopes. There is an intensive gravitational reworking of glacier debris. Older moraine-mound complexes (at a greater distance from the present glacier front) have low relief through advanced ice-core decay. The surface of this older zone of moraine-mound complexes is relatively stable due to the weakening of gravitational sedimentary processes. Meltwater from degraded ice cores accumulates in kettle lakes between moraine hummocks. The line of maximum glacier extent during the LIA maximum stage in some glaciers is marked by a morphologically prominent ridge of latero-frontal moraines (for example, small glacier snouts in Munindalen, Ragnarbreen, Nordenskiöldbreen (Fig. 14.4).

Fig. 14.4: Latero-frontal moraine (LIA maximum) of small glacier tongue in Munindalen. The glacier reached to this moraine in 1936. Photo from 2013 (Hanáček).

Debris-covered glaciers also form in the lineaments of connected valley glaciers as medial moraines or debris strips (Ebbabreen, southern part of Nordenskiöldbreen). The glacier snout may be entirely covered by debris (f.e. Longyearbyenbreen, Bertilbreen, Muninbreen). This debris was originally englacial (dirty ice), but by vertical melting of the ice, it reached the glacier surface as supraglacial debris.

Next to the ice-cored hummocky moraine terrain, glaciofluvial sediments are another essential component of the post-LIA proglacial landscape. These are mainly gravels, sandy gravels, gravelly sand, and, less frequently, sands. Glaciofluvial gravels and sands are sediments of meltwater braided rivers and streams. Supraglacial and subglacial streams feed proglacial rivers. These rivers flow through moraine-mound complexes and beyond its boundary form outwash fans (on the coastal plains of Petuniabukta). Inside the long valleys (Munindalen), glaciofluvial valley trains are formed. Wide outwash fans form at the mouths of these valleys before they merge into the large valleys (f. e., Munidalen mouth in Mimerdalen). In both types, outwash fans and valley train rivers form midchannel bars, side bars, and primary and secondary channels (Fig. 15.4). In the proglacial zone of Hørbyebreen, a long, zigzag gravelly-sandy ridge is preserved, which was infill of a sub-englacial tunnel (esker).

Fig. 15.4: Gravelly bars and channels in the distal part of a braided outwash fan in the Svenbreen proglacial zone. (Hanáček)

Outside the glacier forefield, the unglaciated surface of Svalbard has a patterned ground with morphological features of freeze-thaw seasonal processes in the active layer of the permafrost. Sorted stripes and polygons are the most common (Fig. 16.4). Along the steep fjord walls colluvial-alluvial fans and fan deltas accumulate.

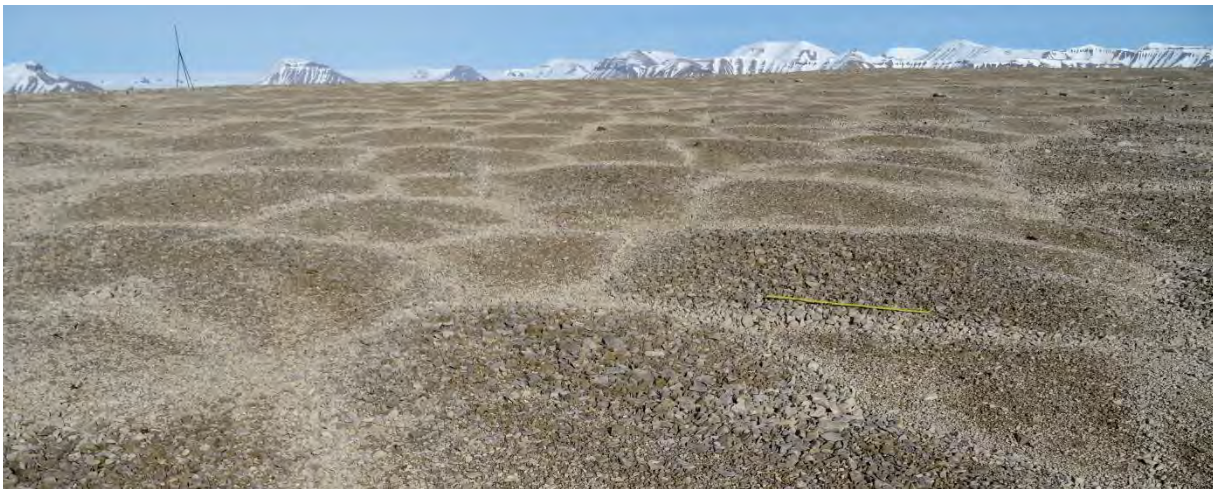


Fig. 16.4: Sorted polygons on the Yggdrasilkampen top plateau. Scale: 1 m (Hanáček).

5. Past and present glaciations and predicted changes in the future

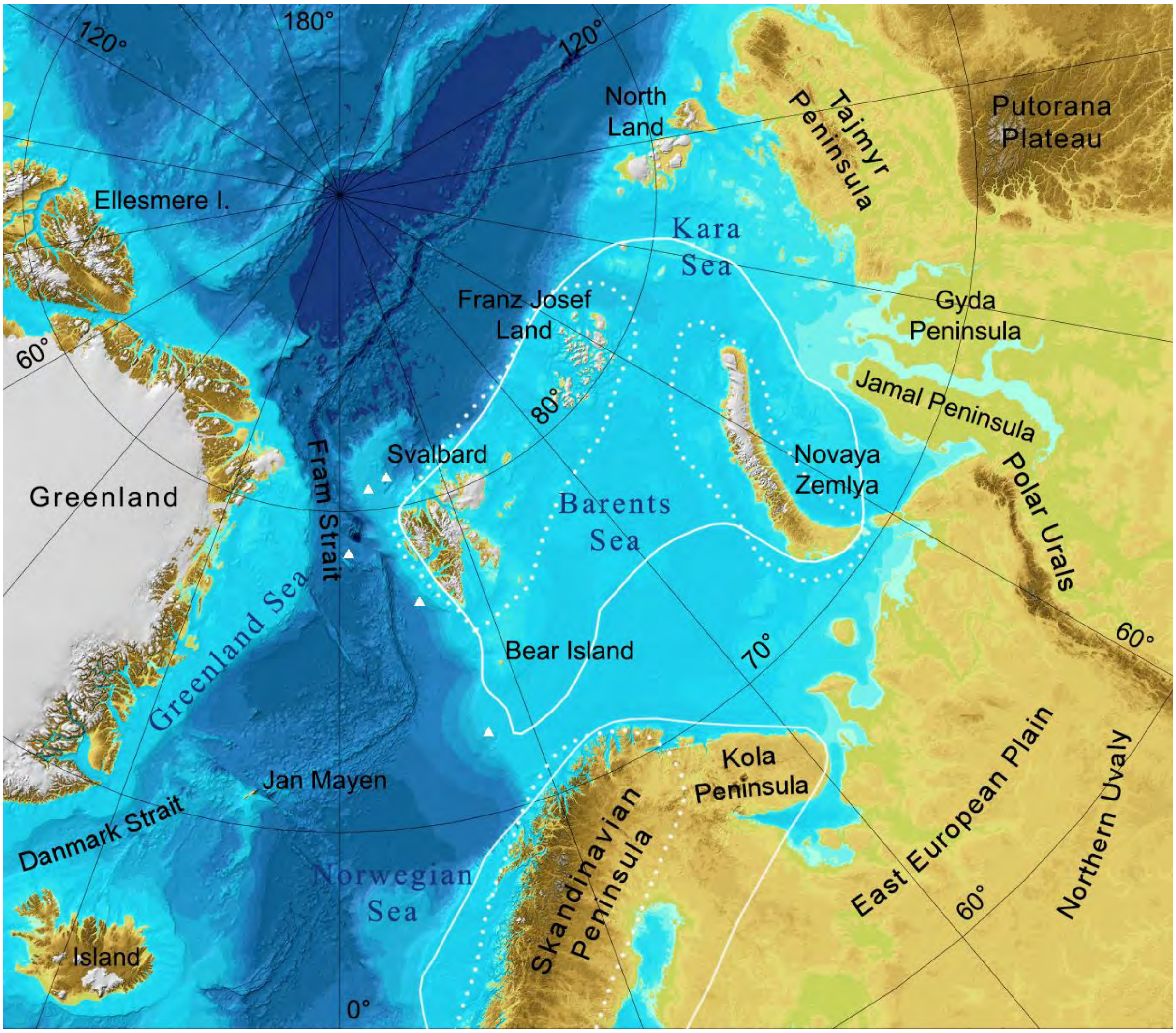
Zbyněk Engel

Glaciers are one of the most important factors influencing the landscape evolution of Svalbard. They started to form in high-elevated areas during the Upper Tertiary and extended over the islands in cold periods since the beginning of the Quaternary. Glaciers became the dominant landscape feature 1 million years ago, when they covered almost the entire archipelago and spread to the adjacent shelf areas. Svalbard became one of the main centres of the vast ice sheet glaciation in the Barents Sea region, which reached its maximum extent in the Quaternary period. Ice sheets arose in the archipelago during the subsequent glacial periods and gradually reshaped the surface of the islands and the surrounding topography, which was flooded during the Late Glacial marine transgression. The last ice sheet on Svalbard reached its maximum extent 24 to 22 thousand years ago (abbreviation ka = kiloannum) and disappeared at the beginning of the Holocene. Glaciers currently cover approximately 55% of the archipelago's surface, but their extent has been shrinking rapidly since the 1990s due to climate change. If the current climate change trends persist, the Svalbard glaciers will lose 50 to 85% of their volume by the end of the 21st century representing ~8% of the total land ice contribution to sea level rise.

The Svalbard glaciers currently represent 10% of the Arctic glacial surface outside the Greenland Ice Sheet. In the Eurasian part of the Arctic, Svalbard, together with the archipelago of Franz Josef Land, Novaya Zemlya and Severnaya Zemlya, is one of the most important areas of glaciation. Due to the significant west-east gradient of climatic conditions in the Atlantic Arctic, Svalbard is located in its warmest part with the highest precipitation. These climatic conditions, together with the position of the archipelago at the interface of relatively warm Atlantic subarctic r Water and cold Arctic water, are the cause of the high sensitivity of the Svalbard glaciers to changes in atmospheric and oceanic circulation. In addition, climate change in the Arctic is more pronounced than in lower latitudes (a phenomenon called Arctic amplification), which is reflected in the rapid decline of local glaciers and sea ice. Amplified effects of global warming can also be predicted in the future in high northern latitudes based on circulation models.

Upper Tertiary and Quaternary Glaciations

The current state of knowledge about the glaciation of Svalbard is based primarily on sedimentary records and geomorphological evidence in the marginal part of the Barents Sea shelf. The glacial sediments on the islands and glacial landforms were largely destroyed during the following glacial periods. Therefore, the basis of paleoclimatic and geochronological reconstructions of glaciation are the sedimentary assemblages deposited at the outlet of submarine depressions through which glaciers flowed on the continental shelf. These depressions were transformed by glaciers into troughs 300–500 m deep. The material transported by the glaciers was deposited at the mouths of the troughs, where they formed extensive alluvial cones. The largest accumulation of this type in the Arctic is located south of Bear Island at the mouth of a 750 km long and 150–200 km wide trough. The alluvial cone reaches a thickness of 3–4 km, includes a continuous sequence of sediments deposited during the last 5 million years, and thus represents an important stratigraphic record of conditions in the Barents Sea region. The evolution of the glaciation of this area was also reconstructed based on sediments from the Yermak submarine plateau, the Fram Strait and the adjacent part of the western continental slope (Fig. 1.5). Sedimentary records and geomorphological documents from the period of the last glacial (Weichselian) period are well preserved, which enable the extent of sub-phases of glaciation to be mapped and their age determined.



PFig. 1.5: Predicted maximum glaciation extent of Svalbard and the Barents Sea in the Upper Pliocene (heavy dotted), Lower Pleistocene (light dotted) and Upper Pleistocene (thin line). The white triangles show the position of the deep-sea sedimentary profiles that form the basis for

the reconstruction of the natural environment of the local area in the Pliocene and Pleistocene (Knies et al. 2009).

Sediment cores indicate the presence of glaciers in the northern polar region long before the beginning of the Quaternary. Dropstones and sandy sediments released from icebergs point to the glaciation of partial parts of the Arctic as early as 46 million years ago (Ma). Cooling occurred in the Northern Hemisphere before ~15 Ma, which coincided with the tectonically driven deepening of the Lena Depression in the Fram Strait and the onset of deep-water exchange between the Atlantic and Arctic Oceans. As a result of the cooling, the extent of glaciation increased across the Arctic, which was reflected in marine sediments from the Middle Miocene (16–12 Ma) by an increased content of ice-derived sediments.

The occurrence of glaciers on the islands of Svalbard and Franz Josef Land has been proven for the Pliocene (5.3–2.6 Ma), based on clay minerals assemblages in marine sediments (Fig. 1.5) During the Lower Pleistocene (2.6–0.8 Ma), ice sheets repeatedly formed on both archipelagos and advanced through the Barents Sea region to the south and southeast, where they connected with the glaciation of Novaya Zemlya. The Barents Sea shelf was above sea level for most of this period, and most of the glaciers terminated on land. Ice advanced to the edge of the shelf about 1 Ma, when glaciation of the northern polar region reached its maximum Quaternary extent. In the Atlantic part of the Arctic, ice sheets covered the entire Barents Sea shelf, and in the Svalbard archipelago they reached their furthest northward advance, as evidenced by sediments on the Yemark Plateau. At the same time, glaciers reshaped the surface of the Svalbard islands producing the pronounced glacial pattern relief of the north-western part of Svalbard. Extensive ice sheets probably formed in the archipelago during the subsequent Middle Pleistocene (0.8–0.1 Ma) glaciations, which is evidenced by the presence of seven to eight sedimentary units of glacial origin in submarine alluvial cones under the western edge of the shelf.

During the Weichselian glaciation (115–12 ka), there were three main advances of the Svalbard ice sheet, which culminated approximately 110, 70–60, and 24–21 ka ago. During the first advance, this ice sheet merged with the glaciations of Franz Josef Land and the Kara Sea, but probably remained limited to the northern part of the shelf (an older hypothesis suggests glaciation of almost the entire shelf). The following processes led to the formation of an extensive ice sheet in the Barents Sea region, which connected with the Scandinavian Ice Sheet in the south (Fig. 2.5). The Svalbard ice sheet reached maximum thickness around 70 ka, when the outer islands in the north-western part of the archipelago were also completely glaciated. The last advance began around 32 ka and culminated 24–22 ka ago when the ice sheet reached the western edge of the shelf. Around 20 ka ago, the ice sheet was already retreating from this area, and before 14 ka it terminated at the mouth of the fjords on the west coast of Svalbard. Rapid recession continued at the end of the Late Glacial and at the beginning of the Holocene (~12–10.5 ka) when glacier outlets retreated from the fjords and the ice sheet broke up into the current glaciation centres.

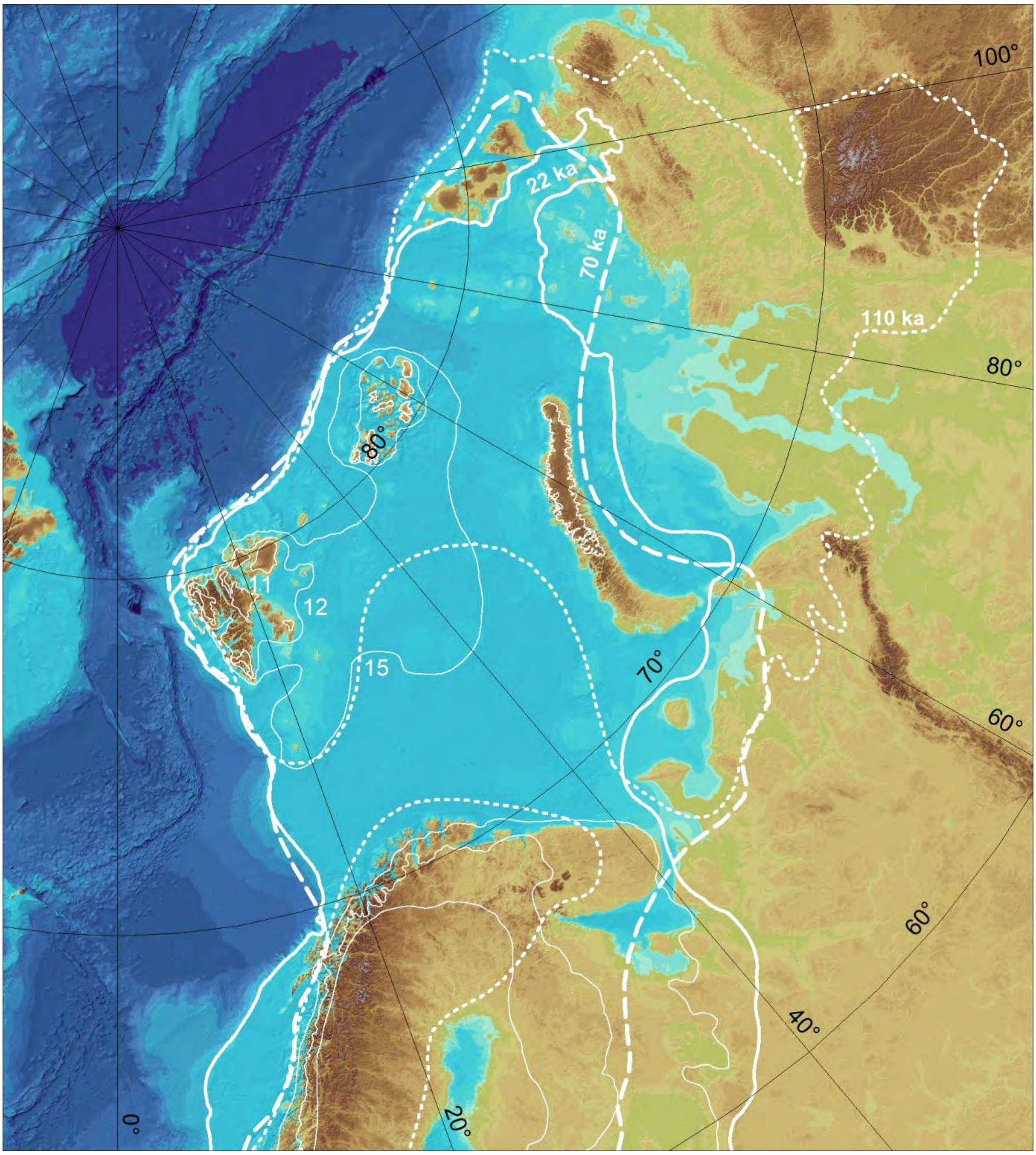


Fig. 2.5: Development of glaciation in the area of Svalbard and the Barents Sea during the Viselian Glacial period. Dotted, dashed and thick solid lines show the extent of glaciation before 110, 70 and 22 ka, thin lines delineate the margin of retreating glaciers before 15, 12 and 11 ka (Larsen et al. 2006; Hughes et al. 2016).

Development of glaciation in the Holocene

As a result of the retreat of the outlets into the inner parts of the fjords, the mouths of tributary and hanging valleys became free, and valley glaciers began to advance into the deglaciated parts of the fjords. The major advances occurred between 11 and 10 ka and lasted for the next millennium in the Wijdefjord and Tempelfjord. In the Middle Holocene (8.2–4.2 ka), the glaciers receded, a large part of the islands became ice-free, and glaciation persisted only in higher elevations. The glaciation reached its minimum extent before 8–6 ka and was concentrated in the eastern part of Svalbard and in Nordaustlandet. The period of the last glacial advance (Neoglacial) began 4 ka ago, culminating in the early phase of the Little Ice Age (1–0.5 ka). According to early views, glaciers reached their maximum Holocene extents during the Little Ice Age, but current research suggests that the total extent of glaciation may have been larger at the beginning of the Holocene. At that time, large areas of the islands were still covered by the remnants of the Late Weichselian ice sheet, and valley glaciers advanced in many places further than during the Neoglacial.

The glacier advances ceased at the beginning of the 20th century, and the period of the Little Ice Age thus lasted significantly longer than in mid-latitude mountains. In the 1930s, as a result of a significant increase in summer air temperatures, the volume of glaciers began to decrease, and mass losses prevailed in the following decade as well. After a temporary cooling accompanied by an increase in the mass of glaciers in the 1950s, the trend of summer temperatures reversed again, and the decline of glaciers has prevailed since the mid-1960s. Similar to other parts of the Arctic, the largest mass losses were recorded at the beginning of the 21st century, when glaciers melted 4 to 5 times faster than in previous decades. The largest losses have occurred in the western and southern parts of the archipelago while the glaciers in the north-eastern part of Svalbard, Nordaustlandet and Kvitøya, have less negative mass balances (Fig. 3.5). Enhanced ablation prevails at low altitudes, but it affects the small glaciers of central Svalbard up to an altitude of 1,000 m. Calving and submarine melting contribute to the decline of the current glaciation of Svalbard. In the years 2000–6, the mass loss of tidewater glaciers was comparable to that of land-terminating glaciers, but their contribution to the Svalbard's ice loss is increasing. The total mass balance of the archipelago's glaciers was balanced in the 20th century, but it has become mostly negative after 2000 (Fig. 4.5). The mean annual mass loss of Svalbard glaciers in the years 2006–16 corresponded to 0.47 m a.s.l., a value comparable to the global average of glaciated areas outside the Greenland and Antarctic Ice Sheets.

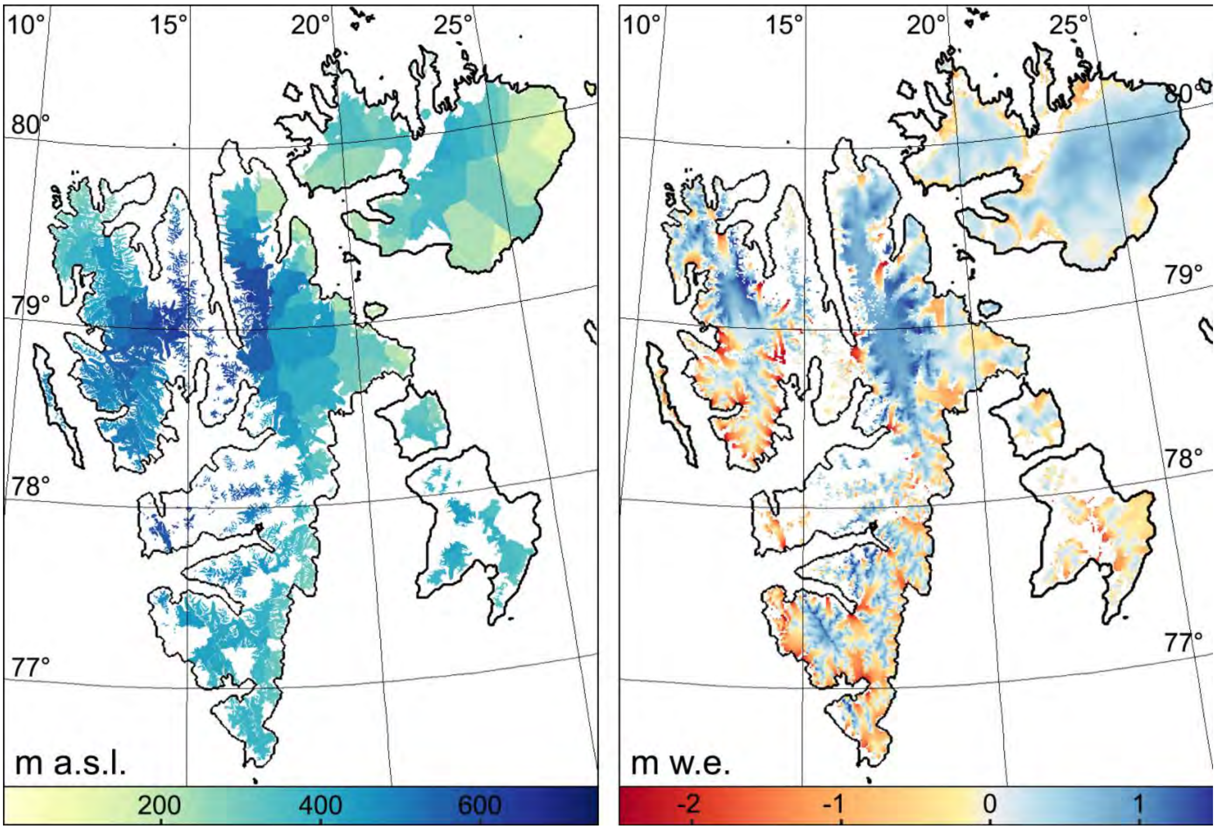


Fig. 3.5: Spatial distribution of the equilibrium line (a) and the climatic mass balance (b) of glaciers in Svalbard (van Pelt et al. 2019).

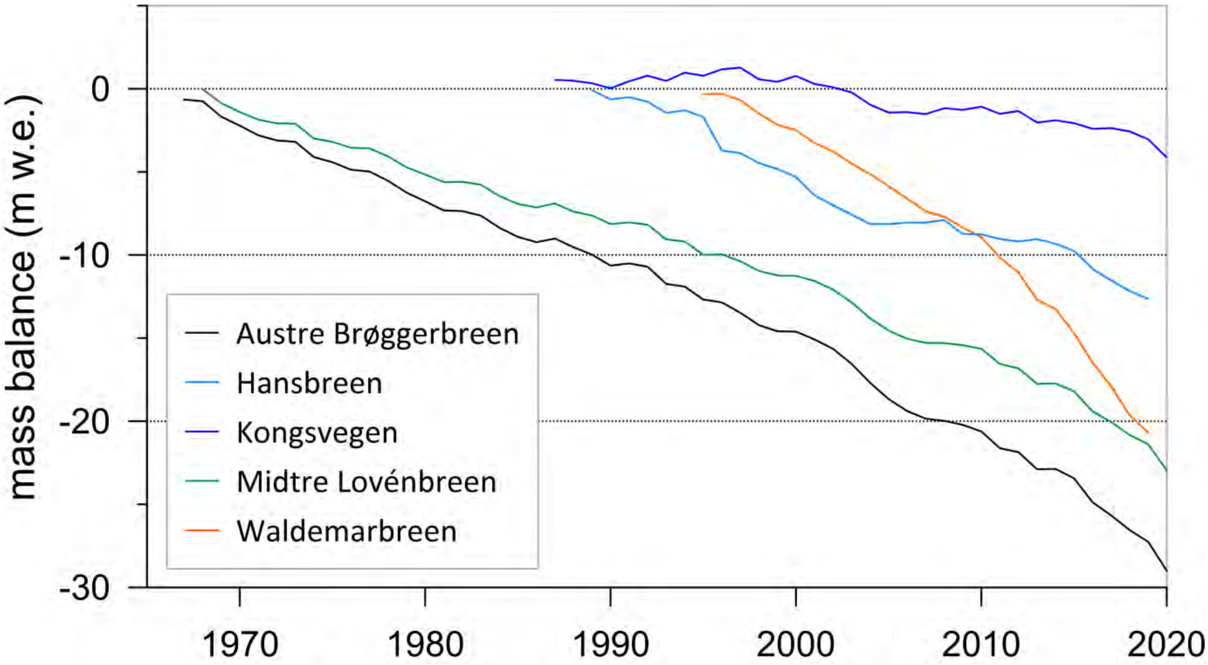


Fig. 4.5: Cumulative mass balance of Svalbard glaciers. The position of the glaciers is shown in the next figure. (Norsk Polarinstitutt 2020; WGMS 2021).

In addition to climatic conditions, long-term changes in the mass of Svalbard's glaciers are also influenced by ice-surges, which are characterized by alternating phases of rapid (102 to 103 m/year) and slow flow (101 m/year). While the period of slow flow lasts tens to hundreds of years, the surge phase occurs in the order of months to years. In the period of increased activity, the transport of mass from the accumulation zone to the ablation zone of glaciers is accelerated, the ice front advances, and the frontal ablation increases. Surges may be accompanied by dramatic advances of glacier fronts, especially in the case of tidewater glaciers. Extreme cases of rapid glacier advances were recorded in Svalbard in the 1930s. In 1935–6, Svalbard's largest glacier (Negribreen) advanced 12 km in the northern part of the Storfjord, followed in 1937–8 by the largest documented advance on the southern coast of Nordaustlandet, where the terminus of the Bråsvellbreen glacier advanced 20 km into the Erik Eriksen Strait (Fig. 5.5). The frequency of surges has increased since the end of the 20th century, probably due to the long-term rise in temperatures in the Arctic and subsequent changes in the thermal regime of glaciers and the hydrological conditions at their base, which influence the internal dynamic processes of glaciers.

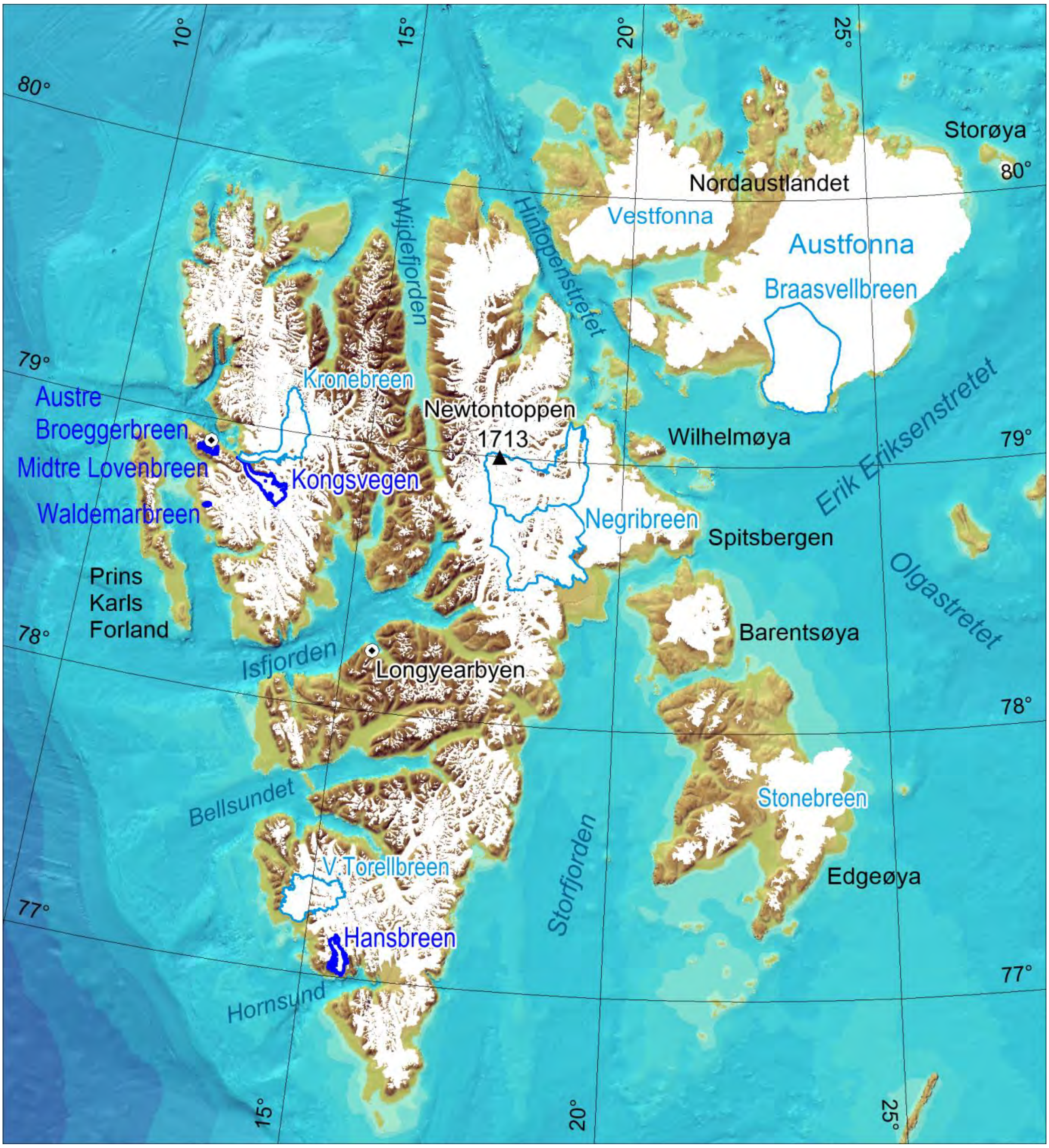


Fig. 5.5: Expansion of current glaciers in Svalbard. Glaciers with the longest series of balance data are highlighted in dark blue, and glaciers mentioned in the text are highlighted in light blue (RGI Consortium 2017).

Current glaciation and its predicted changes

The spatial pattern of the current glaciation of Svalbard, the occurrence of glacier types on the individual islands, and their total area reflect the topographic and climatic conditions of the archipelago. Conditions suitable for the occurrence of glaciers are indicated by the low position of the equilibrium line (equilibrium-line altitude or ELA) of the glaciers, which defines the part of the glaciers with a positive mass balance. Its course is determined in Svalbard mainly by atmospheric precipitation, which reaches the highest annual totals in the south-eastern part of the archipelago, from where it decreases towards the northwest (see chapter 6). Climatic conditions of Svalbard). In areas with high precipitation, the ELA varies between 100 and 400 m, reaching a minimum in Nordaustlandet (Fig. 3.5) The ELA rises in the central part of Svalbard and culminates above 700 m at around 79°N latitude.

In accordance with the regional ELA, Kvitøya (95%) and Nordaustlandet (74%) are the most glaciated islands in the north-eastern part of the archipelago, where large ice caps are located (Tab. 1.5). The Austfonna (8067 km^2) and Vestfonna (2367 km^2) ice caps in the eastern and western parts of Nordaustlandet (Fig.5.5) are the largest glaciers of Svalbard. Glaciers also cover most (78%) of north-eastern Spitsbergen, which hosts ice caps and long valley glaciers. These glaciers are tens of kilometres long and their source areas have an area of the order of 102 km^2. Hinlopenbreen, the largest valley glacier of the archipelago, is nearly 70 km long. Cirque and valley glaciers predominate in the rugged western part of West Spitsbergen, where the length of glaciers ranges up to 50 km in the northwest (Kronebreen) and 35 km in the south (Vestre Torellbreen). The lower islands with a less rugged surface in the eastern part of the archipelago host mainly ice caps that cover 25 to 55% of the islands' area. The smallest extent of glaciarized area is on Prins Karls Forland and reflects the influence of the warm West Svalbard Current and the leeward precipitation shadow of Western Spitsbergen.

Tab. 1.5: Glaciated area in Svalbard. Data source: RGI Consortium (2017).

Island	Land area (km^2)	Glacier area (km^2)	Glacier covering (%)
Spitsbergen	37 673	20 088	53
Nordaustlandet	14 443	10 683	74
Edgeøya	5 074	1 785	35
Barentsøya	1 288	509	40
Kvitøya	682	646	95
Prins Karls Forland	615	68	11
Wilhelmøya	120	30	25
Storøya	50	28	55

Most of the glaciers in Svalbard are polythermal with temperatures close to the pressure melting point in the accumulation region and predominantly cold conditions in the ablation zone. Only small ice caps and cirque glaciers with a thickness of less than 100 m are frozen in their entire volume. Cold ice and permafrost conditions near the glacier margin belong to the reasons for the relatively low basal velocities of local glaciers. The lowest velocities are associated with land-terminating glaciers, which move by several millimetres to tens of mm per day. Tidewater glaciers reach daily velocities in the order of meters, but in surge phases they move up to 100 meters per day. Most glaciers (up to 90% according to some authors) are characterized by a fluctuating length due to alternating phases of slow and fast movements. Approximately 15% of the glaciers, whose source area occupies 68% of the total glaciation area of Svalbard, extend into the coastal zone, where the breakup (calving) of the glacial fronts into large blocks of ice (icebergs) occurs. Most of the icebergs do not exceed 10 m along their longer axis, but sections of glaciers longer than 100 m are separated from the long floating snouts on the east coast of Nordaustlandet and Kvitøya. According to the Randolph Glacier Inventory, there are 1,567 glaciers in Svalbard, which, based on satellite images from 2001–10, occupy an area of 33,837 km^2. The total volume of glaciers is estimated at 5–10 thousand km^3, which is equivalent to 13–24 mm of sea-level rise.

Glacier volume and future climate scenarios are used to estimate the further development of local glaciation. According to model studies, the annual precipitation totals and mean annual air temperature could increase by approximately one fifth and 3–8°C, respectively, during the 21st century (see section 6. Climatic conditions of Svalbard). As a result of climate change, the mass loss of glaciers and runoff from glaciated basins is expected to increase. The runoff should culminate in the middle of the 21st century when it should be up to 50% higher compared to the current state. After that, the runoff declines, and by the end of the 21st century, it should be about 10% lower than it is now. The contribution of meltwater from glaciers to the total runoff should increase from the current 51% to 68% until 2100. By this time, glacier volume will be reduced by 50–85%, which corresponds to a sea-level rise of 10–21 mm. Svalbard is expected to contribute almost 8% to the rise in sea level from melting glaciers (excluding ice caps) at the end of the 21st century (215 ± 21 mm). Within the Arctic, which accounts for over 60% of the modelled sea level rise, Svalbard is one of the most important meltwater source areas with a potential contribution comparable to the glaciers in the marginal part of Greenland. The volume of water bound in Arctic glaciers is an order of magnitude smaller than in the case of the Greenland Ice Sheet, but during the 21st century it is expected to be one of the main causes of sea-level rise and changes in ocean circulation.

6. The climate conditions of Svalbard

Kamil Láska

Climate factors and their importance

The climate conditions of Svalbard are shaped by a set of climate-forming processes and factors, which are most often divided into astronomical, geographical (local), circulation and anthropogenic factors. The main astronomical factor related to the Earth's orbit around the Sun and the tilt of the Earth's axis is the solar elevation angle. The geographical latitude in which the archipelago is located (74° to 81° N) therefore determines the maximum (noon) elevation of the Sun above the horizon and the duration of the polar day and polar night (see Chapter 3). When the sun's rays pass through the atmosphere, there is a significant decrease in the intensity of solar radiation when the Sun is at a low elevation, mainly due to large atmospheric absorption and scattering. During the polar summer, the lower incoming radiation is partly compensated by the prolonged sunshine duration, as a result of which the daily totals of global solar radiation in Svalbard (20 to 25 $MJ \cdot m^{-2}$) are often comparable to measurements in the lower latitudes, e.g., Czech Republic (25 to 30 $MJ \cdot m^{-2}$).

The total gain of radiant energy is, however, fundamentally modified by the physical properties of the Earth's surface, especially its reflectivity (albedo). This geographical factor often causes large spatial differences in the amount of energy absorbed by the Earth's surface. Compared to a tundra surface with a typical albedo between 0.10 and 0.25, which can absorb up to 90% of incident solar radiation, snow and ice surfaces have high reflectivity (0.55 to 0.95) and thus reflect most of the radiant energy.

The consequence of this high reflectivity of snow cover is the prevailing energy losses caused by upward long-wave radiation from the ground surface and the associated cooling of the surface and the near-surface atmosphere. Above all, during the polar night, which lasts from the end of October to the middle of February at 78° N, a negative net radiation budget prevails in the Svalbard region. Energy losses are the greatest in the winter months along the western coast of Svalbard and also in the Greenland Sea region, where they range from −7 to −8 $MJ \cdot m^{-2}$. Small spatial differences with an average net radiation between −3 and −4 $MJ \cdot m^{-2}$ occur in the central part of the Arctic Ocean.

In areas of open water that remain ice-free (polynyas), the surface net radiation drops to −5 $MJ \cdot m^{-2}$. The importance of polynyas lies mainly in the fact that, due to the exchange of energy and mass between the ocean and atmosphere, the adjacent air heats up and at the same time the amount of water vapour in the atmosphere increases. Suitable conditions for the development of phytoplankton and zooplankton are created in their immediate surroundings, and therefore they fulfil an important function within the Arctic marine ecosystems. In the vicinity of Svalbard, the closest polynyas occur, for example, in the Kara Sea or the eastern part of the Laptev Sea.

As the spring snow melts, the large areas of tundra along the Svalbard coast experience very rapid changes in surface net radiation, going from negative to positive values. However, the period of positive net radiation is relatively short in Svalbard, lasting usually from May to the end of August. The average totals of the net radiation budget in these months along the west coast of Svalbard reach 8 to 9 MJ·m^{-2}. The lowest values were measured on the ice cap of Austfonna (Nordaustlandet) and amounted to only 2.5 MJ·m^{-2}. On the contrary, the highest totals of the net radiation budget occur during the summer along the sea ice edges (10 to 11 MJ·m^{-2}) and open water areas (not covered by sea ice), for example in the western part of the Barents Sea and around Bjørnøya Island (13 to 14 MJ·m^{-2}). The occurrence of higher values here is conditioned by a smaller amount of cloud cover and the increasing intensity of global solar radiation towards the subarctic region.

Atmospheric circulation

As a result of high energy loss and the prevailing net radiation deficit in the Svalbard region, atmospheric and oceanic circulations become more important, through which a large amount of heat flux is transported from the equator towards the pole (Fig. 1.6). In the Northern Hemisphere, the greatest accumulation and transport of heat flux (~ 5·1015 W) takes place between the equator and 30° N. In the poleward transport, approximately 60% of the heat is transferred by the atmosphere, and the remaining 40% is accounted for by the oceanic component. Circulation factors therefore play an important role both in the climate conditions of Svalbard and in the entire Arctic region.

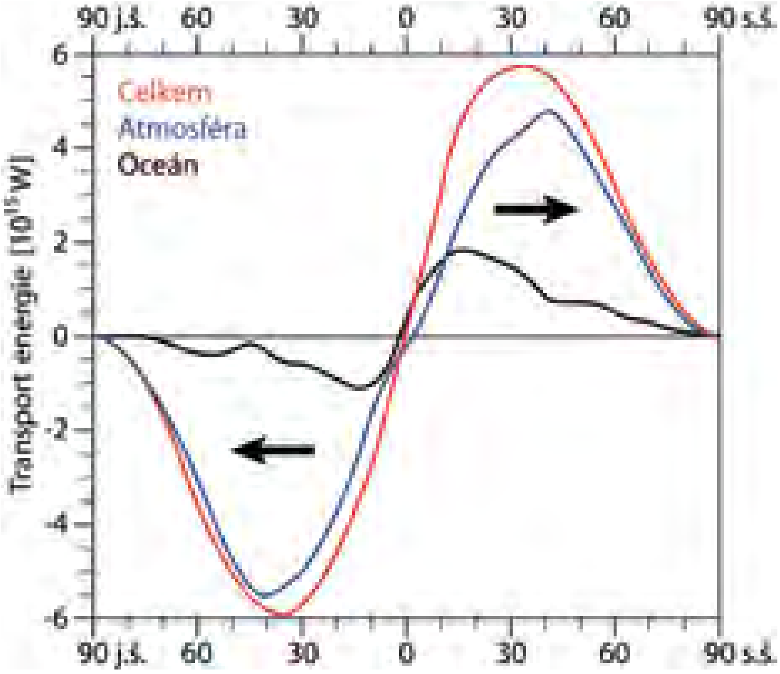


Fig. 1.6: The poleward transport of heat flux from the equator to the North Pole divided by individual components: atmospheric (red), oceanic (blue) and total (black; modified according to Trenberth et Fasullo 2017).

Atmospheric circulation in the Svalbard Archipelago is affected by the atmospheric centres of action, the most important of which are the Icelandic Low and the area of high pressure, which is part of the Greenland High. The Icelandic Low and its eastward low-pressure system known as the Iceland-Kara Trough extend across the North Atlantic to the Barents and Kara seas, and the southern part of Svalbard. This permanent centre of action is located in a region of strong baroclinity (i.e. horizontal temperature gradient) associated with the Atlantic branch of the Arctic front, where cold air masses from the Arctic Ocean meet warmer air over the Atlantic Ocean.

The different properties of both air masses are manifested by intense cyclogenesis, the formation and movement of cyclones (known as depression tracks), allowing penetration of warmer air as far as the Svalbard Archipelago. In the autumn and winter, the temperature differences of the air masses (baroclinity) are the highest, which strengthens cyclogenesis. On the contrary, in the spring and summer months, as a result of smaller baroclinity and weakening of the action centres, the cyclonic activity associated with the Icelandic Low also gradually weakens. The springtime weakening of cyclonic activity is encouraged by the ridge of high pressure from the Greenland High, while in the summer a weak anticyclonic pattern over the pole region plays a role.

The described pressure fields over the Arctic, together with their high seasonal variability, are of decisive importance in shaping the specific weather conditions on the Svalbard Archipelago. Cyclonic situations associated with low pressure systems (57% of all cases) prevail over anticyclonic (43%) during the year. In winter, the share of cyclonic pattern increases to 65%, which is associated with large temperature variability, higher cloud cover and precipitation. Most often, it is an eastern advection in connection with a low-pressure system over the Norwegian Sea. In the summer months, the share of cyclonic and anticyclonic situations is balanced. In July, a south-easterly advection, allowing propagation of relatively warm air towards the Svalbard region, occurs most often.

Local circulation and related meteorological phenomena

The mountainous and highly fragmented surface of most islands, together with the small height of the Sun above the horizon, affects the distribution of solar radiation and creates spatial differences in the net radiation budget and heat transport between the ground surface and the atmosphere. The distinct alpine relief of Svalbard also has a significant influence on the surface wind field and flow distortion, conditioning the formation of local flow and circulation systems, for example in valleys, fjords, or behind/over the orographic barriers.

In Svalbard, the local flow of the foehn (föhn) and breeze types, as well as valley, mountain, and katabatic winds, are the most common. The foehn wind occurs here most often during east, northeast, or west advection; an important (but not the only) condition for its formation is the flow direction, which should be approximately perpendicular to the mountain range. When the flow speed is high enough and other thermodynamic conditions are met, the rising air cools, becomes saturated, and then precipitation often falls on the windward side. On the lee side, the descending cloud-free air warms, which manifests as a drier and warmer downslope flow. However, the foehn wind may occur without moisture removal on the windward side of the mountains. The foehn often accompanies the formation of a typical orographic cloud covering the top parts of the mountains. If the cloud is observed from the lee side, it appears to us as a foehn (bank) wall (Fig. 2.6). The foehn causes a reduction in precipitation totals as well as a lower frequency of rainfall occurrence on the leeward slopes of Svalbard. Another type of flow is the sea/land breeze, i.e., a system of local (coastal) circulation with a typical daily periodicity. In Svalbard, the breeze is often created during an anticyclonic circulation along the coastal zone and the adjacent part of the sea or fjord.

Fig. 2.6: Foehn wall forming during an eastern advection over the Lomonosovfonna ice cap towards Petuniabukta in the central part of Svalbard (Láska).

In periods with negative radiation budgets (e.g., in the night hours or during the polar night), the topography and properties of the Earth's surface play a more significant role than in periods of positive budgets. Due to the cooling of the Earth's surface by long-wave radiation, a stable atmospheric boundary layer and significant temperature inversions are often created. They are also related to the occurrence of extremely low minimum temperatures in the Svalbard region, especially on snow/ice surfaces, or sea-ice inside narrow (isolated) fjords, e.g., Billefjorden, Kongsfjorden, Van Mijenfjorden, Wijdefjord.

The largest energy losses and cooling of the atmospheric boundary layer occur on glaciers. Due to gravitational forcing, cold and dense air flows down the glacier's surface into the valley, which is why it has the character of a "fall type" katabatic drainage flow. This katabatic (downslope) wind moves above the glacier's surface in a layer of tens to hundreds of meters thick. In Svalbard, the occurrence and speed of katabatic winds, unlike in Greenland or Antarctica, is a less frequent phenomenon related to the length and thermal conditions of the glaciers in this area. Therefore, near the Spitsbergen coast, the katabatic flow usually reaches mean wind speeds of about 10 $m \cdot s^{-1}$, in contrast to Antarctica, with speeds up to about 50 $m \cdot s^{-1}$.

The extensive mountain systems in the Svalbard archipelago create good conditions for forming lee waves and wave (orographic) clouds, most often as altocumulus lenticularis. In simple terms, these arise due to a stationary flow perpendicular to the orographic obstacle during a neutral or slightly stable stratification of the atmosphere. On the leeward side of the obstacle, a rotor motion (vortices with a horizontal axis) develops forming wave deformations and crests. The emerging waves cause an ascending flow above the wave-front, the air cools, and some of the water vapour condenses. In the wave crest, a characteristic orographic cloud is formed, which has a lens- or disc-shape with an elongated horizontal axis and distinct contours. Depending on the temperature stratification, wind speed, and dynamic modification over the obstacle, a series of waves may form. A larger number of clouds above the mountain crest and lee side are often stacked with each other, possibly arranged (replicated) in several rows up to a distance of several tens of kilometres from the mountain barrier (Fig. 3.6).

Fig. 3.6: Orographic clouds (*altocumulus lenticularis*) over the central part of Svalbard (Láska).

Temperature and precipitation conditions

Together with Iceland, Svalbard belongs to the warmest regions of the Arctic. Its western part is heated by the West Spitsbergen Current all year round. As a result, the climatic conditions of the Svalbard archipelago and the western coast of Spitsbergen, in particular, are considerably milder compared to other regions at the same latitude (for example, inland parts of Canada or Russia). Therefore, the air temperature pattern also corresponds to the heat exchange between the ocean and atmosphere, with mean annual air temperatures ranging from −4 °C in the southern and southwestern parts of the archipelago to −12 °C on the highest glaciers in northern West Spitsbergen and Nordaustlandet. The annual course of air temperature at the meteorological station in Longyearbyen as well as other stations on Svalbard is characterized by a simple wave with a maximum in July (6.4 °C) and a minimum in February (−13.5 °C). Monthly mean air temperatures in the northern part of the archipelago are up to 2 °C lower than in Longyearbyen; this also corresponds to the average summer (5.2 °C) and winter (−15.8°C) temperatures, for example, on Nordaustlandet. The highest air temperature to date (21.7 °C) was recorded at Longyearbyen station on 25 July 2020, breaking the temperature record (21.3 °C) observed on 16 July 1979. On the other hand, the lowest temperature (−46.3 °C) was registered at the same station on 4 March 1986. In the spatial distribution of air temperature in Svalbard, the predominant oceanic character of the climate is clearly visible, with a significant temperature gradient from the southwest (warmest) to the northeast (coldest) parts of the archipelago (Fig. 4.6), These spatial temperature differences are greatest in winter (up to 7 °C) and in spring (3.5 to 4 °C). In general, the climate inside the fjords (due to orography and local airflow modification) has a more continental character, characterized by lower winter and higher summer temperatures, than along the western coast of Svalbard.

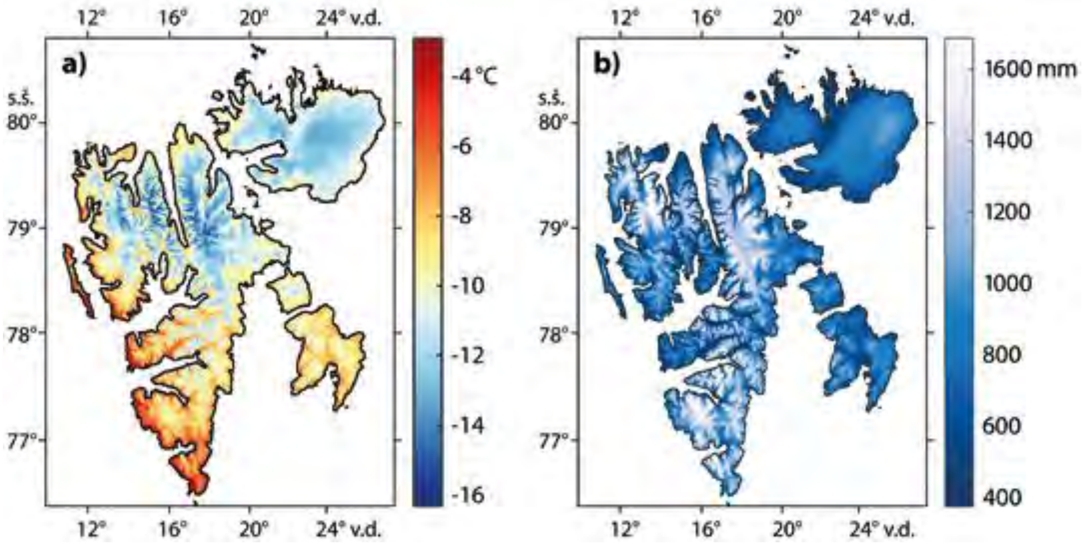


Fig. 4.6: Spatial distribution of (a) mean annual air temperature and (b) precipitation totals in the Svalbard archipelago for the period 1961 to 2012 (modified according to van Pelt et al. 2016).

Intense cyclogenesis linked to the Icelandic Low, or the Iceland-Kara Trough, brings extensive clouds and relatively high precipitation totals to the Svalbard region. The spatial distribution of precipitation is quite variable due to the steep orography of the archipelago and related windward and leeward effects. A sparse network of meteorological stations, most often located near the coast, together with the technically challenging measurements, complicates the reliability of precipitation observations and their estimations in remote regions and at higher altitudes. The highest (modelled) annual totals occur in the southwestern and western part of the archipelago, ranging from 500 to 600 mm near the coast and up to ~ 1300 mm in the highest (windward) locations of Spitsbergen Island (Fig. 4.6).

The next humid areas include Edgeøya Island (with annual totals of ~1200 mm) and the southwestern part of Nordaustlandet (900 to 1000 mm). On the contrary, the leeward slopes of the islands, the central parts of the fjords (e.g., Billefjorden, Van Mijenfjorden, Wijdefjord), or the straits between Spitsbergen and Nordaustlandet are drier regions, with annual totals between 250 and 400 mm.

Precipitation often occurs as snow for most of the year; in the summer months, it takes the form of drizzle, or more persistent rain, if it is connected to frontal precipitation and low-pressure systems (deep polar lows and main storm tracks) in the northern Atlantic extending into the Barents and Kara seas. The orographically enhanced precipitation frequently occurs in autumn and winter due to cyclonic activity and the intensifying inflow of relatively warm mid-latitude air masses from the region of the Icelandic Low. This also corresponds to the annual course of precipitation totals, with the highest monthly totals between 50 and 60 mm in September. On the contrary, the lowest totals occur in spring (April, May) reaching 20 to 25 mm.

Climate change and future development scenarios

Some of the oldest and most continuous meteorological observations in the Svalbard archipelago come from Isfjorden Bay in the central part of Spitsbergen Island (station Svalbard-Airport, Longyearbyen, Isfjord Radio, and others). The compiled instrumental time series going back to 1898 shows a significant temperature increase, which in the case of annual means is 2.68 °C / century (Fig. 5.6). Largest increase has been in spring (3.98 °C / century) and winter (2.98 °C / century), while warming was the slowest in summer (1.08 °C / century). This fact is also reported by the latest Intergovernmental Panel on Climate Change (IPCC) report, which points out that the Arctic region (defined by 60°N) is warming up to three times faster than the global average. The atmospheric warming in the North Atlantic has been accelerating, especially since the 1990s. A similar or even faster temperature increase has occurred in Alaska, western Canada, and Siberia. These regions have been warming up to seven times faster than the global average in the last decade.

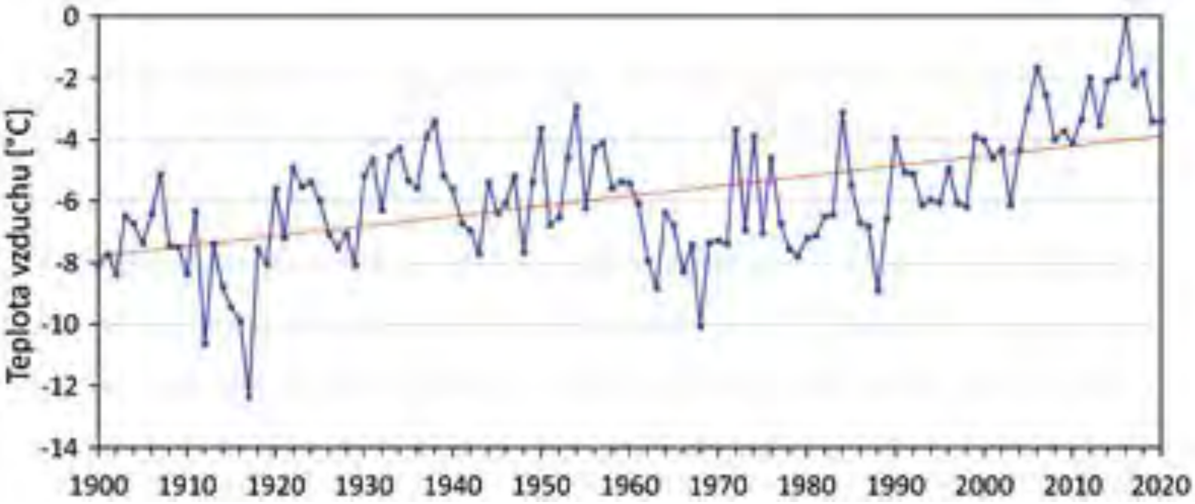


Fig. 5.6: Time series of mean annual air temperature supplemented by a linear trend (red line) at the Svalbard-Airport/Longyearbyen station from 1900 to 2020 (after Nordli et al. 2014 and eklima.no).

This polar (Arctic) amplification of climate change refers to the enhancement of near-surface air temperature change in the Arctic relative to lower latitudes and the global mean, respectively, is best explained as a positive feedback mechanism between the ocean surface albedo and near-surface air temperature. A decrease in the ice and snow albedo, for example, due to a reduction of sea-ice extent, will cause greater absorption of solar radiation by the ocean, resulting in heating of the ocean surface and further melting of sea ice. This results in additional shrinking of sea ice extent and heating of the lower atmosphere from the ocean surface with less sea ice.

In contrast to air temperature, precipitation time series on Svalbard do not show a clear long-term trend. This is due to the large inter-annual variability of precipitation totals, local factors, related orographic effects, and, last but not least, instrumental (systematic) errors of rain gauges. According to some studies (e.g., Hanssen-Bauer et al., 2019), annual precipitation totals slightly increased in the area of Bjørnøya and Hopen islands between 1971 and 2017. The increase was approximately 20 to 30%, mainly caused by higher precipitation in winter and spring. On Spitsbergen Island, autumn precipitation totals increased the most, especially in its northern and northeastern parts. In the long-term perspective, the southwestern and central part of Spitsbergen appears to be the relatively driest, where an insignificant or decreasing trend was recorded in spring and summer. As a result of atmospheric warming, the proportion of precipitation falling as rain has increased significantly, especially in summer and autumn. This applies primarily to the southwestern part of Spitsbergen, where there is significant ice mass loss, intense snowmelt (earlier spring), and a corresponding extension of the growing season in the last few decades.

The climate projections based on the medium emission scenario RCP4.5 most likely predict an increase in Arctic air temperature between 2 and 9 °C by the end of the century. Most model ensembles agree that the Svalbard region can be expected to have an even greater increase in annual temperatures, about 4 °C, and at the most extreme of 10 °C, compared to the reference period 1971 to 2000. An even greater increase in temperature is expected by the end of the century on Svalbard in spring (at least by 6 °C) and winter (up to 9 °C). At the end of the 21st century, according to model estimates, total annual precipitation will increase by up to 10%. Autumn and winter precipitation totals will most likely increase, particularly in the northern and north-eastern part of Svalbard (at least by 20%, in extreme cases by up to 40%). Simultaneously with the increase in moisture content in the atmosphere and precipitation totals, it can be expected that an increasing portion of winter precipitation will fall as rain instead of snow. Climate model simulations further predict an increase in the frequency of extreme daily precipitation totals by approximately 20% compared to the reference period. These heavy rainfall events are closely related to an intense south-southwesterly flow with advection of water vapour from warmer North Atlantic areas and strong local topography influences.

7. Hydrological conditions of Svalbard, lakes, wetlands and watercourses

Linda Nedbalová, Miloslav Devetter and Josef Elster

Classification of freshwater habitats

Due to the very significant seasonality (long winter period and short summer) and the presence of permafrost, which prevents surface meltwater from seeping into the subsoil, a large number of lotic (flowing) and lentic (stagnant) freshwater ephemeral biotopes are created during the spring thaw. During this period, a significant part of the tundra ecosystem is covered by meltwater, and the area and diversity of freshwater habitats in the Arctic is large. In sloping terrain, meltwater drains away, and the terrain dries out quickly, on the other hand, in terrain depressions systems of shallow wetlands and waterlogged soil are created. Winter snowfall is a source of water for all types of aquatic environments, and its melt is often spread over much of the summer. Only in some cases are lakes subsidized by permanent inflow. Polar conditions are characterized by the dynamic emergence and demise of freshwater ecosystems (Marszalek et Gorniak 2017). Their classification is based on water availability (Elster 2002).

1. **Hydric ecosystems** (lakes, in rare cases glacial streams) are systems where liquid water is available year-round. This type of freshwater ecosystems has a limnic character and exists for a long time, tens to thousands of years.

Fig. 1.7: In the central part of Svalbard, in Billefjorden Bay, where the Nostoc terrain station is located, there are several types of lakes: (a) a proglacial lake in the foreground of the Ragnar glacier, with it is in direct contact; (b) a shallow lake on the sea terrace, one of the oldest of the area, in the old Scottish mining settlement of Brucebyen; (c) karst lakes in the area with gypsum formations (Mathiessondalen); (d) a lake of tectonic origin in the foreland of the Nordenskiöld glacier; (e) Lake Garmaksla blocked by a landslide (CPE Archive).

2. **Hydro-terrestrial ecosystems** (shallow wetlands) where liquid water is available for most of the summer season. These are both lotic (Fig. 2.7 and lentic (standing Fig.3.7) ecosystems. Both types differ in their duration (presence of fresh water), trophy (content of available nutrients), content of entrained mineral particles, occurrence of fauna and a whole range of other ecological characteristics (Fig. 4.7). In the second half of summer, shallow wetlands gradually dry out and freeze with the onset of winter.

Fig. 2.7: (a) The great abundance and variety of flowing habitats is an important part of most of the valleys on Svalbard, the bay of Billefjorden; (b) a small seasonal stream in the Endalen valley around Longyearbyen, central part of Svalbard (CPE archive).

Fig.3.7: (a) Endalen valley in the vicinity of Longyearbyen with waterlogged meadow; (b) paleoecological research of sediments in shallow wetlands, Brucebyen, central part of Svalbard (CPE Archive).

Fig. 4.7: (a) Glacial rivers carry large amounts of sediment; (b) in flat valleys, large amounts of sediment settle and form various geomorphological formations, Billefjorden Bay, the central part of Svalbard (CPE Archive).

3. **Terrestrial ecosystems** are defined as environments where liquid water is found only in the form of adsorptive and capillary soil water and gravity water is present only for a very short period during snowmelt and after precipitation. Water is the limiting factor here.

Lake types

Freshwater lakes of often very different origins are found in the high Arctic environment. This is reflected in the diversity of their morphometric, hydrological and hydrochemical parameters, which can be observed even in a small area. The primary factor involved in the formation of lakes in the Arctic is glaciers and their dynamic action. Through their activities, they changed the surface not only locally, but also on the scale of the entire landscape. Erosion activity created numerous depressions, as well as the enormous amount of transported material was an ideal environment for the formation of dammed lakes and smaller bodies of water. Glacial lakes can thus be classified into several types depending on the processes leading to their formation and the environment in which they were formed. In addition to lakes of glacial origin, the Arctic also contains lakes on marine terraces, karst lakes, lakes of tectonic origin and spring lakes (wetlands). The source of water for all types of lakes is primarily winter snowfall, which in some cases is supplemented by the gradual melting of snow in the basin during the summer. A wide spectrum of lake types with different environmental conditions can be found, for example, in the vicinity of the Czech field station "Nostoc" in Petunia Bay (Billefjorden, West Spitsbergen, Fig. 1.7). In the text below, examples from this area are often given. Systematic research of the local lakes began as part of the Polar Ecology field courses organized by the FS USB. The classification of lakes in this area, their bathymetric maps and physical-chemical characteristics were published in the work Čepová (2013).

The following text gives an overview of the types of lakes in the Arctic according to their origin based on the classification according to Pienitz et al. (2008). We can divide the diverse group of **glacial lakes** into two categories, depending on whether they are in direct contact with the glacier or whether they are no longer in the area of influence of the glacier and are just a remnant of its former activity. The first group of **glacier-dammed lakes** includes **supraglacial** lakes on the surface of glaciers, **englacial** lakes inside the glacier, **subglacial** (covered by a glacier) and **proglacial** Fig 1a.7) or **epiglacial** lakes adjacent to the glacier. Supraglacial lakes are typically very young and appear only during the summer thaw. Their level can fluctuate significantly depending on the amount of available water and the permeability of the glacial flows that drain the lake. In the ablation zone of glaciers, we often find very small lakes of a round shape, which are called **cryoconite** holes. They arise as a result of increased melting in places where there is dark sediment (cryoconite) on the surface, which causes a decrease in albedo. They are typically only a few centimetres, tens of centimetres at most in diameter. They freeze periodically or may be permanently frozen. These are important centres of biological activity on glaciers. Englacial and subglacial lakes are among the least explored lake types due to poor accessibility. Compared to Antarctica, only a small number of subglacial lakes have been documented in the Arctic. Among proglacial lakes we include, for example, Lake Ragnar, which is the largest in the vicinity of the Czech field scientific station "Nostoc" in Petuniabukta Bay. It was created in the 1980s after the accelerated retreat of the glacier, it is covered by its frontal moraine and ends at the front of the glacier. Thanks to the continued retreat of the glacier, it continues to increase in size, on the other hand, the lake is very quickly clogged with sediments coming from the subglacial flow that feeds it. In general, these lakes usually undergo a very dynamic development, often suffering from catastrophic spillage when a rapid dike breach occurs. Epishelf lakes, like subglacial lakes, are specific to polar regions. They are formed when the ice shelf drains the freshwater outflow from the land in the bay, and it forms a lake, but it is hydrologically connected to the ocean. They are permanently frozen and represent a very extreme type of freshwater environment. They are currently disappearing rapidly due to global warming. These changes are best documented on the northern coast of Ellesmere Island, where Milne Fjord currently contains the only known deep epishelf lake in the Arctic (Veillette et. al. 2008).

The second group of glacial lakes consists of **postglacial lakes**. It was created by glacial erosion and/or sedimentation in the currently deglaciated area. **Tarn** or **moraine-dammed** lakes were created by the action of the mainland glacier, either by deepening the bedrock or by blocking the depression with material transported in front of the glacier. We divide them according to the time of their formation into old (more than 1,000 years old) and young, which were mostly formed after the retreat of the glacier from the Little Ice Age, and their age is therefore a maximum of a few hundred years. Old glacial lakes have well-stabilized shores, impermeable bottoms and stably retain water even after the surrounding permafrost melts. They usually have a tributary or a larger catchment, so the level does not fluctuate as much during the season. They are characterized by relatively great depth, they do not freeze to the bottom in winter, and more species of organisms are alive than young lakes. **Kettle** lakes are a specific type of young lakes, which are created by the melting of the ice lens (so-called dead ice) in the moraine. They usually do not have a fully stabilized bottom, which is partly made up of permafrost ice and can lose water very quickly after it is disturbed by melting during the summer season. These lakes do not have stabilized shores, contain mainly snow water, can dry up during the season and are oligotrophic. Due to the instability of the shores, they are not a very suitable environment for the formation of microbial growths, and most organisms therefore live in open water, where only a species-poor community lives. There are a large number of these lakes around the Nostoc station in Petuniabukta Bay, and their age probably does not exceed 100 years.

The most abundant type of lakes in the low Arctic are undoubtedly **thermokarst lakes**, which fill depressions by intruding permafrost degradation. These are also very dynamic systems, but their development is usually not as fast as in the case of submerged lakes. Their drainage occurs by catastrophic discharge or gradual filling with sediments.

The lakes on the marine terraces were formed in the depressions of the sea shelf after the melting of the ice from the last ice age and the subsequent lifting of the land from the sea (the so-called glacio-isostatic uplift). These are very shallow (typically the depth does not exceed one meter) stable lakes, usually circular in shape, which freeze to the bottom in winter. Their age usually reaches the first thousand years. These lakes with vegetated shores are attractive to waterfowl that stay on the shores and eutrophicate the water. Their relatively great age and stability make them an ideal environment for preserving sediments from which the development of the lakes and the surrounding landscape in the younger Holocene can be reconstructed. In general, during development, the water of these lakes changes from salty to fresh, but the development of the chemical properties of the water can be very different, some lakes are purely freshwater, and others can be even hypersaline (van Hove et al. 2006). An example of this type of lake is the lake in Brucebyen in the bay of Billefjorden (Fig. 1b.7).

Karst lakes are linked to the presence of partially soluble rocks, mainly gypsum and limestone, they are rare in polar regions. In the Arctic, geological and geomorphological conditions are suitable for their formation, especially in Svalbard, Siberia and Canada. They are relatively deep, often round in shape or can be elongated in the direction of cracks and fractures. In the vicinity of the Czech station, they can be found, for example, in the area of Mathiesendalen, which is made up of gypsum formations. Karst processes in these climatic conditions are relatively slow, however, thanks to aerial photographs, for example, the creation of one of the sinkholes between 1960 and 1990 was documented. In the area, there are six large lakes, which reach a depth of up to 14 meters, on a raised marine terrace of Holocene age. In addition to several sinkholes partially filled with water, the underground water supply system of these lakes is proof of their karst origin (Fig1c.7).

Lakes of tectonic origin were formed in tectonically formed depressions of the bedrock, they can have different sizes, shapes and depths and, depending on deglaciation, they can be of different ages. They often host complex biological communities. They are relatively rare in the Arctic. The most famous example is the vast Icelandic lakes Þingvallavatn and Þórisvatn. Glacial activity also played a part in their formation, but originally, they were trench depressions (graben) created in the divergence zone on the Mid-Atlantic Ridge. Smaller lakes formed in tectonically conditioned depressions in places of faults can be found, for example, in the forefield of the the Nordenskiöld glacier in the area of the Billefjorden Bay (Fig 1d.7).

Lakes dammed by landslides are typical of mountainous terrain and can be quite large and deep. They mostly only exist for hundreds to thousands of years, as they are prone to often catastrophic overflows and rapid sediment filling. So far, little attention has been paid to them in the Arctic. The depression created by the landslide along the fault zone in Billefjorden Bay was filled by Lake Garmaksla, which is characterized by a very good paleolimnological record. From another point of view, this lake can be considered tectonic. It was possible to collect an almost 80 cm long sedimentary core with distinct lamination, which represents the history of the lake and its surroundings over a period of several thousand years (Fig. 1d.7).

Fluvial lakes were formed by the erosion or accumulation activity of flowing water. They are most abundant around large rivers, such as the Lena or Mackenzie. Deposition of Aeolian (wind-transported) material on the banks plays a significant role in the formation of lakes found in flat river floodplains. This creates shallow depressions, saturated with water from melting snow on the one hand, and on the other hand from small watersheds flowing below the surface through the permafrost. The water levels in these lakes and wetlands usually drop during the season and often dry up completely later. Most of them are only hundreds or even only a few decades old. Polar conditions are characterized by the continuous dynamic creation and disappearance of many lakes of this type (Marszalek et Gorniak 2017).

Volcanic lakes are not very common in the Arctic, they are found only in Iceland and Alaska.

Abiotic conditions of lakes

Polar lakes are generally characterized by long freezes, cold water temperatures, and extreme seasonal fluctuations in solar energy input due to the alternation of polar day and polar night. Regarding the temperature characteristics of lakes, individual types according to their formation are usually characterized by a typical shape, which is then reflected in different temperature regimes. The entire water column of very shallow lakes can heat up significantly more in the summer than in the case of deep lakes. The water temperature of shallow lakes can routinely exceed 10°C even in the high Arctic during sunny summer days. On the other hand, shallow lakes can freeze to the bottom in winter, which brings completely different conditions for the organisms living there. This is also typical for shallow wetlands, which are among the most productive Arctic ecosystems. Fig. 5.7 shows the course of temperatures at a depth of 0.5 m in two different types of lakes in the area of Billefjorden (Petuniabukta). While Lake Ebba is a shallow lake on the marine terrace, up to 1 m deep with a very small catchment and freezing to the bottom (red), Lake Blue is, on the other hand, deeper (5.5 m) with a stable water level that is nowhere near freezing (blue). The growing season in Ebba Lake begins in late May and June, in Blue Lake almost a month later. Ebba, however, freezes if it does not dry even a month earlier. In the shallow lake, temperatures in summer normally reach 10–15 °C, in the deep lake they rarely exceed 10 °C. The layer of ice on Blue Lake and other lakes reaches a thickness of 130 cm or more, and it is also covered with a layer of snow, which prevents the penetration of sunlight in the spring. Ice, which closes the surface of the water surface for eight months of the year or more, also prevents gas exchange and can cause hypoxia despite the prevailing oligotrophic nature of the lakes. Long-term freezing is a key feature of Arctic lakes, which fundamentally affects the biological processes in the lakes. As a result of warming, the frost-free period is currently being extended, which necessarily leads to fundamental changes in the temperature and light regime of lakes (van Hove et al. 2006).

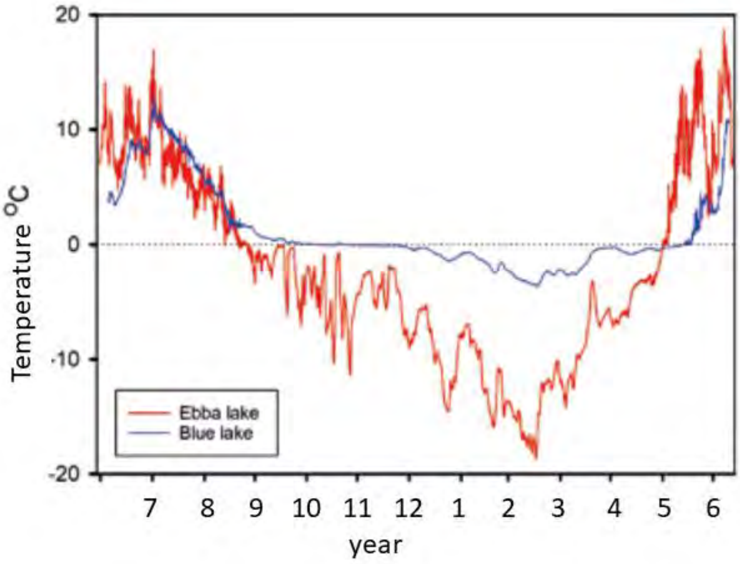


Fig. 5.7: Course of water temperature at a depth of 50 cm in 2 contrasting lakes in the vicinity of the Czech base Nostoc - in the shallow Ebba Lake and the deep Blue Lake (Devetter).

Lakes that are deep enough to stratify can be divided into several categories in terms of temperature regime (Vincent et al. 2008). In general, **monomictic** lakes predominate in the high Arctic, which thaw in the summer, mix at a temperature close to 4 °C, and therefore do not undergo temperature stratification. In milder climates, we can also find **dimictic** lakes (for example, the long-term studied Toolik Lake in Alaska), which mix twice a year (in spring and autumn) and are stratified at least for a short period in summer. At the opposite end of the spectrum are **amictic** lakes, which are permanently frozen and do not mix as well as the previous two types. Some mixing of the water column also occurs in amictic lakes, for example due to convective mixing. However, permafrost lakes are relatively rare in the Arctic compared to Antarctica. The last type are **meromictic** lakes, where there is no mixing of the entire water column due to significant gradients in salinity. A frequent cause of meromixing is the presence of relict seawater in the lower layers, for example the already mentioned lakes on marine terraces (van Hove et al. 2006). Another type is the so-called crenogenic meromix, when the lower layers of the lake are influenced by springs with high conductivity, an example of such a lake is Kongressvatn near the mouth of the Isfjorden Bay, Western Svalbard (Holm et al. 2012).

The period of photosynthetic activity is thus determined by practically zero light in the winter and all-day light in the polar summer. In addition, a ray of light falling on the surface at a very low angle in summer is 100% reflected, and the darkness below the surface is disturbed only by a small amount of diffuse radiation. However, this condition occurs for a large part of the polar summer, so the period of photosynthetic production is limited to a relatively short period. In this period, on the other hand, it can take up to 24 hours. In the water column, the penetration of light is affected by the amount of dissolved substances and living and non-living particles. In general, polar lakes are characterized by high transparency. Due to the low productivity of lakes, the influence of phytoplankton and other organisms present in open water is usually small. Reduced transparency can often be observed in lakes directly affected by glaciers due to the large amount of sediment produced by their erosion (glacial "flour"). Of the dissolved substances, the concentration of organic carbon plays the biggest role, higher concentrations of these substances can be found in climatically milder regions of the Arctic (Vincent et al. 2008).

The annual amount of light radiation decreases significantly with increasing latitude. It is reported that the decrease of this parameter is about 50% if we move from 30° to 80° latitude. The extreme light regime of Arctic lakes, primarily determined by the alternation of polar day and night in the regions beyond the Arctic Circle, is accentuated by the presence The content of dissolved substances in Arctic lakes is found in a wide range of values, some are characterized by extremely low conductivity, others, on the contrary, by high salinity due to direct proximity to the sea or content relict seawater. The pH values are also characterized by great variability. In general, it is possible to summarize that the diversity of biogeochemical parameters of lakes is determined by the nature of their contact with marine and terrestrial ecosystems, properties of the geological bedrock and climatic conditions, which determine, for example, the intensity of weathering or the nature of vegetation in the basins. Last but not least, chemistry is influenced by biological processes taking place in lakes, for example pH is significantly influenced by photosynthetic activity. Nutrient concentrations are usually very low, and nitrogen or phosphorus, or both elements together, are among the factors limiting the overall productivity of lake ecosystems (Lyons et Finlay 2008).

Fig. 6.7 hows seasonal changes in abiotic conditions in the Blue and Ebba lakes. In both lakes, however, the concentration of ions, pH, nutrients and undissolved carbon fluctuates greatly, often to an extent quite unusual compared to lakes at lower latitudes. It is likely that this may be related to extreme pressure from invertebrate consumers and predators. The variability of the water chemistry of lakes on marine terraces in the Ebbadalen valley in Petuniabukta Bay was studied by Mazurek et al. (2012). The observed seasonal differences as well as differences between individual lakes were determined by the source of water (melting snow, permafrost), the geological substratum in combination with the intensity of biological processes.

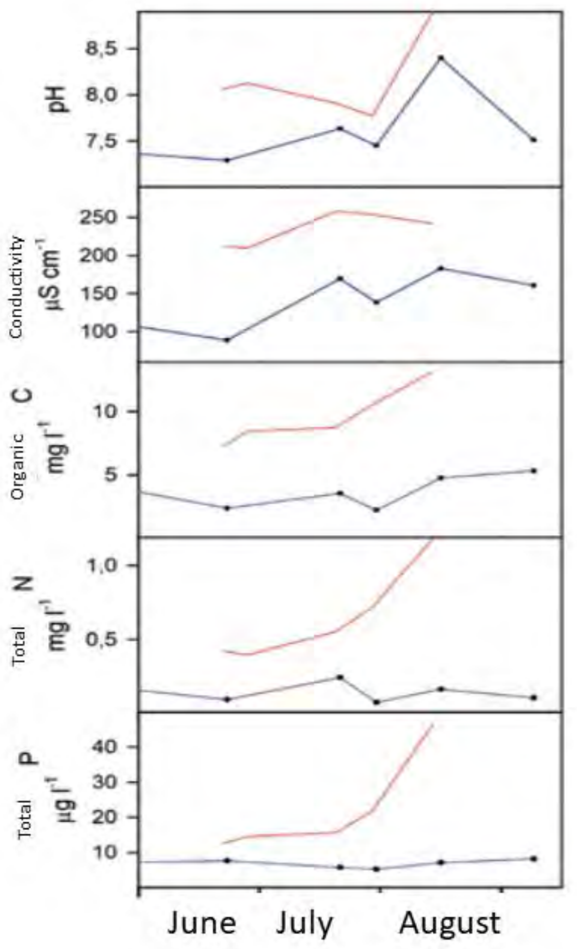


Fig. 6.7: Summer course of selected chemical parameters of lakes Ebba and Blue Lake (Devetter).

Impact of climate change on Arctic lakes

The current significant warming of the Arctic is of course also greatly affecting lake ecosystems. Long-term monitoring of several dozen lakes on Ellesmere Island in north-eastern Canada has shown that the response to rising air temperatures may not be smooth. In 2006, there was a sudden dramatic drop in the water level or even a complete drying up of the monitored lakes, whose age often reached many thousands of years (Smol et Douglas 2007). We can also currently observe the disappearance of lakes in the low Arctic, where thermokarst lakes are collapsing as a result of the continued melting of permafrost. A study conducted over a large area in Siberia showed that at the end of the last century, the number of lakes larger than 40 hectares decreased by eleven percent during 25 years. Of course, most of them did not disappear completely, but there was a significant reduction in their size, so that the total area of lakes in the region decreased by six percent (Smith et al. 2005). The paradox is that the rise in air temperatures initially enabled the formation of thermokarst lakes, but its continuation has fatal consequences for them.

The warming of the climate is also related to the lengthening of the period when the lakes are thawed, which is less noticeable at first glance. It is reported that over the past 150 years, the freezing time of Arctic lakes has decreased by an average of two weeks (Wrona et Reist 2013). However, even this relatively small change can significantly affect their functioning, as it changes the amount and spectral composition of solar radiation entering the water column, their heat balance, the stratification and mixing regime, as well as the supply of substances from the basin.

To document these changes, however, we still have long-term monitoring of physico-chemical characteristics for only a small number of Arctic lakes. An example is the meromictic lake Kongressvatn near the mouth of Isfjorden bay (Western Svalbard). It was found that air and water temperatures increased by 2 °C between 1962 and 2010 and the lake level dropped by 4 m. The warming was also reflected in the hypolimnium during the stratification period. It is therefore clear that the temperature regime of lakes changes rapidly depending on changes in air temperature. However, the retreat of glaciers and the melting of permafrost also have a significant effect on the conditions in the lakes (Holm et al. 2012).

The answer to the question to what extent these changes are exceptional in the historical context can be found in the lake sediments, which represent unique natural archives recording the conditions in the lake and its surroundings. Thanks to sedimentological and chemical analyses, it is possible to record environmental changes that occurred during the lake's history. No less important are the records made by organisms whose remains are well preserved in the sediment, such as small algae with siliceous structures (diatoms, chrysophyta) and various invertebrates (e.g., cladocera or chironomidae). The species composition of the communities depends on the physical and chemical properties of the water. In this way, we can retroactively estimate what the environmental conditions were in the past. Paleolimnological analyzes are now available from a number of localities, including the vicinity of the Czech Science Station in Petuniabukta Bay, and demonstrate the sudden change in communities that took place in the recent past. The most significant changes are observed in the high Arctic, where warming is fastest (Wrona et Reist 2013).

Watercourses

Streams and rivers are a prominent feature of the Arctic landscape, and their ecology reflects the extreme conditions of the polar environment. While in the Antarctic flowing waters are limited to small deglaciated areas and are mostly very short streams, in the Arctic we also find large streams that bring huge volumes of fresh water, sediments and dissolved substances into the ocean (Yenisej, Ob, Lena, Mackenzie). Their extensive watersheds extend far to the south and are therefore significantly influenced by forest ecosystems. On the other hand, there are a huge number of streams whose basins are located entirely in polar conditions. Even within this, however, we can find very different types - from glacial streams to meandering slow-flowing rivers flowing through meadow tundra. During the melt season, streams and rivers are a source of water for wetlands and lakes, which represent important habitats in terms of biodiversity and productivity.

The extreme hydrological regime of Arctic streams is largely determined by the presence of permafrost. Like wetlands and shallow lakes, freezing to the bottom is an important feature of smaller streams with the onset of winter, at the same time most of the precipitation falls in the form of snow. There is thus zero flow for a long period. An ice cover forms on the larger rivers, but the water under the ice flows throughout the winter. In the spring, intense melting raises flows to maximum values, when more than half of the annual flow can flow through the stream during a relatively short period. The summer period follows, when there is a gradual decrease in flow. Summer also sees most of the biological activity in streams. (McKnight et al. 2008, Huryn 2021). The chemical composition of the streams is influenced by a combination of many factors, among which are particularly significant seasonality and the source of meltwater, the geological bedrock, the nature of the vegetation in the basin and possible interaction with groundwater. The dominant form of carbon is often dissolved organic carbon, which reaches higher concentrations in arctic rivers than in temperate rivers. This is mostly allochthonous carbon originating from terrestrial ecosystems. Similarly, the dissolved organic fraction is the predominant form of nitrogen, dissolved forms of inorganic nitrogen are mostly present in significantly lower concentrations. Extremely low concentrations of phosphorus (or nitrogen as in the case of lakes) may be one factor limiting the productivity of streams (Lyons et Finlay 2008).

The character of the river network in Svalbard corresponds to the morphology of the terrain. Unlike other parts of the Arctic, for example the flat accumulation regions of Siberia or northern Canada, this is a very mountainous area with a number of short valleys and significant glaciation. Short and steep valleys correspond to the length and shape of the river network, together with other characteristics of the watercourses – large gradient, high flow speed and high carrying capacity. This results in the occasional shifting of riverbeds, which is one of the processes that actively transforms the face of the local landscape. From the point of view of the classic division of the longitudinal profile of the water course, the rivers and streams here mostly have the character of "upstream". Only a few of the longest watercourses form floodplains, where the watercourse has a low gradient and velocity and meanders. Streambeds are usually very unstable, which is due to the nature of the subsoil and the absence of vegetation on the banks. Frequent changes in the shape of the transverse profile complicate the measurement of flow rates and the installation of automatic hydrostatic pressure measurement. Glaciers are the most important source of water for streams. In addition to water, they are also a source of material that the glacier and subsequently the water stream carries away. Entrained material is transported in two basic ways: in suspension or as bottom sediment. It plays an important role in the transformation of flat areas flowed by glacial rivers, so-called glacifluvial alluvial plateaus. One of them is located near the Czech field station in Petuniabukta bay in front of the Ebbabreen glacier. It shows all the characteristic features of wild streams in the forefield of glaciers. When viewed from the glacier, the riverbed begins with individual incised beds, which after a few hundred meters begin to branch until finally turning into a system of very wide and shallow channels. Together with changes in morphology, sediments also develop. Closer to the glacier, these are coarse gravels with boulders up to over 20 cm in size, which become finer with increasing distance from the glacier into gravels with boulders around 1 cm in size. Further downstream, layers of sand are deposited into the fine gravel until the stream eventually becomes completely sandy. The trend from coarse gravels to sands reflects the decreasing carrying capacity of the water in the river.

8. Glacier retreat and colonization of deglaciated substrate

Josef Elster

Snow cover in the Arctic is closely linked to global climate change and is dependent on local temperature and rainfall. Changes in snow conditions are reflected in the local climate and hydrological parameters. On Svalbard, snow cover affects the local climatic conditions for a period of 7 to 8 months, and the duration of the snow cover depends on atmospheric circulation, warming, increasing precipitation together with the intensity of the frequency of winter rainfall and thaws (Fig. 1.8 – snow precipitation). For example, between 1958 and 2017, the period when the landscape around Longyearbyen is covered with snow was reduced from 340 to 320 days, while coastal areas were covered with snow for less than 300 days a year (Hanssen-Bauer et al. 2019).

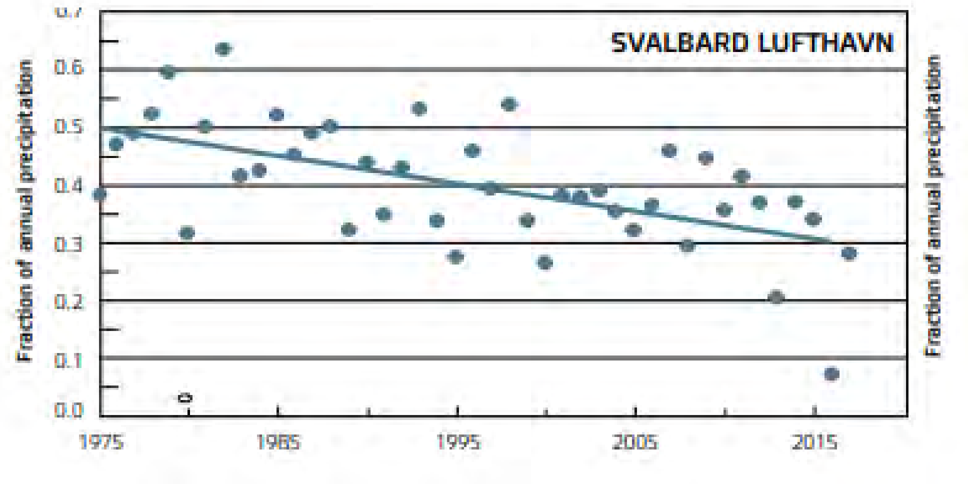


Fig. 1.8: Average annual snowfall between 1975 and 2015 measured at Longyerabyen Airport, Svalbard (Hanssen-Bauer et al. Eds. 2019).

The continental glaciers on Svalbard are a very complicated system and their long-term behaviour is conditioned by interaction with the climate. Approximately 60% of the surface of the Svalbard archipelago is covered by glaciers. About 7% of the continental glaciers have melted over the past 32 years, with an average of 0.2% per year. There has been a negative balance of ice volume in the Svalbard glaciers since about the end of the last "Little Ice Age – from the second half of the 19th century (the behaviour of glaciers on Svalbard is discussed also in chapters 5. and 16.). About 10% of Arctic continental glaciers are located on Svalbard, about 1,100 glaciers, and their area varies greatly from small valley glaciers (Fig. 2) to large plateaus and glaciers (Fig. 3.8).

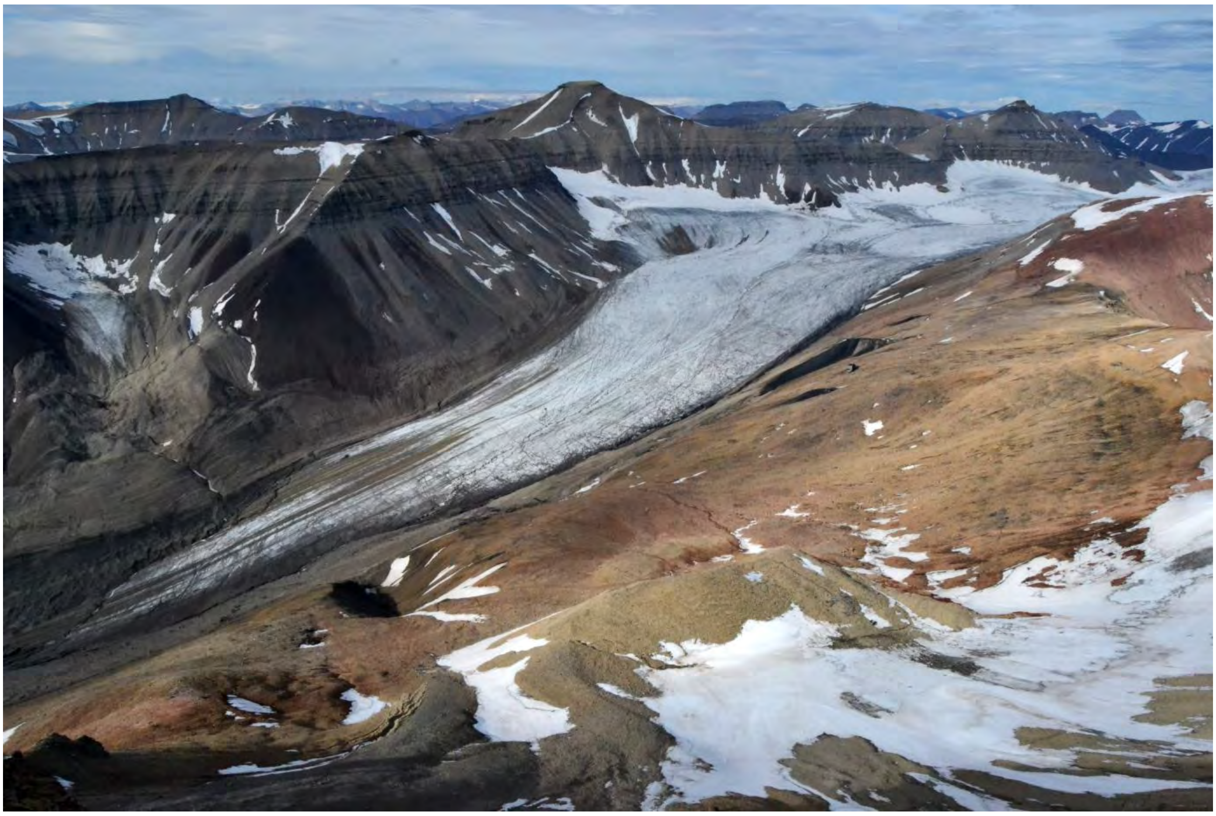


Fig. 2.8: Hørbyebreen valley glaciers, north-western Billefjorden region, central part of Svalbard (CPE archive).

Most of the glacier faces on Svalbard end on land (Fig. 4.8) and only about 15% calve directly into the sea (Fig. 5.8). However, the amount of ice that is directly transported to the sea makes up to 60% of the ice of the total ice cycle on Svalbard. Most of the glaciers on Svalbard are polythermal; the ice is made up of a mixture of cold and warm ice. General information about snow conditions and glaciers in Svalbard was drawn from the publications Hanssen-Bauer et al. Ed. 2019, and Dallmann, Ed. 2015.

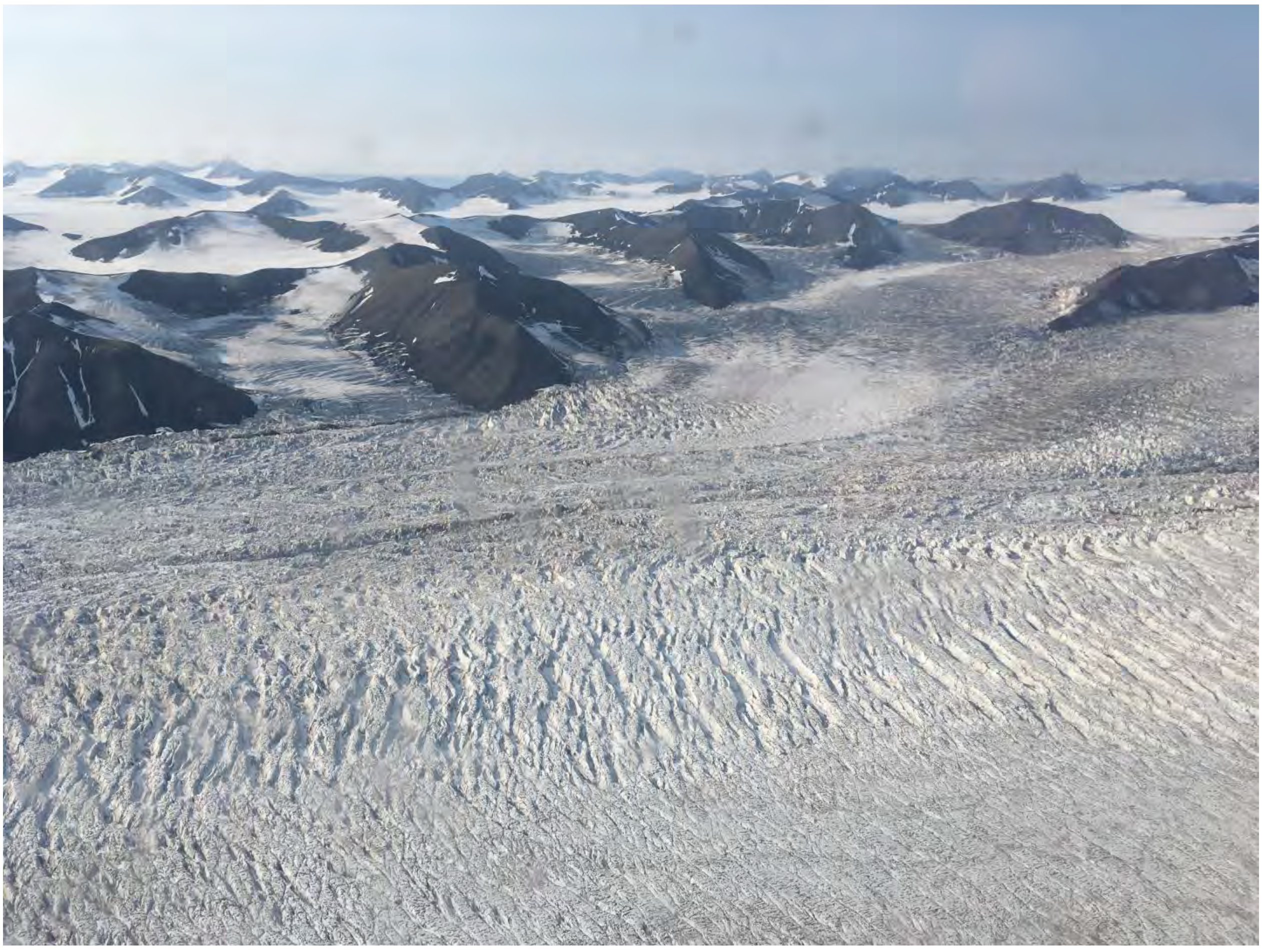


Fig. 3.8: Glaciated landscape of Oskar II Land with many nunataks protruding above the ice, western part of the Svalbard archipelago (CPE archive).

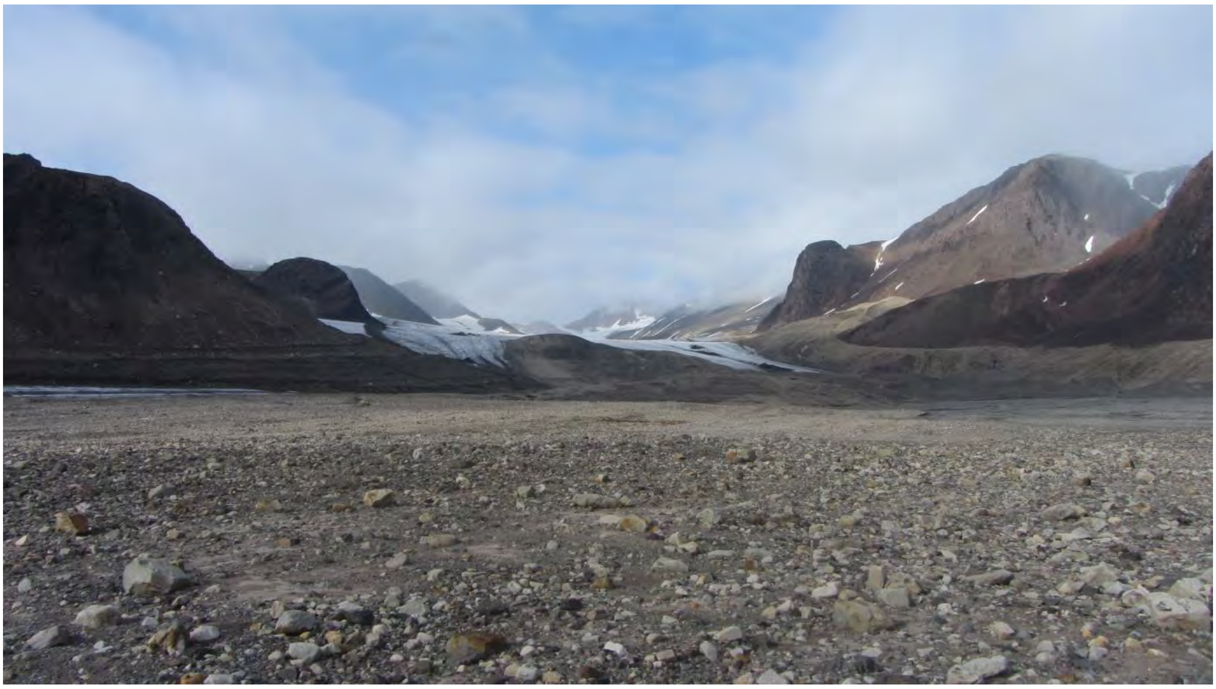


Fig.4.8: Hørbyebreen glacier foreland, north-western Billefjorden area, central part of Svalbard (CPE archive).

Fig. 5.8: Kronenebreen glacier in Kongsfjorden Bay flowing into the sea, western part of the Svalbard archipelago (CPE archive).

Glacier retreat and colonization of deglaciated substrate

On land, the most well-known and most detectable loss of ice mass is the melting of glacier faces (Fig.6.8). Aerial photographs from the first half of the twentieth century to the present show that the glacier fronts on Svalbard have melted by 0 to 100 m in one year during this period, which is an average of 30 to 40 m per year. At the same time, we have a number of glaciers on Svalbard which are characterized by a periodic shift (in periods of several months, to several years) of the ice mass in the direction of the glaciated valley. However, the glacier front is continuously melting again and creating a geomorphologically very complex and diverse periglacial – deglaciated area (Fig. 7.8). The newly deglaciated - periglacial environment is formed by a dense network of lotic (Fig. 8a.8) and lentic (Fig. 8.b.8), freshwater ephemeral and permanent, differently sized biotopes, which together with variously elevated moraines, various types of deglaciated hillocks, form a very diverse mosaic of terrestrial (Fig. 9.8) and freshwater environments. The development of these deglaciated areas is further influenced by the local regional climate, the rate of deglaciation and the type of substrate. Most newly deglaciated substrate is very unstable and prone to various geomorphological disturbances, such as landslides associated with local floods. Last but not least, lotic freshwater systems transport large amounts of sediment, which is generated by glacial abrasion. The glacial sediment is then very susceptible to further transport, both by water and wind erosion.

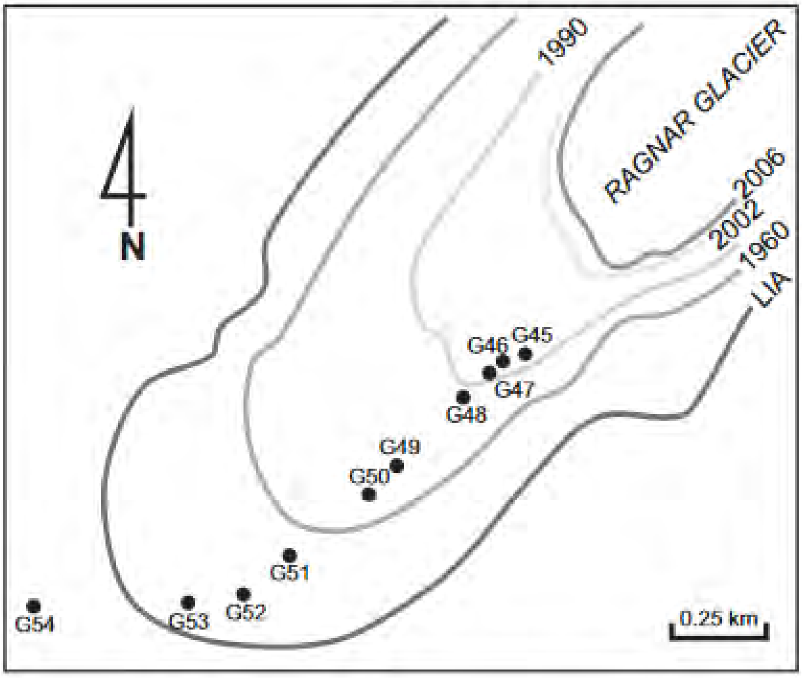


Fig. 6.8: Ragnar glacier with chronosequence of ice melting, Billefjorden bay, central part of Svalbard (Prach et Rachlewicz 2012).

Fig. 7.8: Hørbyebreen glacier foreland, north-western Billefjorden region, central part of Svalbard (CPE archive).

Fig. 8.8: (a) Glacier stream leaving Hørbyebreen glacier, Billefjorden Bay, central part of Svalbard. Glacial water is rich in transported mineral sediment. (b) Small ephemeral lakes – puddles in the foreground of the Hørbyebreen glacier, valley glacier Hørbyebreen, north-western area of Billefjorden, central part of Svalbard (CPE archive).

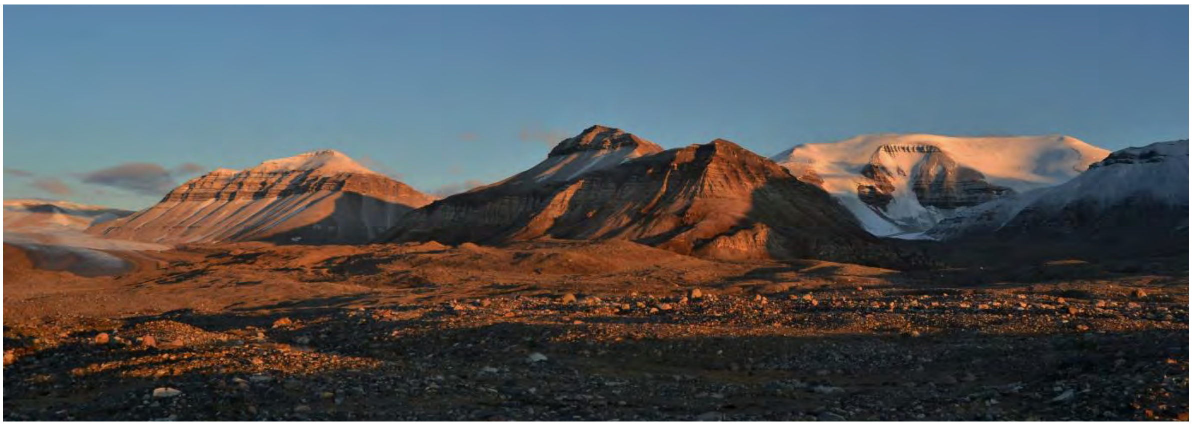


Fig 9.8: Foreground of the Hørbyebreen glacier with a mosaic of moraines (hillocks) and various wetland biotopes, Billefjorden Bay, central part of Svalbard (CPE archive).

Succession of life in newly deglaciated areas

Biological succession, migration of all species and types of organisms, is a response to changes or disturbances in the environment, both natural (e.g. retreat of glaciers – deglaciation) and caused by human activities (anthropogenic disturbance). It is an ecological concept of ecosystem changes on time and spatial scales, at both abiotic and biotic levels. In ecology, the term succession is most often used in plant ecology, but it is possible to apply the principles of succession - migration of organisms also in the microbiological and zoological fields. Ecological and theoretical principles of succession are also used in the reconstruction and revitalization of disturbed environments. However, the relationship between an environmental factor and the process of succession is very complicated and still largely unknown. More about plant succession is in the monograph (Prach et Walker 2020).

In the Arctic and Svalbard, considerable attention was paid to biogeochemical development, as well as microbial and plant succession of deglaciated areas. The process of returning life to deglaciated areas is initiated by a wide range of organisms (autochthonous - local and allochthonous - introduced). The processes of invasion of microorganisms are discussed in Chapter 16 (Anthropogenic influences on Svalbard).

Microbial communities that begin the process of biotic establishment after deglaciation are mainly represented by heterotrophic bacteria, microscopic fungi, autotrophic prokaryotic cyanobacteria and eukaryotic micro-algae. The microbial components of succession after deglaciation concentrate minerals in their cells, significantly contributing to the development of the soil horizon and the development of communities of cryptogams (bryophytes and lichens) and vascular plants. In general, when studying succession after deglaciation in the Arctic, we describe the development of the deglaciated area over time, the rate of development of biological communities (chronosequence of development) and to what final stage (climax) the biological community of a particular locality reaches. The great ecological diversity of the glacial and periglacial environments, including local point sources of mineral nutrients, including inorganic nitrogen contained in melting snow and ice, and old organic carbon reserves (originating from interglacial periods), significantly influences the development of microbial communities at specific deglaciated sites. Last but not least, the microbial communities of the glacier, those of the immediate surroundings of the glacier and the surroundings of the deglaciated area largely define the process of the onset of microbial communities in the deglaciated area.

The character of the glacier is essential for the subsequent succession of microorganisms. The retreating glacier and the water from the melting glacier bring large amounts of nutrients and microbial inoculum that has formed on the glacier. The glacier is a large factory (aquaculture) of carbon and nitrogen fixation. Thanks to this influence, succession can take place quite differently even on glaciers that are not too far apart. Another equally important influence on microbial succession after deglaciation is the participation of invasive alien species that may participate in succession in some steps of community development. The problem of invasive species (discussed in Chapter 16) is topical in Svalbard especially in areas intensively exposed to human influence, including tourism. Microorganisms participating in succession are brought to the surface of glaciers and deglaciated areas by wind, precipitation, migrating animals and birds living in the surrounding tundra and debris from the surrounding environment (mountain cliffs, walls, moraines, etc.). The most important source of inoculum of microorganisms is water, which comes from the melting glacier (flowing from sub-glacial = subglacial, glacial = englacial and the surfaces of melting glaciers – supraglacial environment). Water and microbial inoculum originating from different parts of melting glacier ice are mixed in polythermal types of glaciers. After leaving the glacial environment, the water including the microbial inoculum brings large quantities of microbial inoculum into the deglaciated environment. Glacier ablation regions are more or less freshwater systems with high primary production. The produced organic carbon and accumulated mineral nutrients make a substantial contribution in the first stages of primary succession after deglaciation. In the first phase of succession, the most important factor is the influence of the glacier and the amount of mineral nutrients and organic carbon, including the microbial inoculum, coming from the glacier. The glacier and the deglaciated area are connected by an umbilical cord; the deglaciated area supplies dust and nutrients to the surface of the glacier, while the glacier subsequently returns dust and nutrients with a large amount of microbial inoculum.

As already mentioned, the process of microbial succession is conditioned by local hydrological conditions. Ephemeral melt water of glaciers and water coming from local deposits of melting snow are water sources that determine the process of microbial succession. It is necessary to distinguish the environment:

a) **Shallow ephemeral wetlands** (lotic - flowing and lentic - stagnant), which are formed during the melting of snow and ice. These are ephemerally flooded localities where water and the amount and geological origin of the transported sediment are an important ecological parameter.

b) Another from the point of view of the availability of glacial meltwater are localities that are **limited by year-round water scarcity**, for example terrain elevations, such as the upper parts of moraines, which are formed by an easily permeable substrate for water, or other terrain elevations (drumlins - geomorphological glacial forms).

Shallow ephemeral wetlands – biotic corridors in newly deglaciated areas

Depending on the temperature parameters of the ice, we distinguish 2 basic types of glaciers in the Arctic region. At lower geographical and altitudes, these are **polythermal glaciers**, characterized by milder ice temperatures, in some cases to the point of freezing, especially in the inner parts of the glacier. This warmer part of the ice, hidden inside the glacier, is covered by a cooler layer of ice on the surface. In these types of glaciers at high-rise breaks and due to massive melting during ablation, a complicated system of glacial fissures and horizontal and vertical channels is formed that transport meltwater and glacial sediments in both horizontal and vertical directions (Fig. 10.8). Polythermal glaciers are characterized by frequent movement, which acts very abrasively on the glacier bed and causes mechanical erosion. The meltwaters of these glaciers transport a significant amount of sediment.

Fig. 10.8: Nordenskiöldbreen glacier face with many cracks, glacial faults and glacial towers, Adolfbukta, Billefjorden, central Svalbard (CPE archive).

Another type of glaciers are the so-called **cold glaciers**, which are located in Svalbard mainly at higher altitudes and at high latitudes. The main part of the glacier body is made up of low-temperature ice that is frozen to its base. This type of glacier is characterized by minimal movement and at the same time limited erosion influence on its subsoil. Glacial water flows mainly from the surface of the glacier during ablation.

The role of cyanobacteria and algae of shallow wetlands in the onset of life in deglaciated areas

Deglaciated areas of polythermal glaciers

In Svalbard in the area of Ny-Ålesund in the foreland (periglacial environment) of the East and West Brøgger glaciers, we conducted a study of the diversity and relative productivity of increasing communities of cyanobacteria and microscopic algae in 2 types of glacial streams and, for comparison, also in a stream saturated with meltwater from a snowshoe. At the same time, we analysed physico-chemical parameters of glacial and meltwater in streams. Glacial waters contained a considerable amount of drifting sediment, while the stream fed from snowfield had water without the presence of sediments, but its duration was only ephemeral – after a period of snow melting (Kubečková et al. 2001). We studied the relative productivity of the growth communities with the help of artificial carriers – specifically nylon nets 10 x 10 cm – placed in the stream streamline. The composition and relative productivity of the growth communities of cyanobacteria and algae in the deglaciated moraine determined the amount and erosive activity of glacial water drifting sediment particles.

For the study of unstable and sediment-disturbed streams, we selected 3 geologically different glacial streams: (a) a very unstable glacial stream with a high content of reddish-brown sandstone sediment, (b) a glacial stream with a high content of grey sandstone sediment and (c) an ephemeral, snow-fed creek without the presence of sediment. In all 3 types of streams, we identified a total of 40 species of phototrophic organisms – 11 species of cyanobacteria and 29 species of algae. A very unstable glacial stream with a high content of reddish-brown sandstone sediment, which disrupts the growth communities, was inhabited only by cyanobacteria (*Phormidium autumnale*, *Phormidium amoenum* and *Schizothrix* sp.).

In similar glacial streams, also disturbed by the high content of glacial grey sandstone sediment, green filamentous algae *Ulothrix* sp. This group of cyanobacteria and algae is very flexible, quickly populates new substrates even in highly unstable and disturbed environments and participates in the settlement of streams in the newly deglaciated environment of polythermal glaciers. In the analysed data, no statistically significant relationship was found between the occurrence of cyanobacteria and algae depending on the physicochemical properties (temperature, pH, conductivity, NO_3-N, NH_4-N and $P0_4$-P) of glacial or meltwater from snowshoes. A statistically insignificant relationship was found between cyanobacteria and algae and inorganic nitrogen (NO_3-N) content. Cyanobacteria and some algae are very flexible organisms, able to inhabit a very unstable and sediment-disturbed environment of glacial streams.

Deglaciated areas of cold glaciers

On of Ellesmere Island in the high Canadian Arctic, a study of the onset of life in a glacial stream on the deglaciated area of the cold Teardrop Glacier was conducted on an ecological model of cyanobacteria and algae studies (Elster et al. 1997; Elster et Svoboda 1996; Elster et Svoboda 1995, In: Jenkins, Ferrier et Kirby Eds.). In the central part of the island of Ellesmere (across the island from east to west) is the deglaciated valley of the Sverdrup Pass, in the middle of which University of Toronto professor Josef Svoboda set up a scientific station where he conducted research with his students. One of their projects was aimed at studying the onset of life after deglaciation in glacial streams in the foreland of the Teardrop Glacier. It was found that the section of the stream flowing through the newly deglaciated moraine is populated by a variety of cyanobacteria and algae, which create visible biomass here, and that the section farther from the glacier front, which was deglaciated more than 100 years ago, is already completely populated with vegetation of vascular plants and bryophytes.

Physico-chemical analyses of glacial water have shown that there is sufficient inorganic atmospheric nitrogen (NO_3-N) in the newly deglaciated moraine and that its content decreases rapidly with distance from the glacier. Based on the ratio between the content of inorganic nitrogen and reactive phosphorus, it has been shown that in sections further from the glacier front, which are already fully covered with vegetation, the development of cyanobacteria and algae is limited by nitrogen deficiency. Verification of the limitation of the development of microscopic cyanobacteria and algae by inorganic atmospheric nitrogen was carried out with the help of a manipulation experiment, within which 3 artificial streams (about 70 m long) were built, which were fed only by glacial water, by water with the addition of nitrogen and subsequently also by water with the addition of a mineral medium for the cultivation of microscopic cyanobacteria and algae. This manipulation field experiment proved that the development of cyanobacteria and algae is conditioned by the presence of inorganic atmospheric nitrogen: the microorganisms sought occurred in the lower parts of artificial streams only in artificial ditches with the addition of nitrogen and mineral medium; In a ditch with glacial water, the development of cyanobacteria and algae was recorded only in the first meters of the artificial stream.

The study of settlement of newly deglaciated areas has shown that glacial streams of both polythermal and cold types of glaciers create corridors of onset of life after deglaciation. And some of the first organisms that participate in the process of the onset of life in the newly deglaciated sites are microscopic cyanobacteria and algae.

In addition to shallow ephemeral freshwater flowing systems, there are various large and deep glacial lakes in the periglacial environment (more in Chapters 7. and 10.) and shallow ephemeral wetlands – periodic pools, puddles and small lakes – also periodically develop. The shallow lotic and lentic wetlands of periglacial areas mostly dry up and freeze out in winter, while large and deep glacial lakes and some larger glacial rivers or streams may contain liquid water throughout the winter. Lentic shallow ephemeral wetlands in deglaciated areas of both polythermal and cold glaciers create a complicated wetland mosaic with varying duration of meltwater presence, glacial sediment content, physico-chemical water parameters and settlement by microorganisms. We can find small lakes inhabited by large biomass of cyanobacteria and algae, so example filamentous cyanobacteria and algae (Fig. 11.8) which represent very diverse communities from the taxonomic point of view.

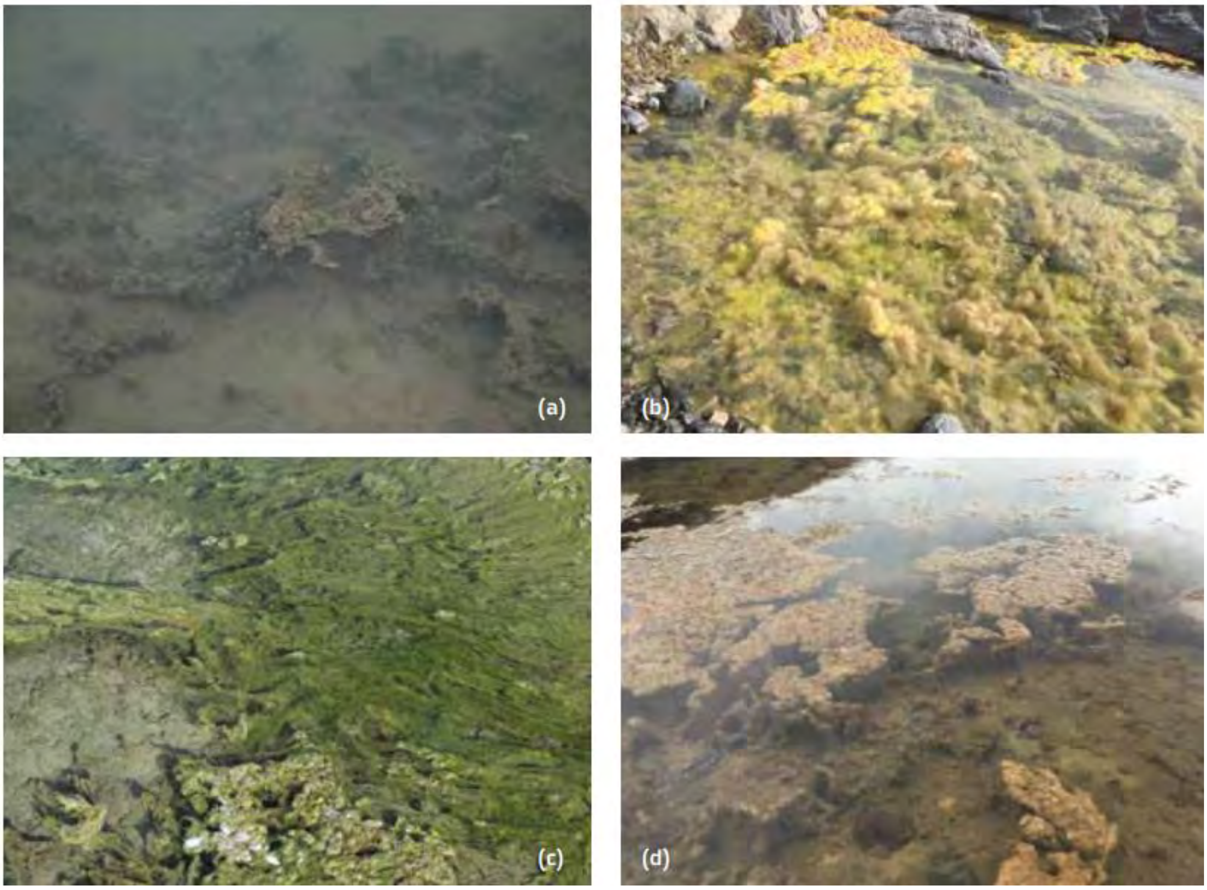


Fig. 11.8: Shallow flowing and stagnant wetlands in the periglacial environment of the glaciers on Svalbard are inhabited by a wide range of cyanobacteria and algae, which very often create visible biomass here. From the taxonomic point of view, these are species-rich communities, with the largest biomass in cyanobacterial localities being formed by (a) filamentous cyanobacteria of the Oscillatoriales group, which are often accompanied by epiphytic diatoms. Of the fast-growing green filamentous algae, the most common are representatives of filamentous algae from group of Conjugatophyceae , (b) *Zygnema* sp., (c) genus of filamentous charophyte green algae *Klebsormidium* sp. and also (d) a brownish-yellow algae from the group Xanthophyceae *Tribonema* sp. (CPE Archive).

In some ephemeral puddles, which heat up quickly in summer, we can find a very specific algae *Haematococcus pluvialis* in terms of potential biotechnological use (Fig. 12.8). Ephemeral pools and puddles with a high content of glacial mineral sediment covering the bottom, which are very unstable from the point of view of colonization by microorganisms, represent very poor types of shallow wetlands in terms of cyanobacteria and algae occurrence.

Fig.12.8: Shallow pools or puddles in the foreground of glaciers, which warm up rapidly for a short time in summer, may be populated by the biotechnologically important and specific algae *Haematococcus pluvialis* (CPE Archive).

The role of cyanobacteria in the development of newly deglaciated soils

A good example of the process of onset of life on newly deglaciated soils (biological soil crusts) is a detailed molecular genetic study of the chronosequence of cyanobacterial diversity on deglaciated soils of several glaciers in the central part of Svalbard in Billefjorden Bay (Pessi et al. 2019). This study was strictly focused on locations that are limited by water scarcity all year round, i.e. on terrain elevations. Melting meltwater from glaciers supplies these sites only for a relatively short period of time, when they are close to the melting glacier or rise above the surface of the glacier in ablation areas. The most numerous organisms that participate in the onset of life after deglaciation are oxyphototrophic prokaryotic cyanobacteria.

Prokaryotic cyanobacteria are evolutionarily very old (their origin dates back to the beginning of the evolution of life on our planet, i.e. to the period about 3.5 billion years ago) photosynthetic bacteria that laid the foundations of all photosynthetic plants. In addition to oxygen photosynthesis, cyanobacteria are also able to bind nitrogen in the air, and thus, in addition to contributing to the functioning of the carbon cycle, they also significantly contribute to the nitrogen cycle. Cyanobacteria are also a common and important component of the glacial ecosystem, in which they play a vital ecological role. Last but not least, cyanobacteria are extremophilic microorganisms, i.e. very well adapted to life in a variety of extreme environments, especially in polar and alpine conditions, because they thrive in very diverse temperatures, including stresses associated with drying out, alternating periods of freezing and high salinity (halophilia, alkalophilia, high radiation or chemically toxic environment; Elster et Kvíderová 2014).

In the study of cyanobacterial succession (Pessi et al. 2019) on newly deglaciated soils during 100 years of return of life on Svalbard, methods of epifluorescence microscopy and sequencing of cyanobacterial 16S rRNA were used. The development of cyanobacterial communities in the deglaciated area was characterized by a decrease in their biological diversity for the first 10 to 20 years after deglaciation, in the following 30 to 100 years the decrease in diversity continued. Changes in cyanobacterial diversity in the succession gradient were associated with the time of deglaciation and the chemical composition of the deglaciated substrate (water content, organic carbon, soil mineral nitrogen NO_3-N and NH_4-N, potassium K and sodium Na). The diversity of cyanobacteria in the first 10 to 20 years after deglaciation was mainly associated with new genotypes that are stored in the central gene bank or with genotypes known mainly from polar and alpine environments. The genotypes of cyanobacteria from the first 10 to 20 years after deglaciation come mainly from the environment of melting glaciers, while the genotypes of cyanobacteria from the later stages of succession of 30 to 100 years come from genotypes that are widely distributed globally. The study showed that the ablation regions of polythermal Arctic glaciers create an ideal environment for cyanobacterial aquacultures to develop.

Microbial succession – settlement of newly deglaciated areas

The previously mentioned research, which we conducted in the past on Svalbard, is very well followed by the published report Pothula et Adams 2022, which summarizes the results of the study of chronosequence of succession of microorganisms after deglaciation from 95 published scientific articles from a wide range of locations of polar and alpine regions. The study does not show a difference between the onset of life in shallow ephemeral wetlands and in sites that are limited by water scarcity for most of the year. This large summarization study covers the entire spectrum of microorganisms (bacteria, photosynthetic and invertebrate microorganisms) that participate in the process of succession after deglaciation and shows that there are 2 basic models of settlement of the deglaciated area.

1. According to the first model, some taxonomic groups increase their abundance and biological diversity throughout the development of the local ecosystem (chronosequence) up to the climax stage.
2. The second model of micro-organism succession documents an initial increase in the frequency and diversity of microorganisms (see, for example, the study of cyanobacterial chronosequence) followed by a decrease influenced by the depletion of resources, especially minerals and melt glacial water, and the subsequent competition between the components of the microecosystem.

Chronosequence of soil development after glaciers retreat in polar and alpine regions

The total carbon content and total organic carbon content of deglaciated soils gradually increase with the time of deglaciation up to about 100 years after deglaciation. After this period, the carbon content of the deglaciated soil begins to increase dramatically. The microbial carbon content gradually increases within the chronosequence of deglaciated soil development. The content of total nitrogen in deglaciated soil gradually also increases with time, ammonium (NH_4-N) and nitrate (NO_3-N) nitrogen increase up to 500 years after deglaciation, then subsequently decrease. The content of available phosphorus increases within the chronosequence of deglaciation while the content of total potassium decreases with deglaciation for 50 years after deglaciation before subsequently increasing in the following period. As with potassium, the water content decreases in the first 50 years after deglaciation and then subsequently increases. Conductivity values show a similar trend, being high in the first 50 years, then decreasing thereafter. pH values decrease depending on the time of deglaciation.

Succession of vascular plants, bryophytes, lichens, microorganisms and invertebrates in polar and alpine regions after glaciers retreat

Vegetation cover and the diversity of vascular plants, bryophytes and lichens increases with the development of the deglaciated area in relation to the biological development of soils.

The most common heterotrophic bacteria of newly deglaciated soils are the taxonomic groups Proteobacteria, especially Alphaproteobacteria, Actinobacteria, and Acidobacteria. The frequencies of Actinobacteria, Chloroflexi and Planctomycetes increase rapidly during the first 50 years after deglaciation before subsequently decreasing. On the other hand, for example, the frequency of Bacteroidetes, Proteobacteria and Betaproteobacteria significantly decreases within the temporal chronosequence after deglaciation.

Ascomycota and Basidiomycota are frequent representatives of microscopic fungi in the period of soil development after deglaciation, with their frequency increasing in the first 50 years after deglaciation. Subsequently, their frequency decreases. The frequency of Zygomycota increases throughout the entire period of deglaciated soils development, even after the first 100 years. The molecular diversity of microscopic fungi increases up to 100 years after deglaciation then subsequently decreases.

A very common component of the soil of deglaciated areas is omnivorous nematodes, whose frequency after deglaciation varies depending on the type of food to which they are bound. Plant-dependent nematodes increase in abundance with plants presence, while nematodes food-bound to bacteria increase in frequency in the first 50 years after deglaciation before decreasing. The abundance of nematodes food-dependent on microscopic fungi increases in the first 50 years after deglaciation then subsequently also decreases, while the abundance of omnivorous nematodes increases in the first 100 years after deglaciation and then decreases.

Collembola – Springtails, Acari - Mites and small earthworms - Enchytraeidae increase their frequency in relation to the development of the deglaciated area. Springtails very often live in all types of deglaciated soil and on the surface of melting glaciers. Spiders (Araneae) and beetles (Coleoptera) increase their representation in deglaciated habitats until about 50 years after deglaciation, after which their frequency stagnates or even decreases.

The development of deglaciated areas consists of a gradual increase in the biodiversity and abundance of the microbial and invertebrate components of the ecosystem together with the content of mineral nutrients (carbon, total nitrogen, available phosphorus). The gradual increase in frequency and diversity as well as substrate development model after deglaciation are linked to the development of vegetation. Some representative species increase their frequency and diversity especially in the first 50 years after deglaciation, then their frequency and diversity subsequently stagnate or even decrease. In some cases, this reaction is associated with the gradually decreasing pH of the deglaciated substrate, decreasing availability of minerals and increase in vegetation, which may lead to greater competition for resources and space.

9. Relationships of organisms in soil and soil crusts

Josef Elster and Miloslav Devetter

Soil crusts

Soil crusts, both abiotic and biological (Fig. 6.9) are an important structural part of the soil surface in arid and semi-arid regions of the world (Belnap et Lange 2001). Their presence contributes to the characterisation of the soil surface and plays an important role in a wide range of ecosystem functions of the soil surface. It is the surface layer of the soil, which differs from the rest of the loose soil, often by a hardened plate surface. **Abiotic soil crusts (ASCs)** are transitional layers of soil surface ranging from less than 1 mm to several cm thick, which are at the same time structurally different from the material immediately below. **Biological soil crusts (BSCs)** are formed by communities of microorganisms that live on the soil surface and perform an important ecological role (including carbon fixation, nitrogen fixation and soil stabilization), altering soil albedo and water relationships, and affecting germination and nutrient levels in vascular plants. Like abiotic soil crusts, they reach a minimum thickness in very locally climatically extreme habitats. On the other hand, in more favourable conditions they reach a thickness of up to several cm. A sharp boundary between abiotic and biological soil crusts does not exist. Both types of soil crusts include living organisms. In abiotic soil crusts, the structure is formed by physico-chemical processes, while in the case of biological soil crusts, organisms populating the soil surface form the structure.

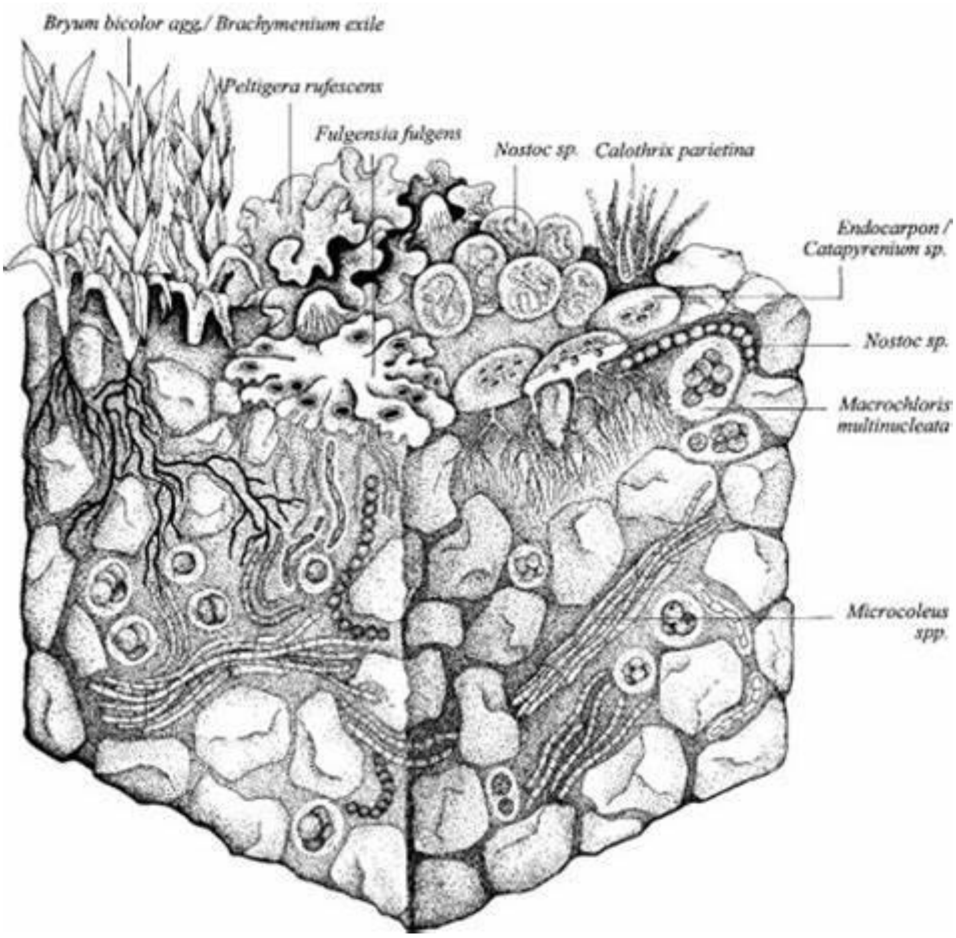


Fig. 6.9: Biological soil crusts (BSCs) form a surface layer of soil that is structurally different from the material immediately below. It consists of a surface substrate and communities of microorganisms (cyanobacteria, algae, microscopic fungi and bryophytes) in varying proportions (Belnap et Lange 2001).

Abiotic soil crusts (ASCs)

In polar arid and semiarid regions, it is primarily the microclimatic conditions on the soil surface that contribute to the formation of abiotic soil crusts. Due to its colour, the soil surface absorbs long-wave solar radiation, which both dries the soil surface and heats it up. At the same time, due to air flow over the soil surface, air moisture is quickly blown away from the soil surface. Due to the drying and heating of the surface layer of the soil, soil moisture rises to the surface of the soil and, at the same time, salts are carried out and accumulate on the soil surface. A good and simple example is the turning of stones lying on the surface of the soil in arid and semi-arid Polar Regions: we often find a visible layer of precipitated salts on the lower hypolithic diet of the stones, which is also found on the surface of the soil. A possible verification of whether the surface layer of the soil is formed by soil organisms or precipitated salts is a tactile test: if the surface of the soil consists of fine crystals and is rough to the touch, then it is precipitated salts. Precipitated salts participate in the formation of abiotic soil crusts and, at the same time, increase the chemical extremeness of the soil surface in terms of physical and chemical properties. The presence of an abiotic soil crust can seal and smooth soil surfaces, reducing rainfall infiltration and increasing the volume and rate of runoff, while simultaneously ASCs can prevent the expansion of vascular plant vegetation. Other physical factors that can contribute to the formation of abiotic crusts are precipitation, possibly pressure from treading or vehicle wheels.

Biological soil crusts (BSCs)

Biological soil crusts, otherwise called cryptogamic soil crusts, are structures on the soil surface that are formed by communities of microorganisms, most often from prokaryotic cyanobacteria, eukaryotic algae, fungi, lichens and bryophytes in varying proportions (Fig. 6.9). The soil particles in this surface layer are aggregated by communities of these highly specialized organisms. BSCs are mainly found in open spaces in dry and extremely cold regions, including a large part of the Arctic region (Fig. 7.9) including Svalbard (Pushkareva et al. 2016), where extreme climatic conditions prevent the growth of vascular plants. Due to the high biological diversity and demanding environment that soil surface microorganisms inhabit, a BSC can be an "evolutionary oven", which creates the conditions for new adaptations and the creation of new genotypes adapted to the special extreme soil surface environment. The study of ecological and genetic variability of microorganisms inhabiting a BSC ecosystem provides insight into adaptive diversification and the functioning of the soil ecosystem (Elster et al. 1999). In many regions of the Arctic, soil crusts are extremely well developed (Fig. 8.9) and may represent more than 70% of the living soil cover. BSCs are key to soil stabilization, water retention and soil fertility. Biological components of soil crusts include cyanobacteria and other bacteria, microscopic fungi, algae, lichens, and bryophytes. Cyanobacteria and green algae are generally the first organisms to colonize bare soil followed by lichens and mosses, which require a stable soil surface for growth. Filamentous cyanobacteria of the genera *Microcoleus* and *Leptolyngbya*, commonly found in soil, secrete a sticky slime around their filaments. When wet, they move through the soil, leaving behind a trail of sticky slime material that sticks soil particles together to form a lumpy soil structure. This roughened soil surface increases rainfall infiltration, reduces the volume and rate of water runoff, and retains seeds and organic matter. To the touch, the surface of a BSC is smooth and slimy, and the tactile inspection is a suitable and quick method to classify whether it is a biological or abiotic type of soil crust.

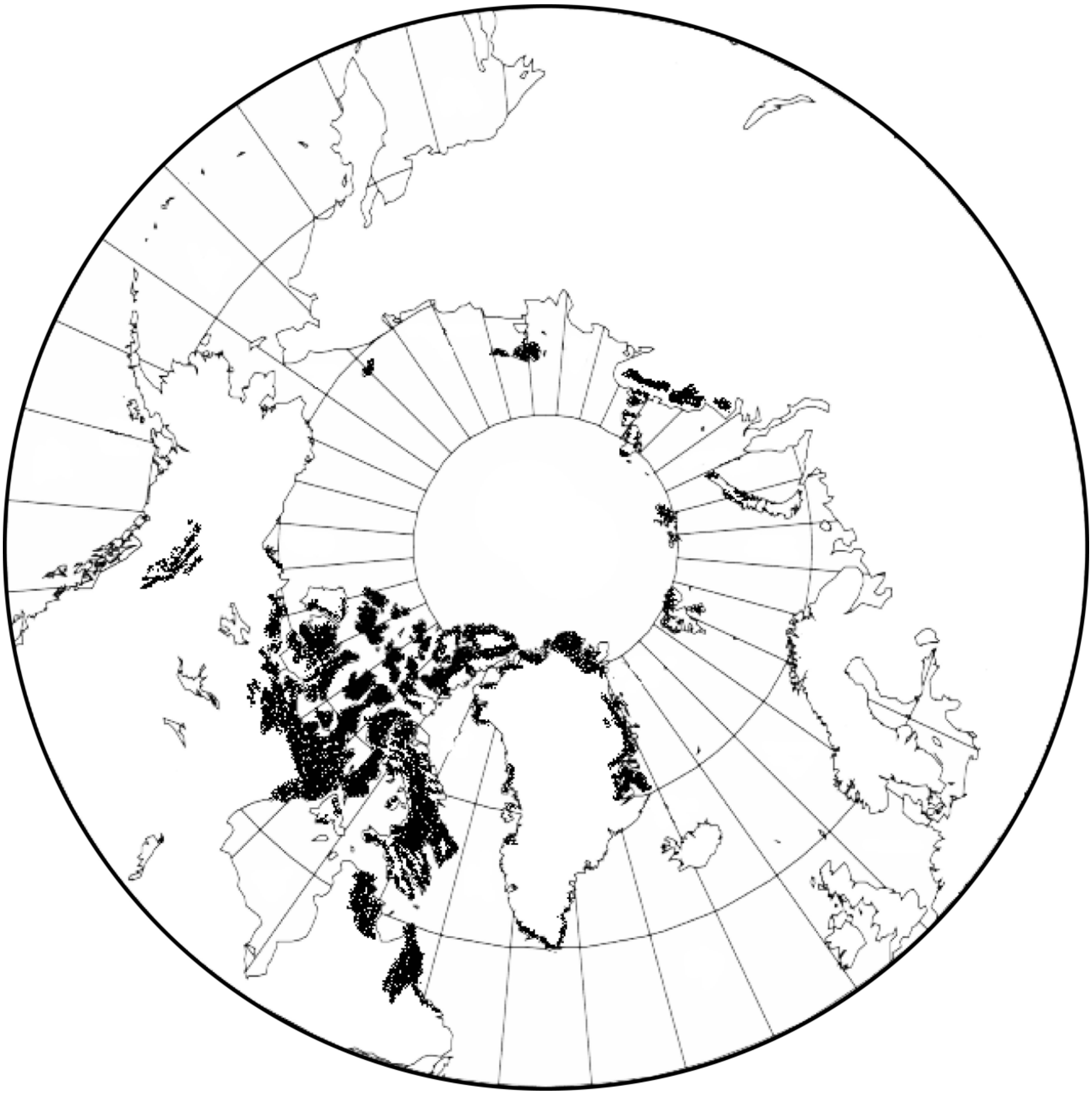


Fig. 7.9: Map of BPK distribution in the Arctic region (Pushkareva et al. 2016).

Fig. 8.9: BSCs together with the vegetation of bryophytes and vascular plants forms a complicated mosaic of the environment, Petuniabukta Bay, Billefjorden, Central Svalbard (CPE Archive).

Climate change and the ecological importance of biological soil crusts

In the High Arctic, BSCs are the main food source for many invertebrates (Pointing et al. 2015) and the first land surface colonizers to emerge after glacier retreat (Pushkareva et al. 2015, 2016). BSCs are of global biogeochemical importance, because they account for about half of atmospheric nitrogen fixation on land (Weber et al. 2015). These communities are also important ecosystem engineers and control many other processes such as soil stabilization, water infiltration, and soil temperature regulation (Pointing et Belnap 2012) through the interaction between minerals, cells and organic polymers that form 3-dimensional mat-like structures (Elbert et al. 2012). Importantly, BSCs facilitate colonization by higher plants by providing nutrients and carbon to the soil and promoting seed germination (Borchhardt et al. 2017). As global warming is amplified in the Arctic (IPCC 2013) and leads to widespread and often dramatic melting of glaciers, BSCs are predicted to facilitate the “greening of the Arctic” (Pointing et al. 2015), i.e. a phenomenon associated with increased BSC biomass coverage and subsequent onset of shrub tundra (Myers-Smith et al. 2015). Coupled climate-vegetation models predict a potential redistribution and expansion of vegetation across the Arctic, with at least half of the vegetation areas expected to shift to a different physiognomic state (Pearson et al. 2013). Global climate models of vegetation discharge are inherently only expert estimates (IPCC 2013), whose predictive power also depends on how well micro- and meso-scale changes in biomass and BSC function can be estimated.

Classification of biological soil crusts

The ecological diversity of BSCs is considerable and corresponds to the diversity of microclimatic and geochemical parameters of the soil surface environment. The diversity of BSCs positively affects the structural diversity of vascular plants, because, with the development of the biological community of a BSC, there is a gradual increase in the soil content of organic carbon and mineral nutrients, which are subsequently used by vascular plants and a rich community of soil consumers.

Cyanobacteria and algae of biological soil crusts

The phototrophic microorganisms (cyanobacteria and algae) of a BSC are especially important in the early stages of soil colonization. A low biomass of cyanobacteria and algae is associated with a colourless or mineral coloration of the soil surface. With a higher representation of cyanobacteria and algae on the soil surface, the area covered by different coloured surfaces increases, including areas lichenized or covered with mosses. The cyanobacterial and algal components of BSCs inhabit the upper few centimetres of soil (Elster et al. 1999, Pushkareva et Elster 2013). One of the ecologically simple approaches to the classification of BSCs is the evaluation according to the character, colour of the soil surface, and the frequency and diversity of cyanobacteria and algae. On this basis, 3 types of soil crusts were specified in the central part of Svalbard in Petuniabukta Bay: 1. black-brown soil crusts (with low diversity of cyanobacteria and algae), 2. brown soil crusts (with high diversity of cyanobacteria and algae) and 3. grey-brown soil crusts (with low diversity of cyanobacteria and algae). The occurrence of similar types of soil crusts was compared at different altitudes, which found that altitude did not affect the biodiversity of cyanobacteria and algae, but it did affect their abundance, which increased with altitude (Pushkareva et Elster 2013). Soil crusts found in conditions with high water content are often dominated by cyanobacteria from the group *Nostoc* sp. The study also confirmed that the dark colour of soil crusts is due to the density of organisms and the dark colour of cyanobacteria, lichens and bryophytes. Another option for evaluating the coverage and microbial diversity of the soil surface is the measurement of the photosynthetically active surface area of the soil surface using chlorophyll fluorescence followed by microscopic (stereomicroscopy and light microscopy) analysis of the diversity of the marked photosynthetically active sites of the soil crust surface. BSCs have considerable photosynthetic potential – their water content and temperature positively influence their photosynthetic activity. In most cases, cryptogamic crusts were dominated by cyanobacteria such as

Gloeocapsa sp., *Nostoc* sp., *Microcoleus* sp., *Scytonema* sp. and *Chroococcus* sp. The dominant green algae were *Coccomyxa* sp., *Hormotila* sp. and *Trebouxia* sp., which were commonly found in lichenized soil crusts (Pushkareva et Elster 2013).

Ecophysiological properties and diversity of cyanobacteria in different stages of soil crust development

As part of our BSCs research in Svalbard, we also studied soil crusts – from poorly developed, unstable crusts, often disturbed by water erosion, to lichenized stable crusts that reach a climax stage in the Petuniabukta Bay environment. We established a gradient of 4 stages of soil crust development – from poorly developed to very well developed – and analysed the molecular diversity of cyanobacteria 16S rRNA on this gradient of soil crust development (Pushkareva et al. 2015). Analyses of cyanobacterial sequences revealed the dominance of taxonomic groups belonging to the orders Synechococcales, Oscillatoriales and Nostocales. The most dominant taxonomic groups in the 4 studied localities were related to filamentous cyanobacteria from the group *Leptolyngbya* sp. The species diversity of cyanobacteria in the studied development types of soil crusts gradually increases from poorly developed and often disturbed soil crusts to moderately developed soil crusts. On the contrary, the diversity of cyanobacteria rapidly decreases in well-developed lichenized soil crusts. The values of pH, ammonia nitrogen and organic carbon in the soil crust environment were correlated with the structure of cyanobacteria communities.

The microbial community of cyanobacteria in BSCs ensures photosynthesis and fixation of atmospheric nitrogen. Within the study of cyanobacterial biodiversity on the BSC development gradient, the rate of photosynthesis in the diurnal cycle and the rate of fixation of atmospheric nitrogen were simultaneously measured (Pushkareva et al. 2017). The wet biomass of cyanobacteria and algae was estimated based on the estimation of the rates of photosynthesis and fixation of atmospheric nitrogen in the gradient of BSC development. The lowest wet biomass of cyanobacteria and algae was found in poorly developed soil crusts due to the initial phase of soil colonization. The gradient of soil development from poorly developed to well-developed soil crusts was accompanied by a change in the rates of photosynthesis and fixation of atmospheric nitrogen. The wet biomass of cyanobacteria and algae increased during the development of BSCs but decreased in the last climax lichenized stage. The rate of fixation of atmospheric nitrogen, on the other hand, was the largest in the initial stage of BSC development and gradually decreased with the age of the BSC. The diurnal course of photosynthetic activity differed between soil crust types showing shifts in the daily minima and maxima; poorly developed soil crusts responded more quickly to changes in temperature and photosynthetically active radiation (PAR). Despite the different microclimatic conditions during the measurements, temperature was the main factor affecting photosynthetic activity, while the effect of PAR was not significant. Higher temperatures led to inhibition of photosynthetic activity and increased dissipation of solar energy, indicating acclimatization/adaptation of soil crust photosynthetic microorganisms to a cold environment.

Soil microbial richness and activity in an altitudinal gradient

Another study dealing with dependence of the ecological role of BSCs in the arctic ecosystem on altitude and soil type (brown and tundra) clarified the spatial heterogeneity of edaphic soil properties (temperature regime, content of organic substances, availability of basic cations, moisture, pH) and their microbial activity and diversity (potential microbial respiration, microbial biomass and microbial community structure using phospholipid fatty acid or PLFA analyses; Kotas et al. 2018). During the research, a significant spatial heterogeneity of edaphic properties was found between sites at different altitudes, notably at the transition from sites with tundra-type soils with vascular plant communities to brown soils covered only with soil crusts. Surprisingly, the microbial biomass of the soil community was not different depending on the altitudinal gradient, while a large variability in the microbial community structure was found depending on the altitude. In tundra habitats with the presence and high soil coverage of vascular plants at lower altitudes, the microbial community was rich mainly in microscopic fungi and heterotrophic bacteria. At sites at higher altitudes with a predominance of BSCs, the bacterial community was represented mainly by cyanobacteria. The BSCs (brown soil type) community without the presence of vascular plant vegetation at higher altitudes hosts a microbial community of a size and activity comparable to the arctic tundra ecosystem (a tundra soil type with high coverage of vascular plants). The key environmental factors that determined changes in the size and activity of the soil microbial community were soil pH, organic carbon content, soil moisture and Mg_2^+ availability (Kotas et al. 2018).

Specific soil of bird cliffs

Bird cliffs represent a very unique habitat. They are some of the oldest sites in terms of uplift from the sea or deglaciation, although they are constantly changing due to instability of the rocks (they are covered by rock that weathers from the cliff), and above all, some of the richest sites in terms of nutrient supply. Especially thanks to the nutrients derived from seabirds, the soils below bird cliffs are a centre of biodiversity both in terms of vegetation and soil regeneration (Fig. 9.9). Steep slopes are ideally exposed to the summer sun, so they are also the warmest places in the landscape (Fig. 10.9). In the short term, the soil temperature here can rise to around 30 °C, even on the northern slopes. The soil contains a relatively large amount of organic matter, mainly in the form bound to inorganic particles. A characteristic species of these habitats is the striking yellow Arctic springtail *Megaphorura arctica*, which forms aggregations of up to several thousand individuals (Fig. 11.9). Bird cliffs are nevertheless a centre of biodiversity for many other groups of soil fauna, for example earthworms (Enchytraeidae; Schlaghamerský et Devetter 2019).

Fig. 9.9. Bird cliffs are romantic places with the most developed vegetation and rich soil communities (Devetter).

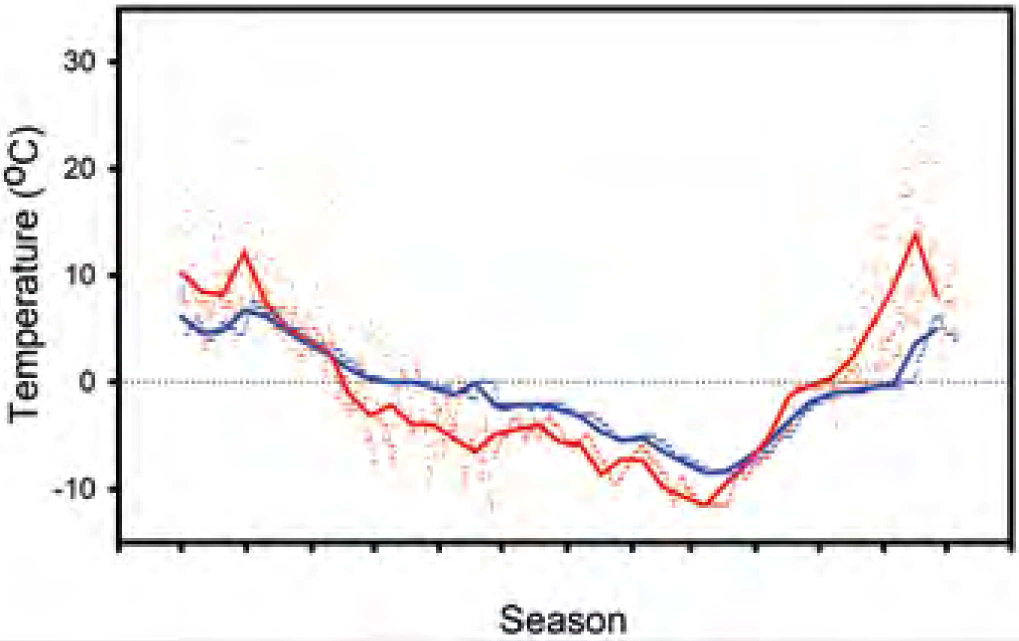


Fig. 10.9: Seasonal temperature changes in the soil under the bird cliff in Skansbukta. Red at a depth of 10 cm below the surface, blue at a depth of 1m below the surface. The line represents the floating average for 24 hours, the dots represent individual measurements (Devetter unpublished).

Fig. 11.9: The Arctic springtail *Megaphorura arctica* is a typical inhabitant of habitats under bird cliffs, where there is often such an accumulation of individuals in one place (Devetter).

Development of soil crusts

The character of BSC is also closely related to the age of the substrate. While on a recently exposed surface in the forefield of a glacier the crusts are poorly developed, on several hundreds of years old substrate they can be developed in terms of strength and the amount of organic matter contained, which is a suitable measure of the degree of development, and clearly structured. Crusts are also often found on periodically disturbed surfaces (for example, riverbeds or boiled soils - Fig. 13.9). On developmentally older sites, crusts are gradually replaced by vascular vegetation, and available moisture plays a significant role in their development. Consumers are also an important part of BSCs: microbivorous soil nematodes (Nematoda) are the leading group in all crust types, and other food strategies are added in more developed types. Also, rotifers (Rotifera) occur here very often already from the earliest stages of succession. In developed BSCs, Tardigrada, soil mites (Acari) and springtails (Collembola) are also found (Fig. 14.9). The abundance of many groups can be higher in crusts than in developed soil covered with tundra vegetation (Devetter et al 2021). Like most locations in the Arctic, crustal soil is significantly limited in nutrients. A local increase in the amount of available nutrients can therefore be clearly visible on vegetation from a distance (Fig. 15.9).

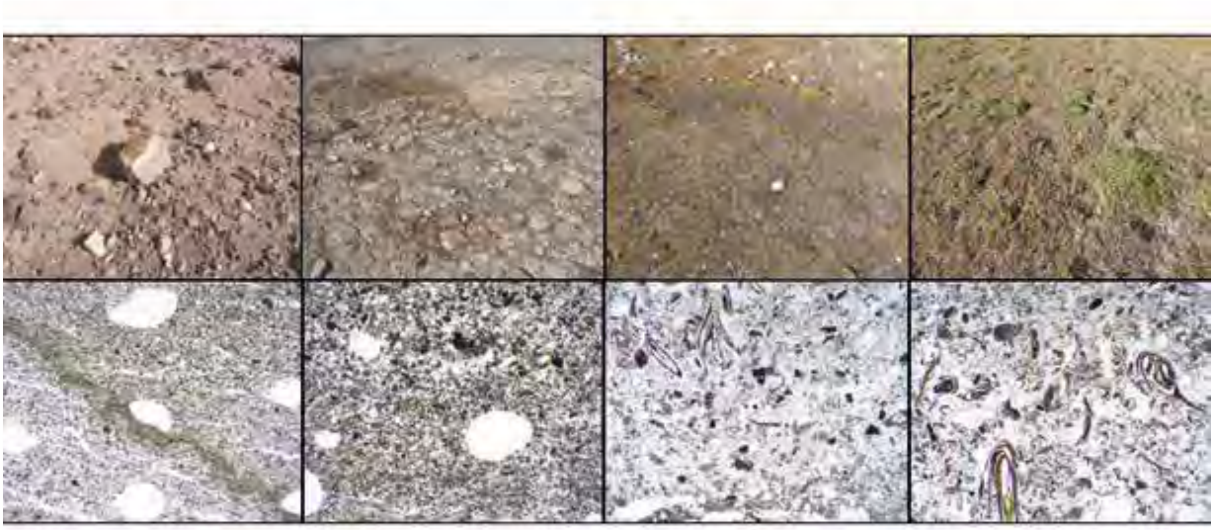


Fig. 12.9: Development of the soil surface on a successional gradient after a glacial retreat. Habitat tens, hundreds, thousands and ten thousand years old. Below, ground cuttings from the same locations, 100x enlarged (Devetter).

Fig. 13.9: Boiled soils are created by selective freezing. A fine fraction of soil remains in the centre of the polygon, while stones accumulate at the edges, so the soil does not move from here, allowing perennial vegetation to establish, such as *Dryas octopetala* in the photo (Devetter).

Fig. 14.9: Community of seasonally waterlogged tundra in a place where there was a local supply of nutrients in the past - usually in the form of a dead animal. The place is recognizable even after decades (Devetter).

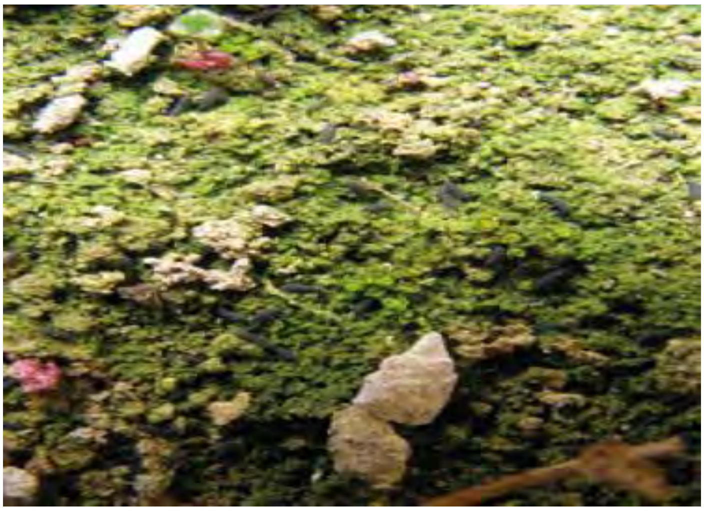


Fig. 15.9: Algal crust on the soil surface under a bird cliff with a strong supply of nutrients from bird excrement. A large community of springtails feeds on algae (Devetter).

Fig. 16.9: Tracks of human techniques stay in the tundra clearly visible for many decades. (Devetter).

10. Life in wetlands, lakes and streams

Miloslav Devetter, Linda Nedbalová and Josef Elster

Diversity of cyanobacteria and algae

Cyanobacteria and eukaryotic algae are the most important primary producers of Arctic freshwater biotopes (Elster, 2002), but our knowledge of the diversity of cyanobacteria and algae in the Svalbard archipelago is very superficial (Skulberg 1996, Kvíderová et al. 2015).

While some cyanobacterial and algal groups inhabit several different habitat types, some species and groups specialize in only one (Fig. 1.10) Komárek et al. 2012). A detailed molecular genetic study showed that filamentous cyanobacteria of the genus *Phormidium* originating from different habitat types in the central part of Svalbard cannot be distinguished on the basis of morphological characteristics, but are genetically (based on 16S rDNA and 16S-23S rDNA) divided into several ecotypes; for example, isolates from freshwater lakes and wetlands where water is available throughout the summer differ from the group that usually occurs in rapidly drying habitats. Another genetically distinct ecotype is formed by a group that prefers to inhabit very cold habitats, such as the surfaces of glaciers, their immediate surroundings, and melting snow (Strunecký et al. 2012).

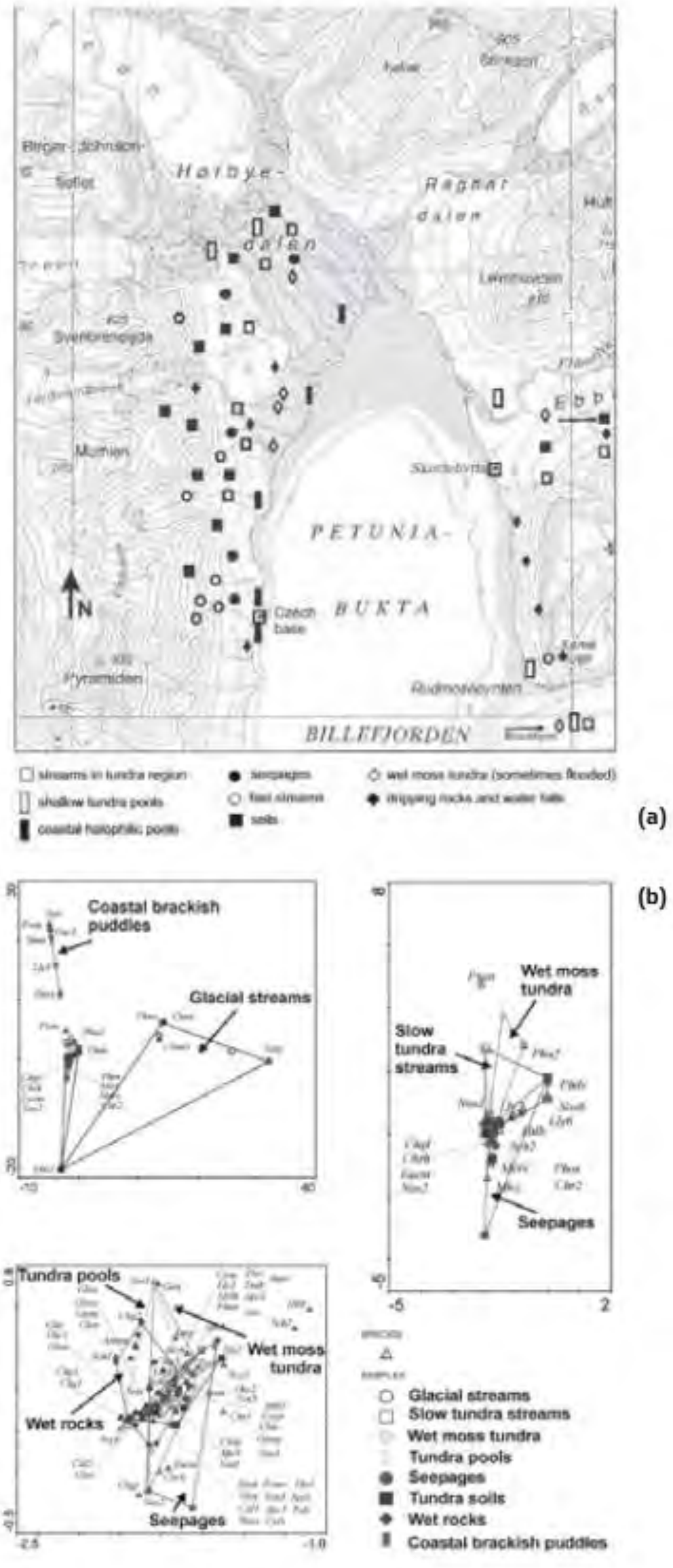


Fig. 1.10: (a) A study of the diversity of cyanobacteria in terrestrial and freshwater habitats showed that cyanobacteria are present at all sites studied; (b) some species were represented in several habitat types, other species are ecologically very distinct and occur only in 1 type of habitat, Petuniabukta Bay, Billefjorden, Central Svalbard (Komárek et al. 2012).

Continuous and long-term study of the diversity and ecology of cyanobacteria and algae, combined with monitoring of selected environmental parameters, allows us to detect changes in ecological relationships in the high Arctic associated with anthropogenic changes, including global warming. This approach makes it possible to identify newly recorded species of cyanobacteria and algae that may be considered invasive and strongly affect the Svalbard archipelago. An example is the spread of the invasive benthic algal species *Vaucheria* aff. *compacta* in the intertidal area of Advetfjorden Bay (Fig. 2.10). which we have detected in several studies (Kvíderová et Elster 2017, Kvíderová et al. 2019, Elster et al. 2023, Souquieres et al. 2023).

Fig. 2.10: (a) Abundant growths of *Vaucheria* aff. *compacta* in the tidal area of Adventfjorden Bay; (b) detail of the growth of the *Vaucheria* aff. *compacta*, Longyearbyen, Central Svalbard (Elster et al. 2023).

Flora of Arctic lakes

The growth of photosynthetic freshwater organisms in the Arctic is mainly limited by the short growing season and the lack of nutrients. Solar radiation is unavailable during the long polar night and long after it ends because of ice cover, which usually effectively prevents light penetration into the water column, depending on the thickness and type of ice. The short Arctic summer is a period when sunlight is available throughout the day. However, its intensity can change drastically depending on weather conditions and time of day, as shown by measurements near the Czech field station in Petuniabukta Bay (Láska et al. 2012). However, thanks to the long-term presence of liquid water, lakes in both the Arctic and Antarctica are considered centres of productivity and biodiversity, especially in arid regions where terrestrial ecosystems are significantly constrained by water availability.

Phytoplankton include eukaryotic algae, cyanobacteria, and anoxygenic photosynthetic bacteria. In contrast to benthic plants, the plankton biomass is subject to significant changes that reflect the seasonality of environmental conditions, particularly the availability of sunlight and nutrients, and the intensity of predator pressure. A wide range of taxonomic groups of algae are represented here, from Chrysophyceae, green algae (Chlorophyceae, Trebouxiophyceae, Zygnematophyceae), Cryptophyceae to Dinophyceae, diatoms (Bacillariophyta) and other groups. Planktonic cyanobacteria may also dominate, but their role is less important compared to algal mats. Coccal types (e.g., the genus *Synechococcus*) or species from group of Oscillatoriales are particularly common (Lizotte et al. 2008). It is also true that benthic algal and cyanobacterial species are common in plankton (Ellis-Evans et al. 2001). Several groups of anoxygenic photosynthetic bacteria can make up the bulk of the plankton biomass under certain conditions. These include green sulphur bacteria, which require an anoxic environment. That is why they are found in the lower layers of meromictic lakes, for example. In lakes of the Canadian High Arctic, their presence was indicated by high turbidity caused by sulphur particles associated with these bacteria (Van Hove et al. 2006).

Most Arctic lakes are oligotrophic to ultraoligotrophic in terms of productivity. Chlorophyll-*a* concentration is most commonly used as a parameter to determine phytoplankton biomass, usually ranging from the detection limit to values on the order of low units of mg/m^3 in the Arctic. The most represented category was lakes with extremely low values (0-1 mg/m^3). Mesotrophic lakes are much rarer and not found at lower latitudes, for example in Alaska and other areas. Eutrophic or even hypertrophic lakes are rare in both polar regions and are associated with seabird or mammal colony influences or anthropogenic pollution (Lizotte et al. 2008).

As mentioned earlier, the productivity of Arctic lakes is limited mainly by the availability of light and nutrients. A number of algae that are successful in this environment therefore feed mixotrophically, obtaining energy and nutrients from organic material. Mixotrophy encompasses a spectrum of strategies ranging from ingestion of dissolved organic matter to consumption of bacteria and other small cells. An example is the genus *Dinobryon*, which is a common component of the phytoplankton of lakes in the Arctic (Fig.3.10). In Ward Hunt Lake on Ellesmere Island, Canada (83°N), for example, the plankton was dominated by *Dinobryon sociale,* accompanied by other colonial species (Bonilla et al. 2005). Representatives of the genus *Dinobryon* are also common in Svalbard lakes (Laybourn-Parry and Marshall 2003).

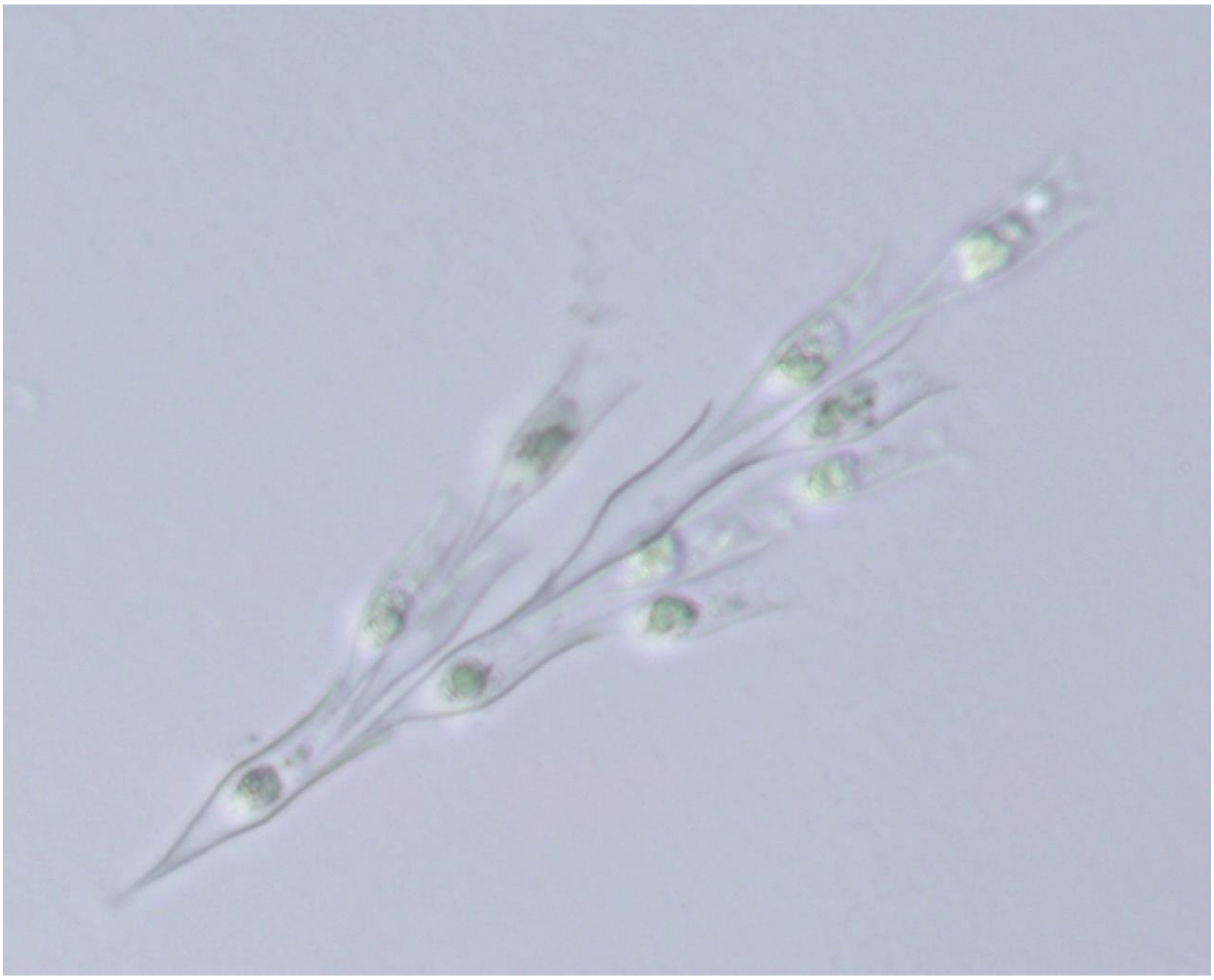


Fig.3.10: Colony of algae the genus *Dinobryon* (Chrysophyceae) from a lake on the coast of Isfjorden Bay, Svalbard (Nedbalová).

Especially in deep lakes, the ability to actively move is key to optimal absorption of solar energy, leading to the predominance of flagellate forms from different taxonomic groups, such as *Dinobryon*. Shallow lakes are mixed to the bottom in summer, so the ability to move around in them is not such a great advantage.

In the lakes of both polar regions, benthic communities are generally characterized by greater diversity and biomass compared to plankton. Similar to plankton, cyanobacteria and algae play a key role as primary producers in the benthos. The presence of microbial growth with a dominant photosynthetic component is a characteristic feature of polar lakes in general. This may be largely surprising under conditions of an extremely short growing season, low temperatures, and nutrient limitation. In some cases, the gradual accumulation of biomass is favoured by low feeding pressure from invertebrate consumers or even their complete absence. Macroscopic growths with a vertical structure, usually dominated by cyanobacteria, are accompanied by algae, various groups of non-photosynthetic bacteria or other groups in algal mats (Fig.4.10). In shallow waters, these accretions are common in various types of lakes in the Arctic, but unlike in Antarctica, there is no record of their occurrence at the bottom of deep permafrost lakes. In Ward Hunt Lake, for example, the cyanobacterial growth consisted of three layers, with the upper black layer formed by the genus *Tolypothrix*, the middle pink layer dominated by cyanobacteria of the genera *Pseudanabaena*, *Leptolyngbya*, and colonies of *Nostoc* sp., and the lower blue-green layer containing various filamentous cyanobacteria from genus *Oscillatoriales*. The black coloration was caused by the presence of scytonemin, a pigment that protects cells from intense UV radiation. Mycosporine amino acids, which also absorb in the UV range, have also been detected in the algal mats (Bonilla et al. 2005). At shallow sites without ice cover, organisms are exposed to high doses of solar radiation throughout the 24 hours during the polar day, and accumulation of these protective compounds is critical for their survival. Cells in the subsurface layers of growth are effectively shaded from the upper layer, and many species are also able to actively migrate and find a location with optimal radiation. In addition to radiation, another important factor is temperature, which can vary greatly even during the course of a summer day. Therefore, most species are not strictly psychrophilous (i.e., with an optimum temperature below 10 °C and a narrow range of tolerated temperatures) but are psychrotrophic species that grow over a relatively wide range of temperatures. Current data suggest that growth is not as constrained by nutrient deficiencies compared to planktonic organisms. This is due to the long-term accumulation of organic material that serves as a source of nutrients. This has been demonstrated, for example, in field experiments with the addition of nutrients to Ward Hunt Lake. While phytoplankton responded with a large increase in biomass, mats did not respond in any way to this intervention (Bonilla et al. 2005).

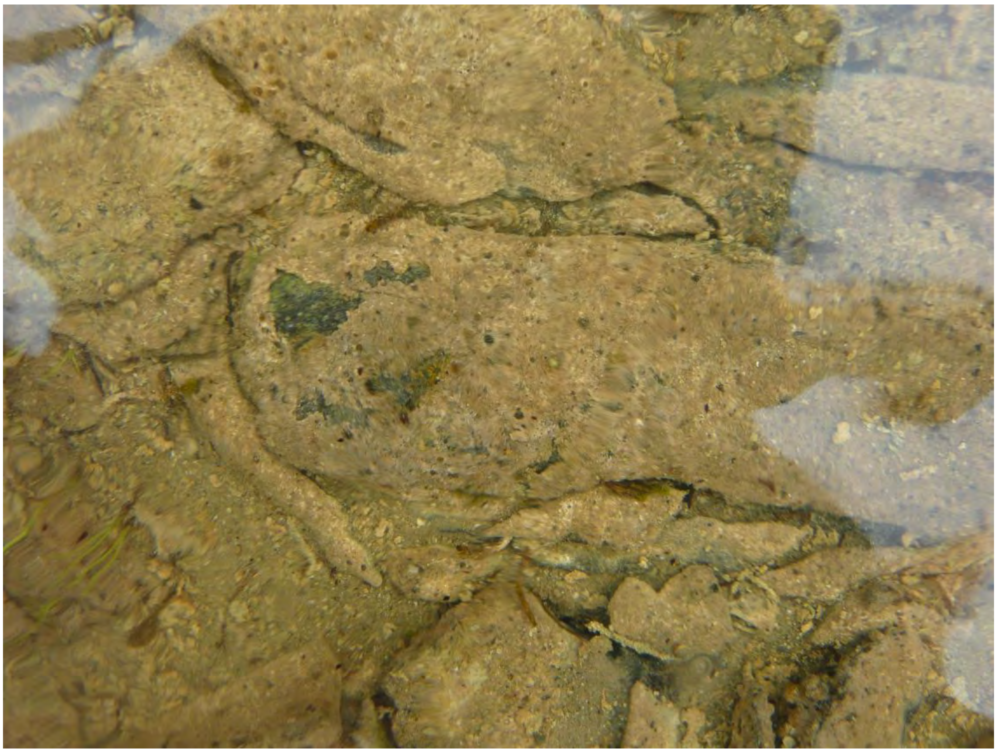


Fig. 4.10: Phytobenthos in the littoral of Lake Ebba, central Svalbard (Nedbalová).

In addition to cyanobacteria, an important group of photosynthetic microorganisms are the pennate diatoms, which grow on all types of substrates, although they may be especially dominant on sand or fine sediment (Fig.5.10). The Petuniabukta Bay area in the central part of Svalbard is a relatively well-studied areas in terms of diatom diversity. A total of 310 taxa from 59 genera were found at 53 sites, with the genera *Achnanthidium* and *Nitzschia* being the most abundant. However, about one-third could not be determined to species, indicating that the diatom flora of the high Arctic is not yet well understood. Key factors affecting community composition include habitat type, pH, and the influence of the marine environment (Pinseel et al. 2017). Differences in diatom community composition were also found in lakes on the north coast of western Svalbard (Zgrundo et al. 2017), where the dominant species belonged to the same genera as in Petuniabukta Bay.

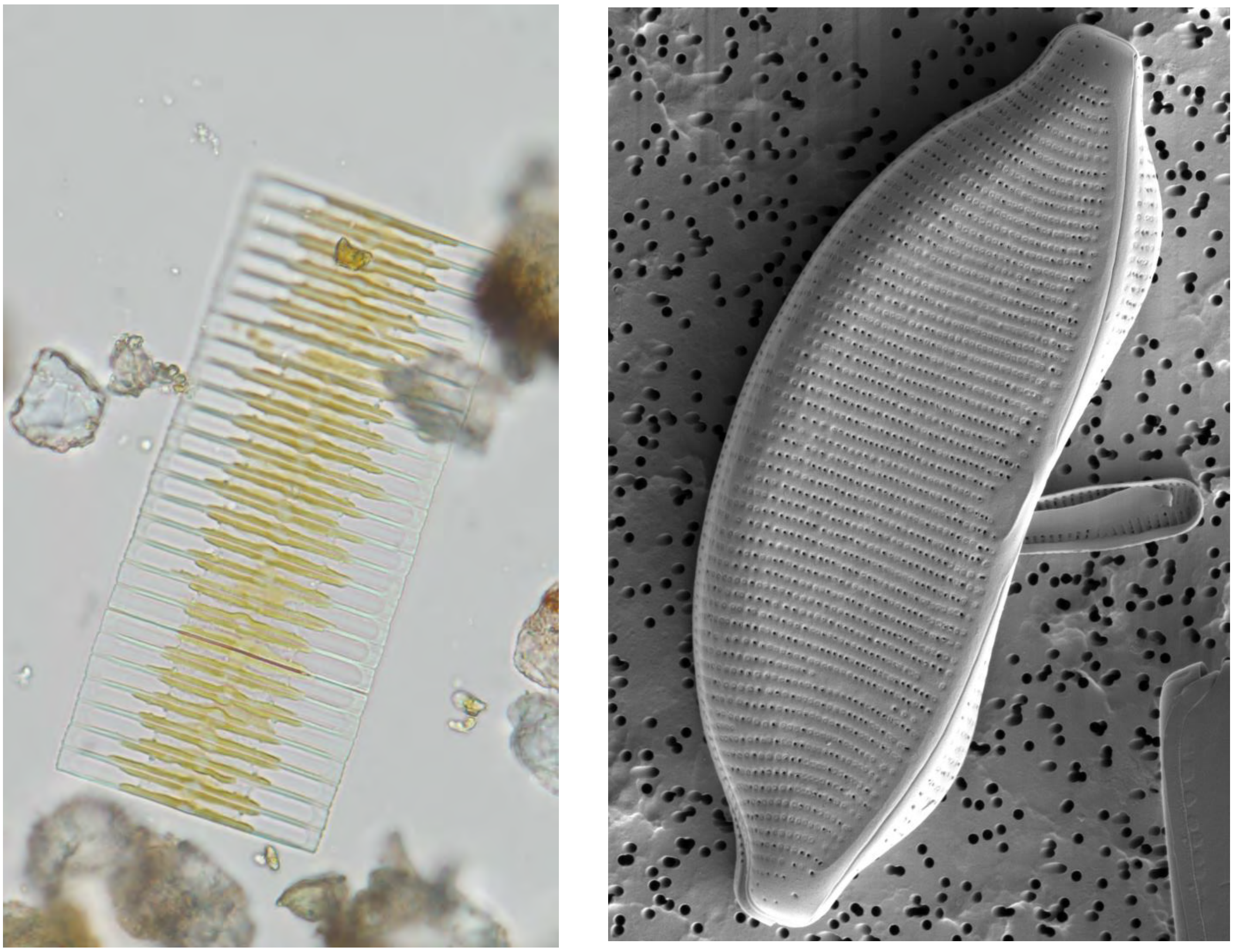


Fig. 5.10: Freshwater pennate diatoms from Svabard: (a) colony of *Fragilaria* sp. from the vegetation community in the stream in the Bjørndalen valley; (b) Silica (frustula) of *Hantzschia abundans* from a karst lake in the area of Mathiessondalen, SEM (Hejduková).

In addition to cyanobacteria and algae, photosynthetic organisms in Arctic lakes are also represented by macrophytes. Their diversity decreases with increasing latitude, and mosses (e.g., from the genus *Drepanocladus*) can be used here at the expense of vascular plants under suitable conditions. While up to several dozen macrophyte species may be present in the subarctic, they are absent or very few in lakes with less favourable climatic conditions. For example, a comparative study of macrophyte diversity over a large area from Alaska to Scandinavia included *Myriophyllum alterniflorum*, *Potamogeton gramineus*, and *Ranunculus reptans* as common species. Regions with the lowest diversity included Greenland, where not a single species of vascular aquatic plant occurred at most surveyed sites (Lento et al. 2019). As mentioned earlier, photosynthesizing organisms in Arctic lakes can be represented to a significant degree by aquatic mosses, which can tolerate even very low levels of solar radiation and form extensive carpet-like growths on the bottom, contributing significantly to overall productivity. Similar to microbial mats, they are typically slow growing, and under low temperature conditions they simultaneously lose little fixed carbon through respiration, decomposition, and herbivore uptake. This severely limits the utility of short-term measurements, which can provide only limited insight into the production dynamics of these long-lived organisms. Detailed studies based on data collection over a longer period of time are rare. In Canada's Char Lake, which was one of the earliest detailed limnological research sites in the high Arctic, primary benthic production by mosses accounted for 80% of the lake's total annual production. The depth limit of moss growth was then determined by the average position of the compensation point during the year, as shown in the classic work of Welch et Kallf (1974).

Fauna of Arctic lakes – invertebrates

The aquatic environment is inhabited by a limited number of animals capable of surviving in the demanding Arctic conditions. Despite their sometimes-small size, these organisms are conspicuous, often catching the eye of even a casual observer.

Lepidurus arcticus (Fig.6.10) is a very conspicuous species of stagnant waters. With a body size of up to 30 mm, it is one of the rather smaller phyllopodan, but in the Arctic environment it is a conspicuous, often highly visible species. It is always found in permanent waters or in places where the water environment is regularly renewed (shallow lakes). It also tolerates annual drying if the water body lasts long enough during the season for the adults to grow and produce eggs. The eggs can withstand drying and freezing, and with their help the species spreads to new locations. *Lepidurus* is omnivorous. The range of their diet is very broad and includes virtually anything digestible in the environment, from algae and cyanobacteria mats, bacteria and organic sediment, to Daphnia, midge larvae, and individuals of their own species. It is capable of foraging not only on the bottom and below the bottom surface, but also in the water column (although it has limited swimming capabilities). It is usually found in very clear water. In deep lakes where it has no natural predators, it can most likely survive several seasons. It does not tolerate salinity above 2 ‰ of dissolved salts and is an indicator of higher water pH, about 7 or more. *Lepidurus* is very undemanding, tolerating a temperature range of 0 to 20 °C, provided sufficient dissolved oxygen is present. It is found in clean, oligotrophic lakes with low productivity (Lakka 2015). In shallow lakes, it becomes food for terns, often leading to their disappearance at the end of the season. Where fish are present, *Lepidurus* is a welcome prey for them and their populations are quickly depleted, but in deeper lakes they have no natural enemies except individuals of their own species (Coulson et al. 2014).

Fig. 6.10: Exuvia of *Lepidurus arcticus* piled up on the windward shore of a lake in Brucebyen (Devetter).

Daphnia are the most conspicuous representative of the zooplankton community. They often catch the eye of observers in the lake at first glance, because they are relatively large (2-5 mm, but in exceptional cases more than 10 mm) and conspicuously darkly pigmented (Fig. 7.10). The dark pigmentation is usually cited as protection against (UV) overexposure, and in the absence of fish, there is no selection factor that prevents such a visually conspicuous adaptation. However, the dark pigment is not always present, even in lakes without fish. Daphnia from deeper waters tend to be less pigmented. They occur in most permanent standing waters and in some periodic waters. Taxonomically, it is a species complex sometimes given as *D*. *pulex*, *D*. *pulicaria*, *D*. *middendorfiana*, and *D*. *tenebrosa*, while in many studies the authors do not give a more precise identification, so we may often encounter the designation *D*. cf. *pulex* or *D*. cf. *pulicaria* (Hessen et Leu 2006, Lods-Crozet 2007, Van Geest et al. 2007). However, they are still the same group. They are characterized by a high clonal diversity (Sarnelle et Wilson 2004), and the species can often only be reliably distinguished by molecular methods. They exhibit the highest clonal diversity at sites with higher trophic levels (Alfsnes et al. 2016). In addition, *D. longispina* also occurs in a number of lakes that can be quite easily distinguished from the aforementioned species but is overlooked by many authors. The main consumer of *Daphnia* is *Lepidurus*, which is a good hunter but a relatively poor swimmer. In deep lakes it is able to hunt for food at a limited distance from the bottom (about up to 1 m). At greater distances, Daphnia are relatively safe from it. Daphnia have no other natural enemies and can grow to unexpected sizes (more than 10 mm).

Fig. 7.10: Dark pigmented *Daphnia pulicaria* s. l. from Svalbard. On the protruding postabdomen, determinative signs are visible (Devetter).

Macrothrix hirsuticornis is very common among the other zooplankton species, found mostly in lakes, but usually in low numbers, as are *Acroperus harpae*, *Alona guttata* and the *Chydorus sphaericus* species complex, which are less competitive and cannot compete with Daphnia under high food pressure. The presence of other species and clones often depends on the popularity of the site for water birds (Alfsnes et al. 2016).

Copepods (Copepoda) exist in evolutionarily ancient and deep lakes. Members of their three orders: Cyclopoida, Calanoida, and Harpacticoida are a relatively rare but regular component of ancient lakes. Cyclopoida are omnivorous and their usual diet changes as the individual develops from nauplius to adult, which is often predatory and cannibalistic at younger stages of development. *Cyclops abyssorum*, also known from deep and mountain lakes in Europe, and *Diacyclops crassicaudis* are the most common. Calanoida are herbivores in the water column. Of these, *Diaptomus* sp. is the most abundant and developmentally linked to the oldest lakes. The harpacticid *Maraenobiotus brucei* or *Tahidius discipes* are found in the sediment of lakes.

Planktonic rotifers are found in the standing waters of the Arctic, but usually cannot compete with Daphnia for food. Their populations are relatively high at the beginning (*Daphnia* have not yet peaked) or at the end of the season (Daphnia have been eaten by *Lepidurus*). *Notholca foliacea* and *Polyarthra dolichoptera* are the most abundant species (Fig. 8.10). The Antarctic phenomenon is the bdelloid rotifer *Philodina gregaria*. It accumulates carotenoids from food in its body and is therefore distinctly orange in colour. It forms dense populations in shallow lakes and ponds, often completely covering the bottom. When disturbed, they react synchronously, causing noticeable colour changes in the bottom. This is why they have been nicknamed the “Flamingos” of Antarctica.

Fig. 8.10: Rotifer *Polyarthra dolichopenera* (Jurníček).

Midge larvae (Chironomidae) are one of the most common organisms in Arctic freshwaters. They occur in standing and flowing waters and colonize, sometimes in masse, older permanent waters. They live primarily burrowed in the sediment or on its surface, but the younger larvae in particular are often found in the water column, attracting attention by their characteristic movements. Again, they feed on a very wide range of foods, from bacteria and algae to plant detritus and animal remains. Adult metamorphosis occurs synchronously and in masse, and the imagoes are a significant fertilizer for the surrounding tundra, causing measurable losses of limiting nutrients from the aquatic reservoir. The most important species are *Paratanytarsus austriacus*, *Psectrocladius barbimanu*s, and *Cricotopus tibialis* (Lods-Crozet et al 2007, Walseng et al 2018). Streams are inhabited by larvae of the midge *Diamesa cinerella*, which inhabits the coldest streams; several species of the genus *Paratanytarsus* and some Orthocladiinae inhabit warmer streams (Lento et al. 2021).

Mosquito larvae (Culicidae) live in shallow, temporary wetlands where the water warms on sunny days. Over the past decade, mosquitoes have widely spread latitudinally due to warming temperatures.

Trichopterans are relatively rare in permanent lakes. The main species, *Apatania zonella*, occurs only at sites with low conductivity and at the lake outlet (Walseng et al. 2018). They are very inconspicuous and can be observed mainly during the swarming season, which occurs only a few days a year on Svalbard, usually in the first days of July.

Enchytraeids (Enchytraeidae) are Oligocheta worms that are very typical of soil environments. However, some species are also commonly found in aquatic environments. For example, *Marionina* sp. (*M. macgrathi* and *M. ulstrupae*) are commonly found on rocky shores of lakes exposed to wave action.

Ostracods (Ostracoda) are very typical in their occurrence, especially in shallow wetlands at the surface of permafrost soils (seepages) (Fig. 9.10) and in some moraine lakes, where their movement and the tracks they leave in the fine sediment are striking. They are about 1 mm in size and are usually found where there are not many other organisms (Wojtasik et Kuczynska-Wisnik 2012).

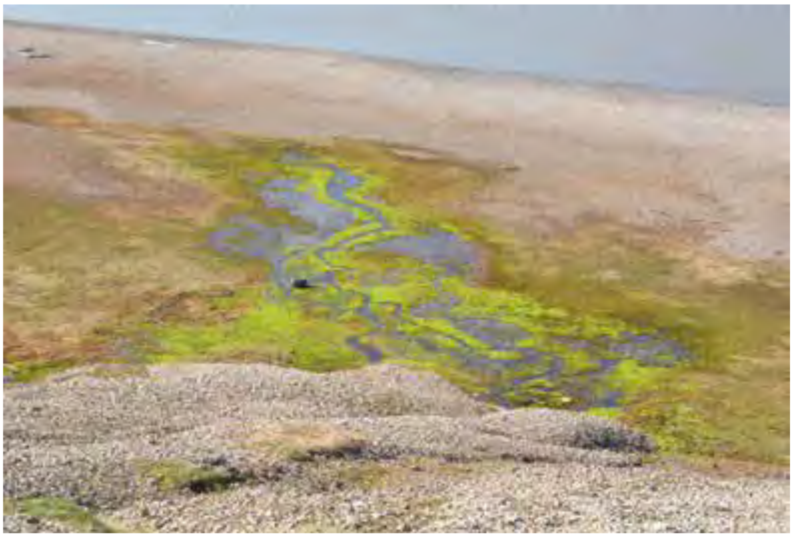


Fig. 9.10: Seepages are the specific home of some species, for example ostracods (Ostracoda); (Devetter).

Not quite typically aquatic, but conspicuous and water-bound are springtails (Collembola). They are very regularly observed on the water surface (Fig. 10.10) where they often form conspicuous mass populations of hundreds of thousands of individuals (thanks to the non-wetting surface of the body) and form entire accumulations on the banks of water bodies of various sizes. Several relatively unrelated species may live facultatively in this life form.

Fig. 10.10: The mass occurrence of springtails on the surface is a typical phenomenon of small lakes in the forefield of glaciers (Devetter).

The overall species diversity of lakes is increasing due to climate change, and new species are being established each year, spreading from lower latitudes (Walseng et al. 2018).

Occurrence and role of fish

There are very few freshwater fish in the high Arctic. In some lakes, especially larger ones, lives the char (*Salvelinus alpinus*), the only native species. It is anadromous, meaning that it always reproduces in the freshwater of lakes or rivers. Outside of the breeding season, it lives mainly in coastal waters, but there are also non-migratory populations inland. Individuals that migrate to the sea reach a much larger size due to better food availability (Borgstrom et al. 2015). In lakes, they fundamentally alter plankton and benthic communities. Their most common food is larvae of chironomids (Chironomidae) and trichopterans (*Apatania zonella*) (Borgstrom et al. 2018). To a lesser extent, they eat ostracods and copepods, but they eat virtually anything living, including smaller individuals of their own species. Where they live, there are virtually no larger cladocerans, *Lepidurus* or other larger zooplankton. They are occasionally food for loon *Gavia stellata* or terns (*Sterna paradisaea*). They are intermediate hosts of the tapeworm *Dihyllobothrium ditremum*, the definitive host being *Gavia stellata*.

Recently, the three spined stickleback *Gasterosteus aculeatus* has spread to Svalbard. Its impact on lake environments is likely to be similar, but it has not yet been studied.

Life in and under the ice

Although the waters are frozen most of the year, life survives here even under the ice. Shallow water bodies and watercourses freeze completely in winter, with all the consequences for living organisms. Single-celled algae, cyanobacteria or bacteria are inactive at this time, while multicellular organisms survive this period in the form of anhydrobiotic stages, cysts or permanent eggs. Anhydrobiosis is carried out by bdelloid rotifers (Rotifera: Bdelloidea), nematodes (Nematoda), tardigrades, and to a limited extent by some insect larvae, such as midges (Chironomidae). In this unfavourable time, single-celled organisms collectively known as protozoa (Protozoa) encyst. Cladocerans, copepods, planktonic rotifers (Rotifera: Monogononta) and *Lepidurus* survive in the form of permanent eggs.

In lakes that do not freeze over even in winter, communities of zooplankton are found under the ice that, thanks to the absence of predators, are often unexpectedly rich, comprising up to tens of individuals per litre. Zooplankton are abundant despite the fact that there is virtually no primary production for many months and herbivores must be severely restricted in their food intake. The concentration of phytoplankton is close to zero during this period. In lakes with the presence of fish (e.g. Linnevatnet), winter zooplankton are very rare.

Lake biodiversity

As noted in Chapter 7, Arctic lakes are of varying ages. Most were formed during the Holocene, and their ages therefore vary from 10-12 thousand years to a few years. Lake life depends largely on the age of the lake and whether they contain liquid water year-round. Sites that dry up and freeze are significantly impoverished, and young lakes are also significantly poorer in species (Walseng et al. 2018). This is apparently related to the colonization rate of new lakes, which is low in the Arctic, and to the stabilization of the shoreline and bottom of older lakes and the creation of a permanent egg store in the sediment. On the other hand, freezing or drying of shallow lakes benefits some species of invertebrates that can survive this period, but are otherwise weak in competition, such as planktonic rotifers.

Because of low precipitation, many lakes in the Arctic have no outlet and nutrients do not leave with the runoff water (*nutrient sinks*). However, the supply of these nutrients tends to be low, and the ecosystem is further depleted by the swarming of insect imagoes, as mentioned earlier (Luoto et al. 2016). On the other hand, waterfowl can provide a significant supply of nutrients when they visit a site (Fig. 11.10). These nutrients usually are from the sea, where the birds forage. In some cases, this can lead to hypertrophy of a lake (Van Geest et al. 2007, Walseng et al. 2018, Jensen et al. 2019).

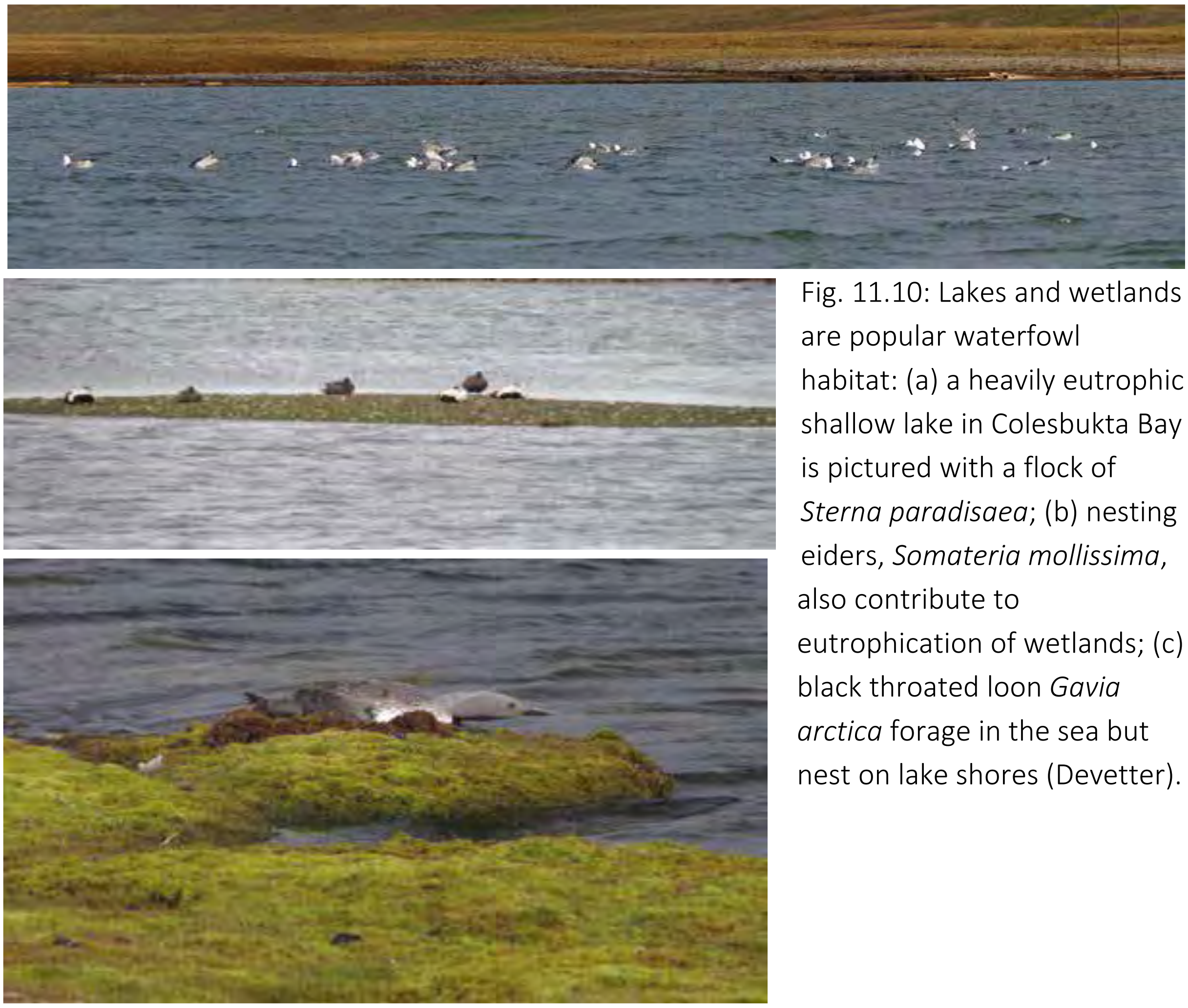


Fig. 11.10: Lakes and wetlands are popular waterfowl habitat: (a) a heavily eutrophic shallow lake in Colesbukta Bay is pictured with a flock of *Sterna paradisaea*; (b) nesting eiders, *Somateria mollissima*, also contribute to eutrophication of wetlands; (c) black throated loon *Gavia arctica* forage in the sea but nest on lake shores (Devetter).

Food chains and seasonal dynamics of lakes

The nature of food chains in Arctic lakes can vary widely, reflecting environmental conditions primarily related to climate and lake basin morphology. In ultra-oligotrophic lakes, which in extreme cases are permanently frozen, the so-called microbial loop plays a key role in the plankton, where the main flow of energy and matter is through different groups of microorganisms, which mainly include phytoplankton, heterotrophic bacteria and flagellates, ciliates and viruses. Ciliates are common in the plankton, for example *Halteria grandinella*, *Limnostrombidium viride* or representatives of the genera *Strombidium* and *Askenasia* (Petz 2003). The zooplankton consists of rotifers and crustaceans, whose species richness increases in milder climatic conditions. For example, in long-studied Toolik Lake, Alaska, there were several species of cladocerans and copepods. In contrast to Antarctica, fish play the role of top predators in a number of Arctic lakes. In Toolik Lake, we find as many as five species that use both plankton and rich benthic communities including midge larvae and mollusks as food sources (O'Brien et al. 1997).

The seasonal dynamics of plankton communities are controlled by the availability of solar radiation, which is the energy source for phytoplankton and the phytobenthos that form the basis of food chains. In fishless lakes, the abundance of Daphnia is also critical. These crustaceans indiscriminately filter seston from the water column using filter combs. They often form abundant populations capable of maintaining seston densities at very low levels, causing very strong inter- and intraspecific competition for food (Hessen et al. 2004). A consequence of this is the exceptional transparency of most lakes. Fig. 12.10 shows a comparison of the seasonal dynamics of zooplankton in shallow, freezing Ebba Lake and deep Blue Lake on Svalbard. Although the total abundances achieved are roughly comparable, the seasonal pattern is quite different. This is due to both the slow warming of the deep lake and the high predation of *Lepidurus* in the shallow lake at the peak of the season. This is best seen in the egg formation of genus *Daphnia* (Fig. 13.10). The seasonal pattern of phytoplankton is strongly influenced by the impact of filter cladocerans: as long as their importance is low, the phytoplankton consists of many groups and individual species (Fig. 14.10). As soon as the abundance of cladocerans increases, the phytoplankton practically disappears and only reappears after the elimination of *Daphnia* (Hessen and Leu 2006, Boopathi 2015).

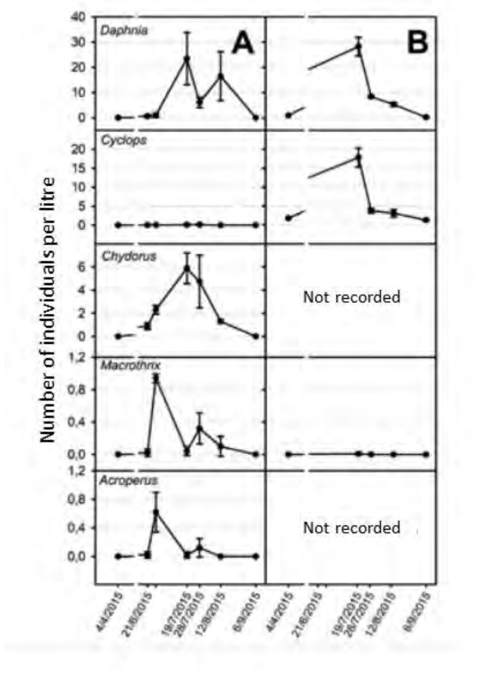


Fig. 12.10: Seasonal dynamics of zooplankton (a) shallow and (b) deep lake in Svalbard (Horký).

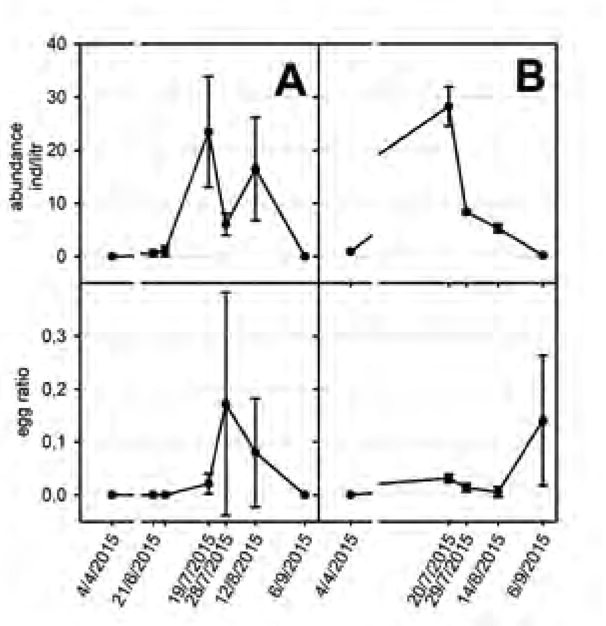


Fig. 13.10: Daphnia egg production of the genus *Daphnia* in the zooplankton of (a) shallow and (b) deep lakes on Svalbard (Horký).

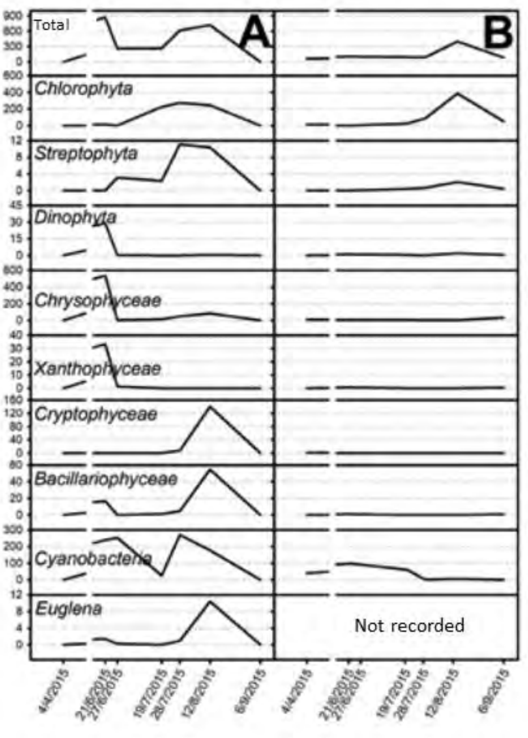


Fig. 14.10: Seasonal development of phytoplankton of (a) shallow and (b) deep lake in Svalbard (Horký et Lepšová)

Shallow wetlands and the continuum of dry and wetlands

Permanent wetlands also have specific communities, where plankton communities are virtually undeveloped. Similar to shallow lakes, rich algal mats of cyanobacteria and algae occur in wetlands (Figs. 15.10 and 16.10). In contrast to deep lakes, water temperature in wetlands can rise to around 20 °C, but at the same time organisms must be adapted to large temperature fluctuations, often occurring even within a day, or to drying of the site.

Fig 15.10: Shallow wetlands are home to rich growths of algae and cyanobacteria (Devetter).

Fig. 16.10: Algae in wetlands have ideal conditions and high production in summer (Devetter).

Zoobenthos communities in the littoral vegetation can also be rich and are closest to terrestrial moss communities in their composition (Muchová 2017). Rotifer diversity increases on the lake-tundra gradient, with the abundance of individual groups also significantly increasing. Individual species show their optima along the gradient, but most of them prefer dry tundra habitats with a dominance of soil species (Fig.17.10).

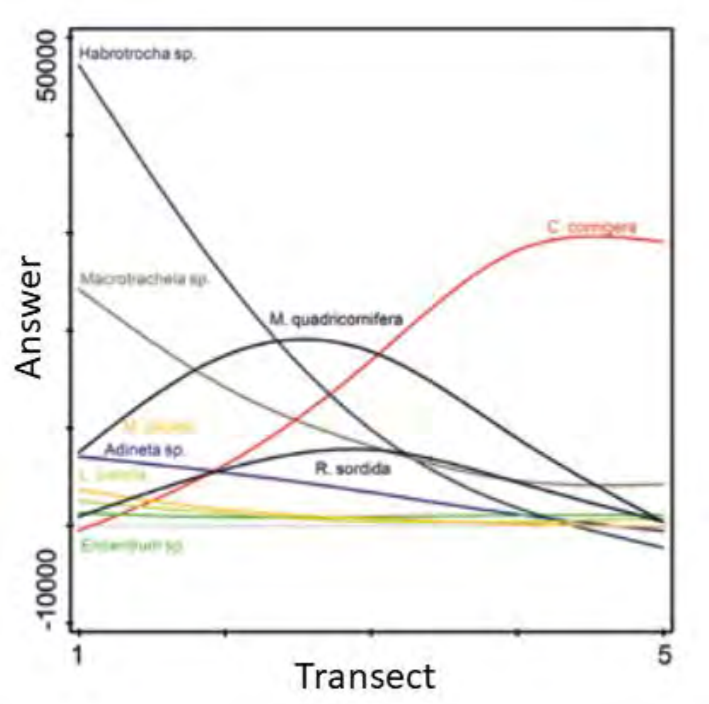


Fig.17.10: Ordination of rotifer species preferences on the terrestrial-aquatic environment gradient in Svalbard (Muchová).

The occurrence of individual organisms in environments atypical for them is generally characteristic of polar regions. There are many examples: Tardigrada form populations on the bottom of lakes, midge larvae (Chironomidae), which are otherwise typically benthic, are found in masse in the plankton of lakes. In soil, the benthic genera *Acroperus* and *Macrothrix* are found in the plankton, while the soil springtails (Collembola) forms mass populations on lake surfaces.

Running water

Arctic streams are characterized by an unstable bed and channel (Fig, 18.10). which is the most important factor limiting the development of any benthic community. These streams also typically carry large amounts of suspended sediment, which causes high turbidity ((Fig, 19.10). A more stable bed is essential for the life of streams. This is usually the case, for example, in streams fed by springs (Fig, 20.10). In addition, temperature, rather than the origin of the water, e.g., from a glacier as has been assumed in the past (Blaen et al. 2014), is critical for the occurrence of biotic communities. Other factors limiting productivity include, similar to lakes, a short growing season, which is also characterized by often very strong changes in flow during the day and over the course of the season, high intensity of solar radiation, possible desiccation, or daily cycles of freezing and thawing. Unlike lakes, benthic communities must also withstand long periods of freezing during the winter season. However, the drop in temperatures below freezing is significantly influenced by the height of the snowpack. Cyanobacteria cope best with these conditions, and sometimes green algae, diatoms, or even mosses may dominate the mats (Kosek et al 2019, Ntougias et al. 2016, Gorniak et al. 2016). Due to the constant availability of light or unlimited nutrient supply by nitrogen fixation, the photosynthetic rate of the mats during the short summer period may even be comparable to sites in the temperate zone.

Fig. 18.10: The river courses are quite unstable in the Arctic (Devetter).

Fig. 19.10: Water flows in the Arctic are typically highly turbid (Devetter).

Fig. 20.10: Some water courses have low turbidity, which in combination with a stable bottom enables the development of benthic communities (Devetter).

There are very few arthropods, which require more time to develop. Nevertheless, streams are often inhabited by the midge *Diamesa cinerella*, which inhabits the coldest streams, several species of the genus *Paratanytarsus*, and some species of the group Orthocladiinae, which inhabit warmer streams. This is a major difference from Antarctica, where mat-feeders are usually completely absent.

11. Life on the sea and shelf seas and food web in the sea: Oceanographic dynamics of Svalbard's fjords and Shelf

Tobias Reiner Vonnahme and Oleg Ditrich

Water masses and currents around Svalbard

Svalbard's marine ecosystems are highly variable in space and time, influenced by different water masses and currents. Hence, it is crucial to understand the physical oceanographic processes in order to understand the marine ecosystem and food web. Svalbard's fjords and shelf are characterized by three major water masses. Their current patterns are mainly influenced by the bottom topography of the shelf (reviewed by Loeng 1992).

1. Warm (>3°C) and salty (>35 PSU) North Atlantic water reaches the Barents Sea as an extension of the gulf stream (Loeng 1992). It flows mainly along the continental shelf west of Svalbard as the West Spitsbergen current (WSC, Fig. 1.11). On its way North, the Atlantic water cools down and mixes with local water masses on the way. Due to the West Spitsbergen current, the climate west of Svalbard is moderate considering its high latitude. A part of the Atlantic water also flows over the continental shelf South of Svalbard, mainly through Bjørnøyrenna and Storfjordrenna Fig. 1.11). At the polar front west and south of Storbanken, the Atlantic water submerges below the Arctic Water.
2. The Arctic water is cold (<0°C) and brackish (34.4-34.8 PSU) coming from the North and East of Svalbard (Loeng 1992). The major current reaching Svalbard flows along its east coast as the east part of West Spitsbergen current (ESC) (Fig. 1.11, Haarpaintner et al. 2001). The ESC extends around the South tip of Svalbard and flows over the shelf along the west coast of Svalbard, mixing with the WSC and isolating the coast from the warm Atlantic water of the WSC (Fig. 1.11). The ESC leads to a colder climate on the east coast of Svalbard, allowing sea ice formation on the shelf. Most sea ice in the east is seasonal and disappears in late summer, but some ice persists in the north and east or can be imported from higher latitudes.
3. The third main water mass is the brackish (<34.7 PSU) and relatively warm (>2 °C) coastal water (Loeng 1992). The coastal water is lighter than both the Arctic and Atlantic water and leads to a strongly stratified surface layer in summer. Currents on the shelves are typically homogenous throughout the water column apart from the polar front where the Atlantic water sinks below the Arctic water (Loeng 1992). Coastal and fjord systems are more stratified than the shelf and have stronger seasonal dynamics highly influenced by locally produced coastal water (Fig. 2.11). Due to very fresh surface water and isolation of the fjords from the Atlantic water by sills (ancient moraines in the entrance of the fjord), sea ice formation can happen, even along the west coast (Haarpaintner et al. 2001).

Locally produced water can be seasonally important, especially in areas with sea ice formation (e.g. north of the polar front, Loeng 1992). In winter, the upper 150m of the water column is Arctic water. In summer, melting sea ice leads to locally produced freshwater (melt water) layering on top of the water column leading to an isolated 5-20m stable surface layer (Loeng 1992). This melt water layer can explain the high phytoplankton biomass on ice edges (Loeng 1992). During sea ice formation, very salty and cold brine is released from the ice structure. This dense water sinks to the bottom forming the bottom water (Salinity >35 PSU, Temperature <-1.5°C) (Loeng 1992). This bottom water is important for destabilizing the water column in winter leading to mixing via haline convection (Fig. 2.11).

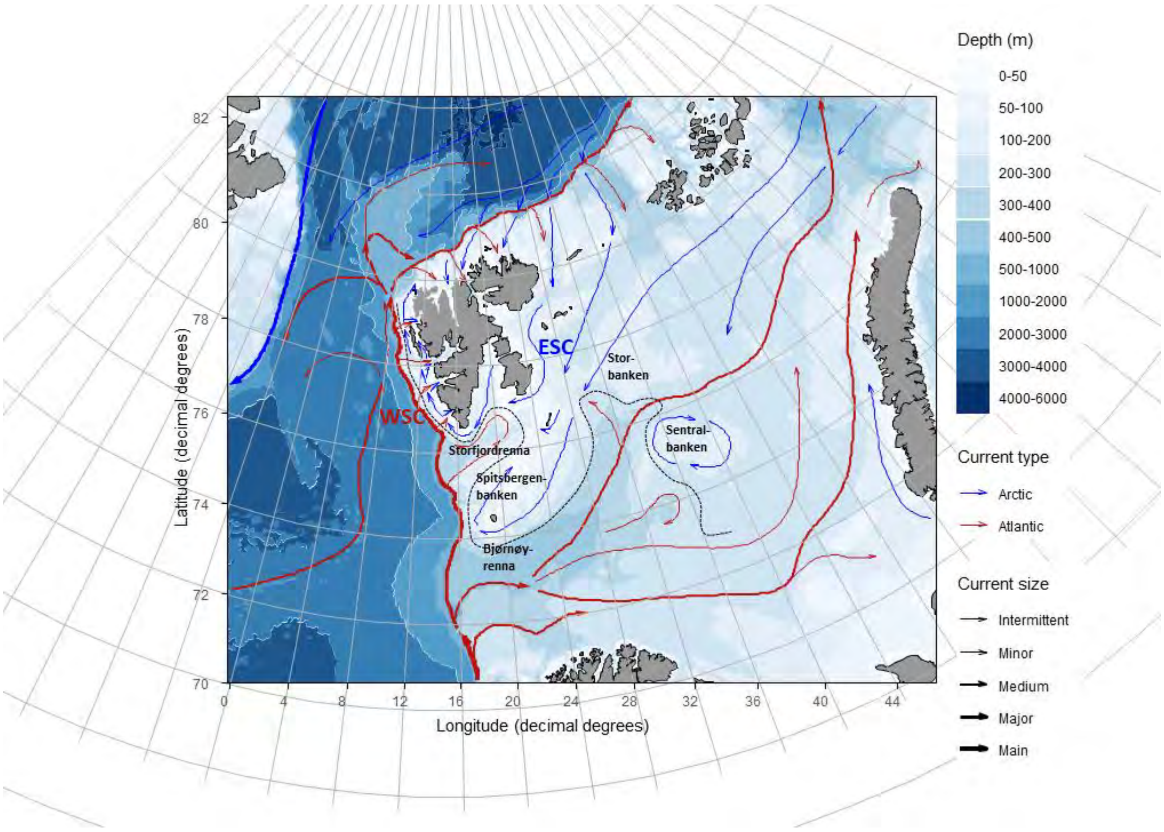


Fig. 1.11: Bathymetric map of the Barents Sea, its major Arctic and Atlantic currents, and bottom structures, controlling the ocean currents over the shelf. The approximate position of the polar front is marked with a dashed line. (Vithakari 2019, Jakobsen et al. 2012, Loeng 1992).

Stratification and vertical mixing

Vertical stratification and mixing are the main controls for primary production. In winter, mixing of the water column is crucial to supply the nutrient-depleted surface with nutrients from the bottom. In spring, a stratified water column may be needed for the onset of a spring bloom, allowing algae to stay in a stable surface layer with sufficient light (Huisman et al. 1999, Sverdrup 1953).

In ice free shelf areas cooling of the surface water in winter allows for vertical mixing down to 300 m (thermal convection) (Loeng 1992). Once the atmosphere is warmer than the water, the water starts warming and slowly re-stratifies in spring, allowing primary production (Loeng 1992). Spring blooms can develop as soon as the heat flux reverses in the water, even before the surface layer physically stabilizes (Harpaintner et al. 2012). Over summer, a 10-20 m well-mixed stable surface layer develops, but turbulent mixing by wind can lead to a warm surface layer down to 50-60m (Loeng 1992).

In shelf areas with sea ice formation, thermal convection is not enough for mixing the water column. Stratification and mixing processes are mainly controlled by sea ice formation and melt. During ice formation in winter, salty and cold brine is released from the newly forming ice. Due to its high density, it sinks down leading to a haline convection mixing the water column. In late spring the sea ice starts melting, leading to a fresh and stable meltwater layer on top, allowing for an earlier spring bloom than in the ice-free areas. Over summer, a typical layering develops with a 5-10 m well-mixed meltwater layer on top, with a slightly stratified Arctic water layer below, and Atlantic water and potentially bottom water at the bottom (Loeng 1992).

Coastal waters are generally more stratified throughout the year, including a weak stratification in winter due to the high inputs of freshwater from land (Loeng 1992). In autumn, the input of local freshwater stops, and the surface water cools down with decreasing air temperatures. Therefore, the water gets denser and vertical mixing by wind enhanced by thermal convection is possible to greater depths (Cottier et al. 2010, (Fig. 2.11). Increased wind in winter then allows mixing of the water column with nutrient rich bottom water reaching the surface if sea ice is absent (e.g. Marquardt et al. 2016). In late winter and early spring, sea ice can form and release very salty and cold brine, which destabilizes the water column more and leads to a haline convection, eventually mixing the entire water column (Fig. 2.11). This process is especially important in the east of Svalbard (Haarpaintner et al. 2001). Wind mixing is blocked by the sea ice, but tidal forces and estuarine circulations can still enhance vertical mixing (Fer et Widell 2007). Since the water column is weakly stratified throughout the year, a spring bloom can develop as soon as light is sufficient (Loeng 1992). In summer, the water column restratifies with large amounts of freshwater inputs from melting snow, glaciers, sea ice, or precipitation. The intermediate water is typically advected water from outside the fjord. This intermediate water is mostly salty modified Atlantic water west of Svalbard. Below the depth of the sill, old salty and cold winter water can persist. The dynamics of Atlantic water, if it reaches the fjord, determines if sea ice can form, and thereby, when a spring bloom can form.

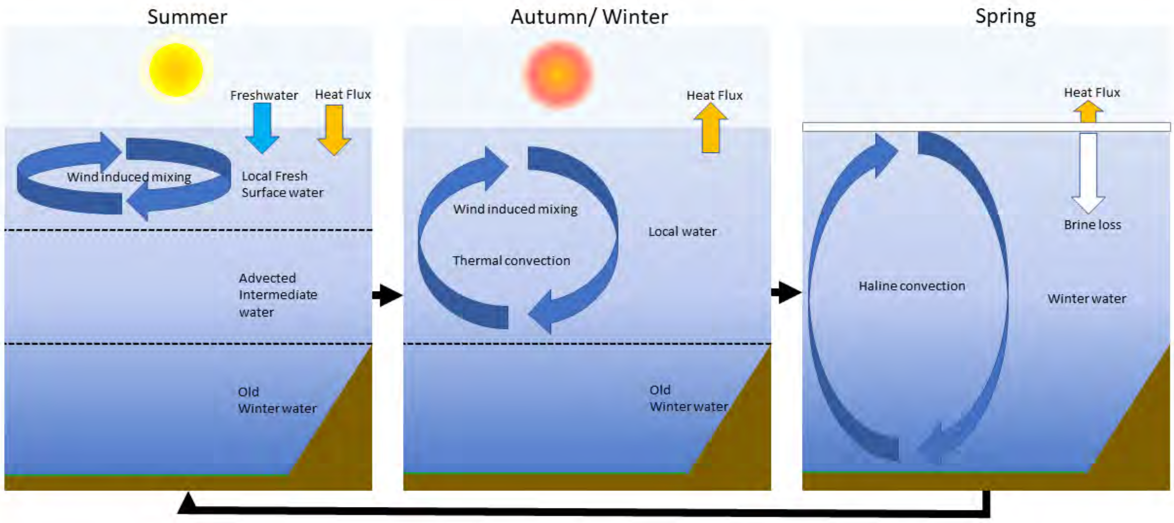


Fig. 2.11: Annual cycle of fjord mixing (Cottier et al. 2010).

Recently, an additional mechanism has been described, allowing summer upwelling in Svalbard fjords with marine terminating glaciers (Fig.3.11. Halbach et al. 2019). In this case, tidewater outlet glaciers terminating in the fjord release large quantities of meltwater from below the glacier into the fjord (subglacial upwelling). This fresh water is lighter than the salty water in the fjord and rises, while pulling the nutrient rich bottom water of the fjord with it (Cape et al. 2019). Strong katabatic winds from the glacier increase the upwelling effect by pushing surface water out of the fjord (Cottier et al. 2010). During this process, nutrients, but also large quantities of sediment, reach the surface. The sediments absorb light and limit primary production right in front of the glacier. The light absorbing properties depend on the type of bedrock (Halbach et al. 2019). In general, this leads to a tidewater glacier induced summer bloom at some distance from the glacier, where nutrient concentrations are still high, but most sediments settled out (Fig.3.11).

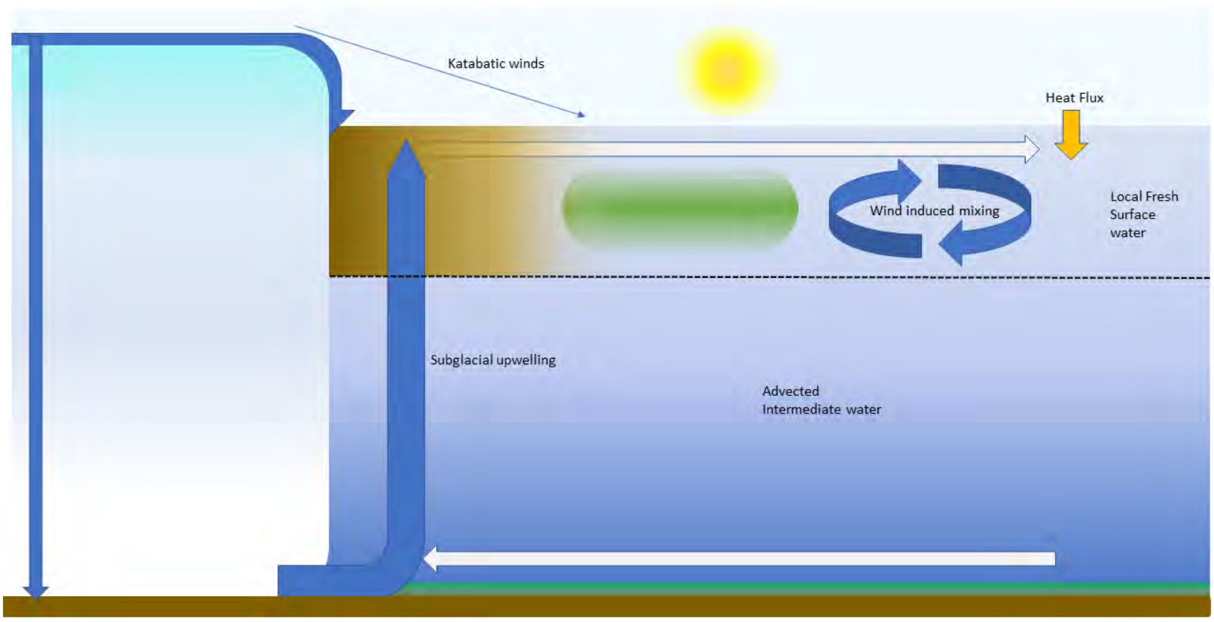


Fig.3.11: Tidewater upwelling scheme (Halbach et al. 2019)

With climate change, sea ice is retreating with direct implications on oceanographic processes. With the absence of sea ice, wind reaches the water surface, facilitating mixing, while the lack of locally produced meltwater leads to the absence of a stable freshwater layer on top of the water column in spring and summer. At the same time, haline advection, controlled by brine release is absent during sea ice formation in winter. This may lead to decreased mixing in autumn and winter, and a less stable stratification in spring and summer (reviewed by Ingvaldsen et Sundfjord, 2018).

Besides the thermohaline effects on mixing and stratification, mechanical forces, such as wind and tidal currents, can be important for local mixing of the water column (reviewed by Ingvaldsen et Sundfjord, 2018). Tidal currents can be rather strong on Svalbard's shelf and fjords. They are typically stronger at shallower depths, where the bottom topography changes quickly, such as at shelf breaks, banks, and islands. Tidal currents can form internal tidal waves that may be enough for vertical mixing, supplying the surface with nutrient-rich bottom water. Vertical mixing based on tidal waves is important at Spitsbergenbanken (Fig.1.11), the northern shelf slope, and the island's north and east of Spitsbergen. In these areas, productivity is high. Strong katabatic winds in fjords with glaciers can lead to specific circulation patterns, such as estuarine circulations and tidewater glacier upwelling (Cottier et al. 2010).

Sea ice evolution

On Svalbard's fjords and shelf, seasonal sea ice is a major feature controlling oceanographic and biological processes. The sea ice itself is a unique habitat consisting of a food web of sea ice algae, bacteria, archaea, viruses, and higher trophic levels, from ciliates, rotifers, nematodes, amphipods, and fish (polar cod). Sea ice can act as a substrate for a biofilm-like structure, stabilized by extracellular polymeric particles (Krembs et al. 2000) often in the bottom porous layer of the sea ice. Salinity can range between 0 and 200PSU and temperatures between 0 to -15°C, selecting taxa adapted to a large range of environmental conditions (Gradinger 2001).

Sea ice in the Svalbard fjords is mostly seasonally present between winter and late spring, often as land-fast ice. North and east of Svalbard drifting pack-ice is mostly present on a seasonal basis but may be imported from higher latitudes throughout summer and may persist for several years in the northeast (reviewed by Vinje, 2009).

Sea ice commonly starts forming as frazil ice, needle shaped crystals of about 3-4mm in diameter. During this process, brine is exuded from the newly forming ice, partly sinking to the bottom of the fjord, or concentrating in a matrix of very salty pockets and channels, concentrating organisms and nutrients. During wind mixing, the newly formed frazil ice may accumulate sticky particles and organisms from the seawater (reviewed by Vonnahme et al. 2020).

Under calm conditions, such as fjords, the frazil ice may connect to a thin smooth layer of grease ice (Fig.4a.11), at the surface which eventually connects to a sheet of nilas ice (Fig.4a,b.11),. As the nilas ice thickens, it gets lighter in colour and may start layering on top of each other (rafting, Fig.4b.11)). Eventually, the ice connects to a stable sheet with a smooth bottom surface (congelation ice) and thickens by freezing from the bottom (Fig.4c.11), reviewed by Vinje, 2009). In systems highly affected by freshwater, such as the Svalbard fjords close to marine terminating glaciers, sea ice is typically more transparent, denser and has a poorly developed brine matrix consisting mainly of brine pockets and lacking a skeletal layer.

Under rough conditions, such as the shelf seas or large fjords, frazil ice may concentrate as slush ice, including frazil ice and snow (Fig 4D). The slush ice eventually forms pancake ice Fig.4e.11), which collide with each other, potentially building ridges, or sliding on top of each other (rafting). Sea ice formed under these conditions is typically uneven (Fig.4f.11),also at the bottom (reviewed by Vinje, 2009).

Fig. 4.11: Different types of sea ice: a) Grease ice (front), partly turned into nilas ice (middle) and second year ice (background) north of Svalbard in October 2016 (Vonnahme); b) Nilas ice with wind induced rafting on the edges north of Svalbard in October 2016 (Vonnahme); c) Smooth congelation ice/ land-fast ice in Billefjorden (Svalbard) in 2018 with a skeletal layer rich in sea ice algae biomass on the bottom (Šabacká) d) Slush ice and pancake ice mixture in Bellsund (Svalbard) in March 2013 (Vonnahme); e) pancake ice in Storfjorden east of Svalbard in February 2013 (Vonnahme); f) Ridged land-fast ice formed under turbulent conditions in Storfjorden east of Svalbard in April 2013 including sediment loaded glacier ice (left) (Vonnahme).

With increasing thickness and snow cover in spring, the bottom of the ice is insulated from the cold air temperatures and its growth slows down and eventually stops. A porous layer on the bottom of the ice often develops called a skeletal layer (Fig.4c.11). This porous bottom layer acts as a substrate for sea ice algae and other small organisms. Once enough light penetrates the ice, sea ice algae can grow, potentially forming a large biomass in the skeletal layer. In the end of the season, the water and air warm up and sea ice starts from above and below, terminating the bloom. In late summer, melt ponds can develop with their own unique community structures, adapted to the low salinities.

Biogeochemcial cycles

Organic matter, which sustains life in the oceans, may come from several sources and is controlled by biogeochemical cycles. In the carbon cycle inorganic carbon (e.g. CO_2) is fixed into biomass or organic carbon (autotrophy) using the energy of light (phototrophy) or chemical reactions (chemotrophy). The organic carbon can further be used by other trophic levels and gets incorporated into biomass (heterotrophs), while some inorganic carbon gets released. Most primary production in the oceans is based on phototrophic algae using light as an energy source.

Chemoautotrophic primary production in the water column is mainly based on nitrification by bacteria and archaea using ammonium and nitrite oxidation as energy sources. Nitrifiers may be important primary producers in surface waters in the polar night due to the absence of light (Christman et al. 2011). In the polar night, photosynthesis is undetectable (Kvernvik et al. 2018) and the water column becomes mixed, leading to high ammonia concentrations in the water column (Christman et al. 2011). At the same time, light has been found to inhibit nitrification, leading to higher nitrification rates in the polar night (Christman et al. 2011). Besides their role as primary producers, nitrifiers can be indirectly responsible for the loss of nitrogen from the oceans. Nitrifiers convert ammonium into nitrate, which is available for denitrification under oxygen depleted conditions with gaseous nitrogen as an end product.

Hydrothermal activities can allow other chemoautotrophic pathways in bacteria and archaea, using oxidation of methane or reduced metals as energy sources. These activities can be important near hydrothermal vents or seeps. On Svalbard's shelf, cold seeps with active methane oxidizers have been found south of Spitsbergen (Gründger et al. 2019). While their contribution of organic carbon to the marine food web is limited to the local benthos, methane oxidizing archaea have an important role in converting the potent greenhouse gas methane into CO_2 before it can reach the water column and atmosphere.

In coastal regions organic matter may also come from the land (allochthonous), which can be a major source in river estuaries and fjords, such as Kongsfjorden (Kulinski et al. 2014). However, its bioavailability is particularly low in the Arctic due to its ancient origin (Kim et al. 2011).

Besides light and CO_2, inorganic nutrients are needed for photosynthetic primary production. In ocean systems, the availability of light and inorganic nutrients are the main drivers of primary production. Light decreases with depth, thus primary production occurs only in the surface layer where light is sufficient (euphotic zone). A stable surface layer is often needed for algal material to stay in the euphotic zone allowing quicker growth than vertical loss (Sverdrup 1953). Generally, nutrients are most depleted in the euphotic zone. At greater depths and in sediments, nutrient concentrations are higher due to microbial recycling of organic matter. The older Atlantic surface water has generally lower nutrient levels then the Arctic surface water in the East (Owrid et al. 2000). Hence, mixing of the water column is necessary to supply the euphotic zone with fresh nutrients (See above).

Additional inputs of nutrients can come from land. As described in chapter 14, seabirds can supply a significant amount of ammonium and phosphate to the marine system. Bedrock weathering, potentially enhanced by subglacial weathering and freeze-thaw cycles, may supply silicate, phosphate, or trace metals, such as iron, depending on the type of bedrock (e.g. Meire et al. 2016, Hawkins et al. 2014, Hawkins et al. 2016). During the flow of freshwater in rivers, nutrients may be depleted by terrestrial or freshwater primary production, but other nutrients may be supplied via organic matter remineralisation in soil, swamps, or ponds (e.g. Klinger et Erickson 1997).

Potentially limiting macronutrients, which are needed in rather high concentrations, are nitrogen (as NO_3^-, NO_2^-, NH_4^+), which is important for building amino acids, proteins, and nucleic acids; phosphorous (as PO_4^-), which is needed to build e.g. ATP, and some amino acids; and Silicate, which is needed by diatoms and silicoflagellates for building their cell walls. Other nutrients may be needed in trace amounts but can still become limiting: iron is crucial as a co-factor in proteins involved in electron transport chains, but also in proteins involved in gaseous N_2 fixation; other potentially limiting micronutrients are vitamin B12, cobalt, and zinc (Moore et al. 2013).

In the marine system, nutrients can be transformed by (bio-)geochemical processes. The form of nitrogen is mainly controlled by biological processes. Some bacteria, such as cyanobacteria, can fix atmospheric N_2 into biomass, making it available to the ecosystem. Degradation of organic matter releases ammonium, which can be taken up by primary producers or converted to nitrite and nitrate (Nitrification). Under oxygen depleted conditions, inorganic nitrogen may be lost to the atmosphere again as N_2 via denitrification, or anaerobic ammonia oxidation (Anammox). In the Barents Sea, oxygen can become depleted in sea ice in spring or in sediments. Silicate, iron and phosphorous are mostly cycled via geological processes as bioavailable forms of phosphorous (PO_4^-) and silicate (SiO_4). Phosphate and Silicate can originate from land or bottom-water.

Organic matter in the oceans enters the heterotrophic food web and can supply secondary producers (microbes recycling organic matter), herbivores (e.g. copepods) and eventually top predators (e.g. seals). Bacteria and Archaea are crucial for recycling organic matter fixed by algae. Bacteria and archaea can either directly convert organic matter into inorganic nutrients or fix it into biomass. Bacterial and Archaeal biomass is available for bacterivorous protists and metazoans (e.g. ciliates) and can thereby reach higher trophic levels. Viruses and phages can lead to lysis of bacteria, archaea and algae leading to the release of intracellular organic matter and nutrients (viral shunt) (reviewed by Vonnahme et al. 2020). Recently, fungi have been described as an important and abundant microbial group important for organic matter remineralization and algae lysis (Hassett et al. 2019).

Seasonal and spatial dynamics of algae production and communties

On Svalbard, primary production is strongly controlled by seasonal variations in light and nutrient availability, as well as the presence of algae inoculum (Fig.5.11). in spring and grazing pressure in summer (e.g. Leu et al. 2015, Hegseth et al. 2019). In spring, as soon as the water column stratifies, high nutrient concentrations from winter mixing allow blooms of phytoplankton and sea ice algae to develop (Hegseth et al. 2019, Sverdrup 1953). The timing of the bloom is strongly controlled by sea ice coverage and may not happen before summer (Owrid et al. 2001). The bloom is followed by reduced biomass and primary production in summer due to grazing pressure, nutrient limitations, and potential light limitation caused by sediment inputs from land. During the polar night, from November to January, primary production is light limited and photosynthesis not detectable (Kvernvik et al. 2018).

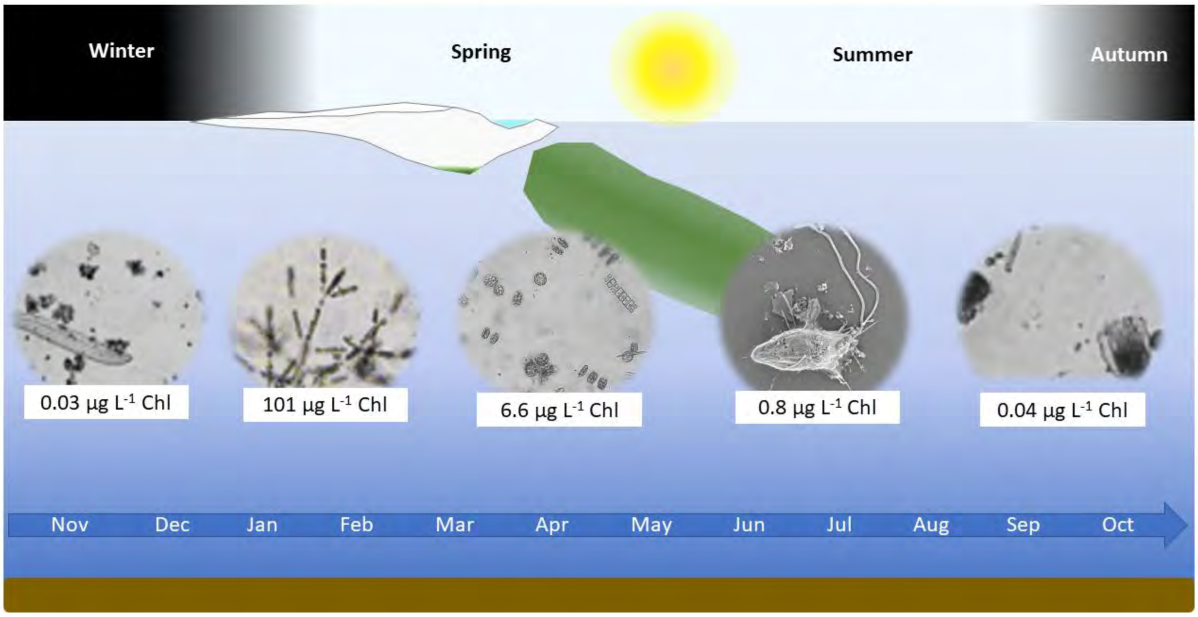


Fig. 5.11: Seasonal cycle of algae biomass and communities in Billefjorden (Svalbard). The cycle starts with a polar night community in November (2017) with very low biomass and a diverse community of ciliates, flagellates and pennate diatoms. In April, there can be either a sea ice community dominated by *Nitzschia frigida* and very high biomass in the lowermost 3cm (2018) Or an early under ice bloom with different pennate and centric colonial diatoms and relatively high biomass may form (2019). By July (2018), there is a low biomass community dominated by flagellates followed by a very low biomass community with ciliates as the abundant group at the onset of the polar night in October 2019. (Vonnahme).

During the spring bloom (March-June), the highest primary production and biomass can be found once the water column starts to stabilize. Mixing of the water column in the previous winter is crucial to supply nutrient-rich bottom water and sediments, including algae spores, to the upper water column for the development of high biomass in spring (Hegseth et al. 2019). In the Barents Sea, phytoplankton are the most important primary producers, but sea ice algae still contribute 20% to the annual primary production (Hegseth 1998).

In sea ice, primary production is the highest at the bottom of the ice, while heterotrophic processes dominate at the surface (Gradinger et Zhang 1997). Sea ice algae blooms are mainly controlled by light and the stability of the bottom layer of the ice (Leu et al. 2015). Sea ice algae growth can be separated into three phases (Leu et al. 2015). The first phase is light limited in winter and early spring with net heterotrophic communities. Once sufficient light reaches the bottom of the ice, stable sea ice algae blooms can form. In the Svalbard fjords, this typically happens between March and June (Leu et al. 2015, Owrid et al. 2001), when light is sufficient for biomass production and a stable skeletal layer is present. In the shelf seas northeast of Svalbard, this state may start later in the season. The bloom is typically terminated in the third phase by the loss of the skeletal layer via melting from the bottom. Typical sea ice algae are pennate diatoms, with *Nitzschia frigida* often solely dominating the community, but also colony forming diatoms, such as several *Fragillariopsis* and *Navicula* species, while solitary diatoms, such as *Pleurosigma*, are common (von Quillfeldt et al 2009). In pack ice, the centric diatom *Melosira arctica* may dominate. *Melosira arctica* can form large strands reaching into the water column, taking up nutrients while the ice is drifting (Owrid et al. 2001).

Sea ice in front of glaciers may form earlier and become thicker due to fresher surface water and increased freshwater supply throughout the winter and spring if a warm based marine terminating glacier is present. High inputs of freshwater have been related to low sea ice algal biomass (Rysgaard et al. 2001), possibly due to light limitation via increased snow accumulation, and potential sediment entrainments in the ice to be the main causes (Leu et al. 2015; Rysgaard et al. 2001). Physical disturbance by freshwater pulses is another possible explanation (Rysgaard et al. 2001). Very fresh sea ice has also very little brine volume and is lacking a skeletal layer. Hence, a simple lack of space may be another reason explaining the low biomass in freshwater influenced sea ice.

A phytoplankton bloom may develop in the surface layer as sea ice melts, with light no longer being blocked by sea ice and snow, and sufficient nutrients available in the water column. Besides light and nutrients, the surface layer has to be stable enough to avoid extensive loss of algal biomass from the euphotic zone (Sverdrup 1953). Sea ice melt can be one way to develop a stratified water column, with fresh meltwater layering on top. This occurs mainly in fjords and north of the polar front. In fact, ice melt induced stratification at the ice edge leads to blooms with high biomass (von Quillfeldt et al. 2009). If no sea ice is present, increasing air temperatures can stabilize the water column, which takes more time and leads to a weaker stratification than sea ice melt can induce. The water column does not necessarily have to be strongly stratified, but once the air temperature is consistently higher than the water temperature, which prevents mixing of the water column, the surface layer can be stable enough for the beginning of a spring bloom (Hegseth et al. 2019). Besides nutrients, light and a stable surface layer, algae inoculum from the sediments is important, too. In Kongsfjorden, phytoplankton blooms could only develop a high biomass if winter mixing supplied the surface layer with resting spores from the sediment (Hegseth et al. 2019). Typically, the phytoplankton bloom starts with chain forming diatom species, such as *Thalassiosira*, *Fragillariopsis*, or *Chaetoceros* species, potentially followed by a bloom of *Phaeocystis* once silicates become limiting (von Quillfeldt 2000). The phytoplankton spring bloom in ice-free areas of Svalbard is comparable to coastal regions and fjords in Northern Norway.

Summer primary production is controlled by sea ice cover and water masses and is spatially very variable. In fjords, primary production decreases due to nutrient limitations in the euphotic zone, and via light limitation in coastal waters with high sediment loads from glaciers and rivers (Hegseth et al. 2019). Some nutrients may be supplied via tidewater glacial upwelling, where nutrient rich bottom water is entrained in subglacial outflow and brought to the surface (Halbach et al. 2019). Also, direct inputs from land or seabirds may be an important source to coastal systems (Kulinski et al. 2014).

Potentially mixotrophic (organisms capable of autotrophic and heterotrophic carbon uptake) flagellates typically dominate summer communities in fjords. On the Atlantic water influenced western and southern shelf, nutrients at the surface are depleted and the chlorophyll maximum is typically deeper in the euphotic zone, which is dominated by flagellates and ciliates. Haptophytes dominate in Atlantic water, while *Micromonas pusilla* often dominates in Arctic or coastal waters (Not et al. 2005). Low phytoplankton and high zooplankton biomass in ice free areas indicates grazing as an important factor keeping algae biomass low (Owrid et al. 2000). Towards the ice edge in the east and north of Svalbard, primary production is actually the highest in summer with *Chaetoceros socialis* and *Phaeocystsis pouchetii* dominating and sea ice algae being abundant. A shallow stratification induced by ice melt at the edge facilitates ice edge blooms (von Quillfeldt et al. 2009). Primary production and phytoplankton biomass under summer sea ice is low with *Melosira arctica*, a typical multiyear ice alga, often dominating (von Quillfeldt et al. 2009).

In autumn, freshwater inflow stops. In fjords, this leads to decreased sediment inputs and light limitation, and a weaker stratification in the surface, allowing mixing of deeper nutrient-rich water masses. This may allow increased primary production, but, with the onset of polar night, light becomes insufficient for detectable primary production and algae abundances become low. North of the polar front and in some fjords, sea ice formation can start with frazil ice rising from different depths, concentrating organisms and particles on its way that are eventually incorporated into sea ice (Petrich et Eicken 2010, Garrison et al. 1989). Sea ice organisms are further incorporated via wave actions, and brine release. Mostly sticky particles and organisms are concentrated during this process. Eventually, the strong variations in salinity and temperature in the sea ice selects the typical sea ice taxa which are able to survive this broad range of environmental conditions (reviewed by Deming et Collins 2017, Vonnahme et al. 2020).

Autumn and winter communities shift from large diatoms to small pennates, such as *Fragillariospsis* (Lizotte 2003). The ability to excrete high amounts of EPS as potential freeze-protecting agents by pennate diatoms may explain their advantage in winter (Niemi et al. 2011). Eventually, the communities are dominated by small flagellates (Zhang et al. 1998, Kvernvik et al. 2018, Lizotte 2003). *Micromonas* may be the most abundant taxa in the beginning and end of the polar night (Leu et al. 2018, Marquardt et al. 2015). Other abundant taxa in the polar night are *Ostreococcus* and cyanobacteria (Vader et al. 2015, Joli et al. 2017, Amargant Arumí 2018). Considering the complete absence of light and any detectable photosynthesis, the abundances and activities of algae found are surprisingly high (Vader et al. 205, Berge et al. 2015, Kvernvik et al. 2018). Polar night algae can maintain their photosynthetic machinery and start photosynthesis quickly once the light returns (Kvernvik et al. 2018). Due to the lack of photodamage in the polar night, keeping photosynthetic proteins may not take too many resources. Hence, the advantage of allowing a quick initiation of the spring bloom outweighs the costs of keeping photosynthetic machinery throughout the polar night (Kvernvik et al. 2018). During the polar night, microalgae may survive via formation of resting spores in the water column or sediments, via storage compounds or heterotrophic carbon uptake.

Some algae may change their trophic mode from phototrophic to heterotrophic. Organisms capable of both phototrophy and heterotrophy are called mixotrophs. Known mixotrophs, such as ciliates, dinoflagellates, or *Micromonas*, are capable of feeding on bacteria or other algae when light or nutrients become limiting. These phagotrophic taxa are indeed common in polar night communities (e.g. Buchy et al. 2011, Vader et al. 2015). In Adventfjorden, the mixotrophic nanoflagellate *Micromonas* dominates the algae community in the beginning and end of the polar night (Marquardt et al. 2016). Diatoms are not capable of ingesting particulate organic matter, but they may switch to a heterotrophic mode via uptake of dissolved organic matter under light limitation (Tuchman et al. 2006). Antarctic diatoms have been described to take up increased amounts of ^{14}C labelled sugars and amino acids during the polar night (Palmisano et al. 1985, Rivkin et Putt, 1987), and similar survival mechanisms are also likely in the Arctic, but its importance is controversial (e.g. Zhang et al. 1998).

Another strategy for winter survival is the use of storage compounds, such as lipids and carbohydrates, while reducing metabolic activities, which may be one of the most important mechanisms for many species (Zhang et al. 1998).

Resting spores is another way to survive the polar night, but its importance is not clear. Only a few species have been found to form resting spores as a response to prolonged darkness (e.g dinoflagellates and *Chaetoceros*), while others are not capable of building resting spores (e.g. *Nitzschia*). Resting spores overwinter mostly in the sediments but may be contained in the water column in low concentrations. For resting spores in sediments to become important for the spring bloom, a full mixing event is needed. In fact, delayed spring blooms in Kongsfjorden have been attributed to a lack of mixing, showing the importance of resting spores for this system.

Food chains and the transfer of nutrients from sea to land.

Biomass created by primary producers is consumed at all levels. The important links of the food chain are shown in Fig. 6.11.

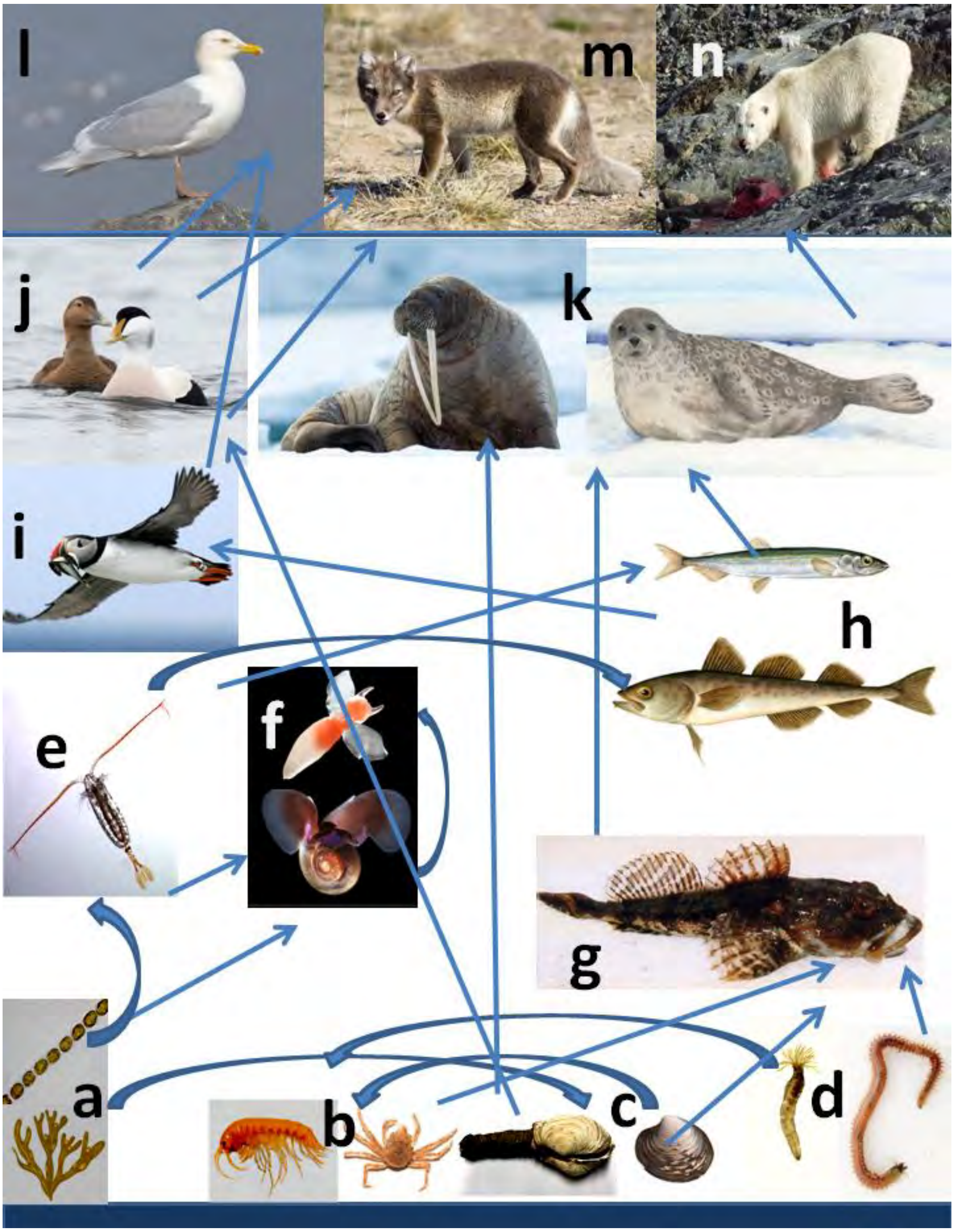


Fig. 6.11: Examples of significant food chain links in the Svalbard shelf seas from producers to top predators: (a) primary producers; (b) benthic crustaceans; (c) benthic molluscs; (d) benthic polychaetes; (e) planktonic crustaceans; (f) planktonic molluscs; (g) benthic fish; (h) pelagic fish; (i) piscivorous seabirds; (j) benthos feeding seabirds; (k) pinnipeds; (l) *Larus hyperboreus*; (m) *Vulpes lagopus*; (n) *Ursus maritimus* (Ditrich).

A large number of animals from different phyla live in the sediments of the seabed. In terms of biomass, polychaete worms (Annelida), including sessile filter feeders, are significant. Another important group are marine molluscs, especially bivalves. In some places, up to hundreds of bivalves of the genus *Astarte* can be found on 1 m^2 of bottom, with very solid shells that resist most predators. Predators prefer bivalves with more fragile shells, e.g. *Mya truncata* is a favorite prey of starfish (e.g. *Marthasterias glacialis*), predatory snails (*Buccinium* spp.), eiders *(Somateria mollissima*) and walruses (*Odobenus rosmarus*). In the shallow waters of the coastal zone, crustaceans of the genus *Gammarus* play an important role, reaching significant densities in some places (Weslawski 1994). In terms of energy flow, the planktonic branch of the food chain is much more important. Planktonic crustaceans of the genus *Calanus* (especially *C. glacialis* and *C. finmarchicus*) play an essential role. In addition to the sea breams *(Mertensia ovum* and *Beröe cucumis*), other important macroplankton include the opisthobranchiate gastropods *Limacina helicina* and its specialized predator *Clione limacina*. Among pelagic fishes, the Arctic cod *Boreogadus saida* plays an important role, mainly due to its ability to live under the ice sheet and transport nutrients to the open sea and back (Lønne et Gulliksen 1989). This species is a favourite prey of larger pelagic fish, piscivorous birds and seals. Also, although it is significantly smaller than most other cod species, it is an important fish for commercial fisheries.

Among birds, the top predator on Svalbard is the glaucous gull *Larus hyperboreus*, which, thanks to the absence of predators, has occupied their ecological niche. Glaucous gulls have also adapted their behaviour and nesting: while on land they behave similarly to other species of gulls socially, but in Svalbard they behave territorially and often build their nests near colonies of other species of birds, which they use as a main food source. Arctic foxes *Vulpes lagopus* also participate in the transport of nutrients from the sea, by eating carrion washed ashore. Polar bears, true top predators, are specialized in hunting pinnipeds, especially seals. We have described only the conspicuous links of the food chain in Svalbard. Marine food chains have been very carefully studied and described in detail in the Kongsfjord area (Hop et al. 2002).

Cetaceans also enter the Svalbard food chains to a significant extent, especially beluga whales *Delphinapterus leucas* and minke whales *Balaenoptera acutorostrata*. The chain continues after their death and beaching, involving birds (fulmars and seagulls) and mammals (arctic foxes and polar bears). With restrictions on whaling, there are more whales in Svalbard's waters, and the carcasses which wash ashore often help the bears survive a season without enough sea ice. Marine birds play a major role in the transport of nutrients from sea to land. Fig. 7.11 shows prominent examples of food-specialized birds transporting nutrients from sea to land.

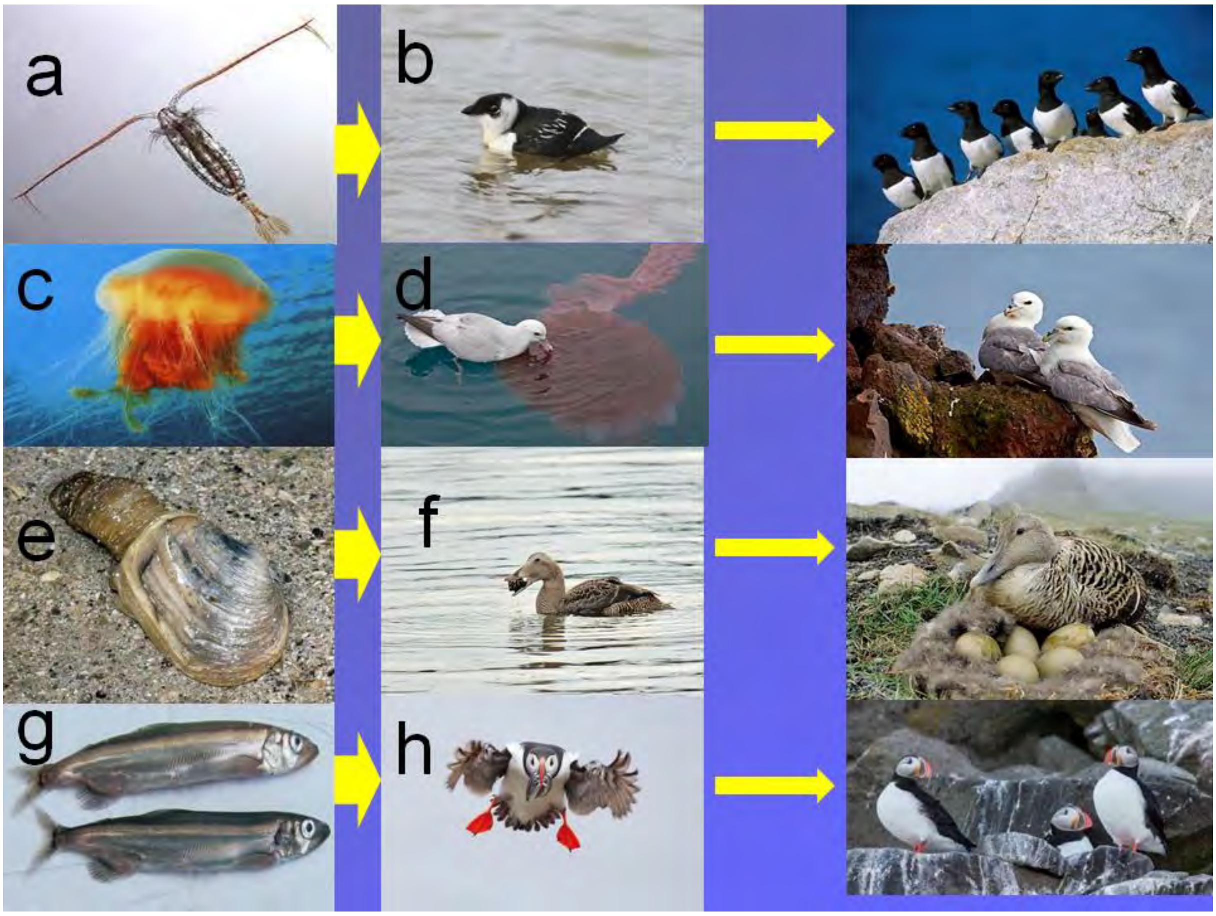


Fig. 7.11: Conspicuous examples of nutrient transport from sea to land in Svalbard by food-specialized birds: (a) *Calanus glacialis*; (b) *Alle alle*; (c) *Cyanea capillata*; (d) *Fulmarus glacialis*; (e) *Mya truncata*; (f) *Somateria mollissima*; (g) *Mallotus villosus*; (h) *Fratercula arctica* (Ditrich)

The transfer of nutrients from the sea to the land differs for individual Svalbard bird species, mainly due to their food specialization and nesting method. For example, the little auk *Alle alle* feeds on planktonic crustaceans, and its nesting sites are often located at greater distances from the sea, which is important for the transport of nutrients. The northen fulmar *Fulmarus glacialis* collects carrion from the sea surface and nests on inaccessible rocks near the sea. Common eiders *Somateria mollisima* on the other hand, specialize in benthic molluscs, especially bivalves with a fragile shell, but when they are lacking, they also consume a considerable amount of sea urchins (for example, *Strongylocentrotus droebachiensis*). They often nest in places far from the sea, for example near freshwater lakes, and thus transport nutrients over a longer distance. The piscivorous atlantic puffin *Fratercula arctica* specializes in capelins *Mallotus villosus* in Svalbard.

12. Vegetation of Svalbard, its origin, development and current appearance: adaptation of Arctic plants and the impact of current global climate change on Arctic vegetation

Viktorie Brožová

The origin of Arctic vegetation and its development to its current form.

The first signs of emerging tundra and methods of studying historical vegetation.

The Arctic biome is very young compared to other biomes. The first vegetation with the characteristic features of the Arctic tundra was only recorded around 2.5 million years ago [1], when the Earth began to cool and slowly changed from the Tertiary to the Pleistocene. At that time, vegetation adapted to cooler and harsher conditions began to dominate near the poles, and the Arctic biome was established (Basinger et al. 1994). Since then, many changes in vegetation composition have occurred due to the relatively rapid climatic changes of oscillating ice ages (glacials) and interglacials. Recent Arctic vegetation is the result of these historical processes, which have left traces on the composition of the biota.

The composition of historical vegetation can be reconstructed by different approaches. The further back in history we go, the more difficult it is to obtain sufficient information about the environment. The most traditional, going deepest in history, but also the least accurate (we often find only parts of organisms and determination of the organisms depends purely on morphology; Sander et Gee 2021) and the most difficult source to access, are fossils. The most common plant fossils are pollen grains. Vegetation in the younger history can be reconstructed, for example, from the pollen record or macrofossils, or from DNA preserved in the soil. Both methods, however, generally fail to provide information older than a few tens of thousands of years, because plant parts and DNA degrade over time. The deepest look into the history of vegetation in the Arctic based on sedimentary DNA was performed by Crump et al. (2021), who reconstructed vegetation in northern Canada during the penultimate interglacial 100–130 thousand years ago.

In the Tertiary, before the Pleistocene cooling, the Arctic was much warmer and covered by continuous forests, as documented in fossil records from Canadian islands in the high Arctic (Basinger et al, 1994) and northern Greenland (Boyd 1990). Representatives of Taxodiaceae, Cupressaceae, Pinaceae, Ginkgoaceae, Platanaceae, Juglandaceae, Betulaceae, Menispermaceae, Cercidiphyllaceae, Ulmaceae, Fagaceae, and Magnoliaceae have been found here, indicating that climatic conditions were humid and temperate. In particular, the presence of the cold-sensitive Taxodiaceae shows that even dark winters without sunlight were free from severe frosts. Cooling towards the Pleistocene began in the mid-Tertiary, when pines became more abundant with the emergence of semi-deciduous forests (Basinger et al. 1994).

[1] By comparison, the formation of the tropical rainforest biome is estimated by some to be as early as 100 Ma (Upchurch et Wolf 1987; Davis et al. 2005).

Arctic vegetation during the Pleistocene cooling

The Pleistocene period started approximately 2.5 million years ago and lasted to 11.7 thousand years before present. This period is characterized by a series of glacials and interglacials. During the glacials, large areas in the Arctic and Antarctica were covered by ice sheets. Repeated glaciation and deglaciation caused extensive changes in the ranges of individual species. In the case of cold-adapted species which are used to harsh conditions and open vegetation, the glacials were usually a period of prosperity when they occupied much larger areas than today. In the interglacials, however, they retreated to marginal ranges. Plants which tolerate harsh Arctic conditions, but have an optimum in milder conditions, had the opposite tendency – retreating to refugia during the glacials and expanding in the interglacials. In both cases, this frequent expansion, contraction and shifting of ranges may have resulted in their overall reduction or complete disappearance (Clarke et al. 2019; Theodoridis et al. 2017).

Species that have persisted to the present day retreated to the southern edge of the ice sheet or to unglaciated refugia during the glacial periods. The most important of the Arctic refugia is Beringia, an area located between the Lena River in north-eastern Russia, the Mackenzie River in north-western America, the Arctic Ocean, southern Alaska, and the central Kurils (Hultén 1937). In the Pleistocene, the Bering Strait was above sea level and thus served as a land bridge between the two current coasts of Beringia. This area did not serve only as an unglaciated refuge, but many species also originated here. Even today, Beringia still has significant species and genetic diversity (Abbott et Brochmann 2003; DeChaine 2008). Although Beringia was the only refugium that remained unglaciated throughout the Pleistocene, several other Arctic refugia existed during the Pleistocene, but they were of minor importance, and / or were present only for short periods. Central Europe and the southern Ural Mountains have been reported as significant minor refugia. Refugia in the Lena and Kolyma rivers have also been proposed on basis of genetic uniqueness (Hewitt 2004). In North America, the most important refugia were situated on Ellesmere and Bathhurst islands, and additional refugia have been suggested in continental parts of the unglaciated Arctic Canada, south of the ice sheet covering part of the USA, and on the east coast of North America (Hewitt 2004).

Modern Arctic Vegetation

The formation of recent Arctic flora began with the gradual retreat of the last ice age glaciers and has continued ever since. The Last Glacial Maximum (LGM) is reported to have occurred 26.5-19 thousand years ago (depending on location; Dyke 2004; Hughes et al. 2016; Young et Briner 2015); at that time, European continental glaciers extended from the north to Poland and England (Hughes et al. 2016). Since then, continental glaciers on all continents have slowly begun to shrink, enabling plants to recolonize the land. At the beginning of the Holocene, the High Arctic also began to deglaciate. The progression of deglaciation has been recorded in detail by Dyke et al. (2003), Hughes et al. (2016) and Young and Briner (2015).

Climatic changes not only occurred in the Pleistocene, but a series of climatic changes also had a major impact on vegetation during the Holocene. The direction of Holocene climatic change was similar across the Arctic, although there were minor local differences in the severity or timing of the changes. The Holocene climatic changes can be illustrated in Svalbard (an archipelago in the European High Arctic, 74°20′ -80°50′ N, 10°30′ -33°30′ E), where climate change has been described in detail. After deglaciation, the so-called Holocene climate optimum occurred, when the warmest and most favourable climatic conditions of the Holocene have been registered (Alsos et al. 2016; Birks 1991; Hald et al. 2004; Hyvärinen 1970; Mangerud et Svendsen 2018; Miller et al. 2010; Salvigsen et al. 1992; Salvigsen et Høgvard 2006; Svendsen et Mangerud 1997); Svalbard is reported to have had a climate up to 6 °C warmer than today (Mangerud et Svendsen 2018). The Holocene optimum was recorded in Svalbard between 10.2–9.2 thousand years ago. During the Holocene optimum, Svalbard had the smallest extent of glaciation and the most favourable temperature conditions, so that plants able to tolerate competition, but the least harsh climatic conditions, had the opportunity to establish. For these thermophilic species, the Holocene optimum was a perfect period for dispersal in general, as warming was evident throughout the Arctic. The Holocene optimum was followed by a cooler period, followed by another slight warming, but less intense than the first one (Mangerud et Svendsen 2018). About 6,000 years ago, the climate began to gradually cool towards current temperatures.

Species dispersal pathways

The pathways of plant dispersal across the Arctic during the Holocene have been well described. Most trajectories led from refugia, or from the southern margins of continental glaciers northwards. Many species found their way eastward or westward from Beringia. Rocky Mountain refugia supplied areas of northern and northwestern North America, Siberian refugia served as a source for the entire Siberian region, and the alpine zones of Europe were essential to the European Arctic (Hewitt 2004). Although long-distance dispersal (LDD; Alsos et al. 2015; Muñoz et al. 2004; Nathan 2006; Robledo-Arnuncio et al. 2014; Sauer 1988) is typical for Arctic plants and minor geographic barriers therefore do not play a significant role in successful dispersal, several major barriers limit dispersal. In general, dispersal barriers are water bodies and mountain ranges (for North Atlantic species, these are the Alps, the Appalachian Mountains, or the Mediterranean Sea; Hewitt 2004). The main dispersal barriers for Arctic species are the Arctic and Atlantic Oceans, the Greenland Ice Sheet, and the Ural Mountains. Smaller barriers are the Siberian Omolon/Kolyma and Lena rivers (Eidesen et al. 2013).

The spatial distribution of each species is a consequence of not only historical processes and geographical constraints, but also several abiotic and biotic environmental factors. The dispersal of a species to a new location is conditioned by the presence of a suitable dispersal vector (wind, water currents, sea ice, or animals; Alsos et al. 2007, 2016), the direction of its action, and the distance of the target site from the source site. Consequently, even if a species is able to spread, there is no certainty that it can establish a viable population - suitable environmental conditions must be found at the target site for this to happen. A suitable climate, a suitable site size, a free niche, and often the presence of a suitable pollinator is necessary for the establishment of a population. The lack of pollinators in the Arctic due to unsuitable climatic conditions is therefore reflected in the reproductive systems of plants in the Arctic. Self-pollination independent of pollinators predominates (Bell et Bliss 1980, Molau 1999, Molau et Prentice 1992, Richards 1986, Savile 1972) while pollinator-dependent species only sparsely occur (e.g. *Pinguicula alpina* in Svalbard).

In summary, the young Arctic vegetation is the result of the interaction of many biotic and abiotic factors and processes. The dynamic history of the Arctic, with repeated glaciations of large parts of the Arctic, has caused changes in ranges and has depleted the flora of some species. In contrast, the Arctic isolated refugia have given rise to new species and unique genetic lineages, which served as diverse sources for interglacial recolonization. Recolonization was mediated by many vectors (especially abiotic ones) and the establishment of populations often depended not only on suitable biological conditions (free niche, presence of pollinators), but especially on abiotic factors (suitable climate).

Current Arctic vegetation - definition, characteristics and composition

The definition of tundra

The Arctic is not strictly defined. Opinions on its definition vary and the concept of the Arctic has become more of a philosophical question. The Arctic is most often defined geographically – by the Arctic Circle, the 10 °C July isotherm, or permafrost extension (Vauget et al. 2021). From a vegetation perspective, it is most sensible to look at the Arctic delimitation specifically in terms of vegetation, and to draw the Arctic line along the northernmost forest line, and southernmost tundra boundaries, respectively. The tundra currently covers only a small percentage of the Earth's surface, which is a consequence of how small the area of land around the North Pole is compared to the oceans. The extent of tundra in Antarctica is almost negligible because of the extensive glaciation of the land and the broad belt of the Southern Ocean. This means that the vegetation stage on land outside of Antarctica misses the tundra stage and moves straight into the boreal stage. Tundra is defined as "low-growing vegetation beyond the cold limit of tree growth, both at high elevation (alpine tundra) and at high latitude (Arctic tundra)" (CAVM Team 2003). For our purposes, we will focus on tundra defined by latitude, not elevation, although the two habitats share many common features.

Composition of vegetation in the tundra

Approximately 2,218 species can be found in the Arctic tundra according to the Pan-Arctic Flora Database (PAF; http://panArcticflora.org). This number is only an approximation, as taxonomy (the field dealing with the classification of organisms) is a living field and the concept of species is conceptualized differently by each author (de Queiroz 1998). Nevertheless, we can use this number and compare the abundance of the Arctic flora with the global flora, which contains approximately 300,000 species (Christenhusz et Byng 2016). The low number of species for the whole Arctic biome is not only a consequence of the small size of the biome, but mainly due to the harsh and specific conditions prevailing in the polar regions. A total of 430 genera in 91 families are found in the Arctic and very few species are purely Arctic specialists. The PAF lists only 106 endemic species, which is one of the consequences of the young age of the Arctic biome. Because the Arctic is so young and its history has been formed by frequent changes in species composition and ranges, the environment has not provided much room for endemic species to evolve. In contrast, the Arctic flora is composed primarily of representatives of generally very species-rich families. The dicotyledonous families, which are represented by more than 100 species in the Arctic, include the Asteraceae, Brassicaceae, Caryophyllaceae, Fabaceae, Ranunculuaceae, and Rosaceae. The most numerous monocotyledonous families are the Cyperaceae and Poaceae.

As described in the previous section, the composition of vegetation in different parts of the Arctic is the result of the combination of many abiotic and biotic factors. In the case of long-distance dispersal, as is common in the Arctic and even necessary in the case of islands, it is often a matter of chance which species can get that far and establish a population. Svalbard, for example, has no representative of the

Fabaceae family, although it is a very common family in other parts of the Arctic. Despite this peculiarity, Svalbard is unexpectedly rich, considering its high latitude location, its relatively small size, and the long distance from source localities. This richness is maintained due to the presence of the warm West Spitsbergen Current, which washes the western coast of the archipelago and stabilizes its climate, and due to its central geographic position between Siberia, Scandinavia, and Greenland, with all three of these landmasses serving as sources of plant propagules (Alsos et al. 2007).

Composition of Svalbard vegetation

Approximately 200 native species are registered in Svalbard, of which approximately 20 are introduced (https://svalbardflora.no). Svalbard has only two endemic species. The first is *Ranunculus wilanderi*, which occurs in a single locality, Cape Kapp Thordsen. It belongs to the group of apomictic buttercups from the *R. auricomus* complex, which is characterized by lineages of asexual species that spread by asexually produced seeds. The other endemic species is *Puccinellia svalbardensis* which is found in four localities and reproduces sexually. How these species came to Svalbard, or how they originated here, is still a mystery (https://svalbardflora.no).

The general characteristics of the Svalbard flora in general can serve as a concrete example of the Arctic flora. The Svalbard flora is dominated by perennial herbs, some are succulent (*Saxifraga aizoides*, *Honckenya peploides* ssp.*diffusa*), some are woody shrubs (e.g. *Dryas octopetala* , *Salix* spp., *Betula nana*, *Vaccinium uliginosum* spp. *microphyllum* , *Empetrum nigrum* spp. *hermaphroditum*, and only two native species are annuals (*Euphrasia wettsteinii*, *Koenigia islandica*). Although most species reproduce sexually (60 % of species in total), a relatively large percentage of species use a combination of sexual and asexual reproduction (22 % in total) and a surprisingly large proportion of the flora rely solely on vegetative reproduction (17 % in total; Brochmann et Steen 1999).

“Raunkiaer's life form system” (Raunkiaer 1934), which defines growth forms according to the arrangement of regenerating buds, can be useful in describing the Svalbard flora. In the Arctic, by definition, tree forms do not grow and as mentioned, therophytes (or annual plants) are very rare. Hemicryptophytes (i.e., perennial plants with regenerating buds just below the soil surface) are the most common, while chamaephytes and cryptophytes are less common (Crawley 1996). In addition to Raunkiaer's traditional forms, we can also find many interesting growth forms that are typical for tundra. The most typical and obvious is the so-called cushion form (Fig. 1.12), which maintains a favorable climate for the plant. It protects organs from wind abrasion, increases the temperature inside the cushion, maintains humidity and attracts a higher number of pollinators due to the high abundance of flowers (Reid et al. 2010, Reid et Lortie 2012).

Fig. 1.12: Cushion form of moss campion *Silene acaulis* (CPE archive).

Bryophytes and lichens

So far, we have discussed only one part of the vegetation concerning the vascular plants. In the Arctic, however, it is important not to forget about mosses and lichens. While on a global scale these two groups are numerically negligible, in the Arctic there are approximately the same number of species of mosses and lichens as vascular plants. In Svalbard, the ratio is even shifted in favour of bryophytes and lichens (Barry et al. 2013).

Mosses, or bryophytes, are small plants that do not have a vascular system for the distribution of water and nutrients; therefore, they absorb water and nutrients through their surface. However, they tolerate a lack of water and can survive long lasting droughts. They also have no true roots and are therefore attached to the soil only by shallow rhizoids. Although they tolerate harsh climatic conditions, they struggle under competition with vegetation of taller plants that easily deprive them of their living resources. These characteristics make mosses good pioneer species for newly colonized environments with undeveloped soils, such as in the Arctic. There are 900 species of mosses in the Arctic (according to The Arctic Biodiversity Assessment (ABA); http://www.caff.is/) out of approximately 13,000 described species worldwide (Magill 2010). Moreover, mosses in the Arctic are not important only due to species richness, but they also create the dominant vegetation coverage of many habitats. In Svalbard, where more than 370 species have been recorded, bryophytes dominate in wetlands, springs, as well as dry and mesic habitats (Elvebakk et Prestrud, 1996). Their high abundance is not only due to the aforementioned characteristics of bryophytes, but also to their easy asexual clonal reproduction, where they form entire colonies of genetically identical plants.

Lichens are a very unique part of the vegetation. They are not single plants, but a symbiosis of algae or cyanobacteria and fungi. Yet, for historical reasons, they have their own classification similar to the species classification of plants. Their ecological characteristics are somewhat similar to those of mosses. However, their tolerance to drought is much higher - on the contrary, they even prefer exposed and elevated surfaces that are free of other vegetation and are well exposed to sunlight. In Svalbard, 742 species have been described, of which 12 species have not yet been found elsewhere, and at the same time more than one third are found in both polar areas (Øvstedal et al. 2009). In fact, wide ranges and bipolarity are typical for lichens (Lücking 2003).

Thus, as mentioned in the previous section, here we have seen that the Arctic flora is young and low in species richness. However, some diversity can still be found here, and this is mainly among lichens, bryophytes, and within the perennial herbs.

Vegetation types in the Arctic - why they exist, how they are formed and their description.

The Arctic biome, or Arctic bioclimatic zone, is defined by the Circumpolar Vegetation Mapping Team (CAVM Team 2003) as an area with tundra, Arctic climate, Arctic flora, and a forest boundary to the south. This definition excludes from the Arctic the oceanic regions of Iceland, the Aleutian Islands and the alpine regions.

Within the Arctic, however, great differences in vegetation composition and structure can be traced depending on latitude. These differences are due to the zonality of climate across latitudes in the Arctic. Light and radiation conditions change significantly with each degree of latitude. However, the regularity of climate change with latitude can be significantly skewed by the positions of landmasses and ocean currents, as has already been described for the Svalbard system influenced by the warm West Spitsbergen Current (see Current Arctic vegetation). Latitudinal zonation is nevertheless well defined. Generally speaking, vegetation cover, the proportion of organic matter in the soil, and the soil nutrient supply decrease with increasing latitude and decreasing temperature. Conversely, unoccupied area increases, and the soil becomes more susceptible to disturbances caused by climate and repeated freezing and thawing of the soil (Wookey et al. 2009). Also, the depth of the active zone (i.e. the layer of soil that thaws over the summer and provides space for plants to grow), the soil water regime and the impact of permafrost on vegetation change with latitude. At lower latitudes, the active layer is deeper, so vegetation has the potential to draw nutrients and water from a deeper profile resulting in a more biomass-rich and continuously distributed flora. In contrast, at higher latitudes, the permafrost is close to the soil surface, the active layer is therefore shallow, and vegetation tends to be much less continuous and has lower growth (Wookey et al. 2009). Based on this zonation, five bioclimatic subzones A-E (hereafter referred to as "zones"; CAVM Team 2003) have been described.

Zone A

This is the most extreme bioclimatic zone. The average temperature in July ranges between 0 and 3 °C. It is mainly barren ground, sometimes covered only with lichens or mosses up to 2 cm high. The moss layer covers 40 % of the soil. Vascular plants have a cover of less than 5 % and often do not exceed the moss layer. Overall, there are less than 50 plant species according to the local flora.

Zone B

The milder Arctic zone has an average July temperature of 3-5 °C. The vegetation here has two layers, a moss layer (1-3 cm high), and an herbaceous layer (5-10 cm high). Within the herbaceous layer, there may be dwarf shrubs, but no more than 5 cm high (e.g. Salix spp.). Herbaceous plants cover 5-25 % of the soil surface, while the mosses can have a cover of around 60 %. We can find 50-100 species depending on the local flora.

Zone C

In the Central Arctic zone, the average temperature in July is 5 to 7 °C. The moss layer here is higher than in Zone B, reaching 3-5 cm. The herb layer grows from 5 to 10 cm and dwarf shrubs can be up to 15 cm tall. Vegetation cover can vary from 5 to 50 %. There can be 75-150 species in this zone.

Zone D

The second mildest zone has average July temperatures between 7 and 9 °C. The moss layer here reaches 5-10 cm, and the herbaceous layer can include dwarf shrubs, which grow 10-40 cm tall. Cover is between 50 and 80 %; discontinuous vegetation is found. There are 125-250 species, depending on the local flora.

Zone E

The warmest Arctic zone has a mean July temperature between 9 and 12 °C. The moss layer here reaches a height of 5-10 cm and the herbaceous layer 20-50 cm. A true shrub layer reaching a height of 80 cm is also found here. The vegetation is continuous with a cover of 80-100 %. The number of species varies between 200 and 500.

The influence of microclimate on vegetation

These definitions obviously correspond to the average characteristics of large areas. In detail, we can find multiple bioclimatic zones in a smaller area and can even find characteristics of multiple zones in a very small area of a few square meters. This is the result of several factors. One of them is the shallow organic soil, which makes the influence of the bedrock more pronounced than at lower latitudes - the pH of the bedrock strongly influences both the composition and density of vegetation (Jónsdóttir 2002). Microtopography also has a significant influence. Small differences in topography can affect the amount of accumulated snow in winter, the rate of snowmelt, water availability and wind conditions during the growing season (Jónsdóttir 2005). In general, elevated sites have lower snow cover during winter due to higher wind exposure, the snow melts early, the active layer is deeper, summer temperatures are higher and due to good soil drainage and low organic matter accumulation, no water is retained, and droughts occur during the summer (Jónsdóttir 2005). Opposite factors affect snow beds, which may occur only a few meters away from elevated sites. In snow beds, the growing season does not start until several weeks later due to high snow accumulation in winter and late thawing. Temperatures in the summer do not reach high numbers due to the more developed vegetation and the high potential to retain water. Therefore, the accumulation of organic matter is also much higher (Jónsdóttir 2005).

Significance of gradients in the Arctic

Other gradients that strongly influence changes in vegetation are reduced salinity moving away from the sea, or below bird cliffs (i.e. rock formations used by bird colonies for nesting), where nutrients accumulate due to bird droppings and nutrient concentrations slowly decrease downslope. The vegetation on this specific nutrient gradient has been well described using the example of the Casimir Perierkammen bird cliff on Svalbard (Odasz 1994). The narrow strip of land directly below the cliff tends to be bare of vegetation due to the extremely high, toxic nutrient concentrations. Below this 'dead zone', the vegetation becomes species poor (Groenland scurvy-grass *Cochlearia groenlandica* (Fig. 2.12) dominates and *Puccinellia angustata*, *Draba arctica*, and *D. rupestris* are commonly found here), but the individuals are several times larger than the average for Svalbard.

Fig. 2.12: Greenland scurvy-grass *Cochlearia groenlandica* (CPE archive)

This also applies for the following zone, which is also very species-poor (*Oxyria digyna*: Fig. 3.12) dominates with *Poa pratensis*, *Draba alpina*, *D. glabella*, and *D. micropetala*. Other zones no longer suffer from an extreme nutrient input and diversity increases. In the next zone dominated by *Cerastium arcticum* (Fig. 4.12) we find, among others, *Taraxaum brachyceras*, *Poa arctica*, *P. alpina*, *Bistorta vivipara*, and *Potentilla hyparctica*. Vegetation at lower elevations varies considerably between sites depending on bioclimatic zone, moisture regime, slope exposure, and soil pH. Odasz (1994) described three more vegetation zones, the first dominated by Saxifraga hieracifolia, which corresponds to a deeper, tall-herbs tundra with well-developed soils. The second zone is dominated by *Saxifraga cespitosa* and is more of a drier and lower vegetation type. In the lowest zone below the bird cliff, they found shrubby vegetation (*Dryas octopetala*, *Cassiope tetragona*: Fig. 5.12, *Salix reticulata*) with a representation of sedges (*Carex misandra*, *C. rupestris*, *C. nardina*: Fig. 6.12) and some broad-leaved herbs (Odasz,1994).

Fig. 3.12: Alpine mountain sorrel *Oxyria digyna* (CPE archive)

Fig. 4.12: Arctic mouse-ear *Cerastium arcticum* (CPE archive)


Fig. 5.12: Arctic bell heather *Cassiope tetragona* (CPE archive)


Fig. 6.12: Arctic sedge *Carex nardina* (CPE archive)

Because Arctic vegetation is so highly variable even within very small areas, it is often difficult to define a proper bioclimatic zone for a larger area. Therefore, the so-called zonal vegetation has been defined

(Walker 2002). This is vegetation on a moderately steep slope with average snow accumulation, soil moisture and disturbance.

Detailed vegetation map of the Arctic

Because of the variability in vegetation cover within each bioclimatic zone, the CAVM Team (2003) created a detailed vegetation map of the entire Arctic based on differences in vegetation. This map includes four degrees of barren land (found in all Arctic zones), four degrees of graminoid tundra (also found in all zones), two degrees of prostrate-shrub tundra (typical of zones B and C), two grades of erect-shrub tundra (extending only into zones D and E), and three grades of wetlands (belonging to zones B-E).

Barren land (Barrens) is subdivided into four degrees with two of these further divided into five to six sub-stages. Degree B1 (cryptogam, herb barren) includes a wide range of dry to wet wastelands with sparsely scattered vegetation, very low herbaceous vegetation (e.g. *Papaver dahianum* (Fig. 7.12), *Draba* spp., *Saxifraga oppositifolia* (Fig. 8.12), mosses and lichens. Degree B2 (*Cryptogam barren complex, bedrock*) is typical of the Canadian Shield and is characterized by a mosaic of exposed bedrock with lichens, lakes and areas of higher density vegetation. The third and fourth stages are mountain-related, with the size and richness of vegetation decreasing with elevation. The third B3 degree (non-carbonate mountain complex) includes acidic rocks, while the fourth B4 degree (carbonate mountain complex) includes basic rocks. The B3 and B4 sub-stages correspond to the affiliation to each bioclimatic subzone (e.g., B3a is found in zone A, B3b in zone B, etc.). The last sub-stage corresponds to nunataks - rock masses protruding above the glaciers.

Fig. 7.12: Svalbard poppy *Papaver dahlianum* (CPE archive).

Fig. 8.12: Purple saxifrage *Saxifraga oppositifolia* (CPE archive).

The first of the four degrees of graminoid tundra is G1 (Rush/grass, forb, cryptogam tundra), which is a tundra dominated by grasses, rushes (*Luzula* sp.), and cryptogam crusts. It is a moist tundra with moderate to full cover of very low-growth vegetation. In addition to grasses and rushes, herbs, bryophytes and lichens grow here. The G2 tundra (graminoid, prostrate dwarf-shrub, forb tundra) is found on non-acidic soils, which can be wet or dry with full vegetation cover. It is dominated by sedges (*Carex* sp.), and prostrate or dwarf-shrubs, namely willows (*Salix* spp., fig. 9.12), *Dryas octopetala* (Fig 10.12) and *Cassiope tetragona* in the snow beds. This is typically the zonal vegetation of bioclimatic zone C. Degree G3 (non-tussock sedge, dwarf-shrub, moss tundra) on non-acidic soils is defined as a moist tundra with a developed moss layer and dominated by non-tussocky sedges (mainly *Carex* sp.) and dwarf shrubs up to 40 cm tall (*Salix* sp.). G4 is a moist tundra of acidic soils with a shallow active layer and dominated by tussocky sedges (*Eriophorum vaginatum*, *Carex lugens*), dwarf shrubs, and mosses.

Fig.9.12: Polar willow *Salix polaris* (CPE archive).

Fig.10.12: Mountain avens *Dryas octopetala* (CPE archive).

Prostrate-shrub tundra has two degrees. The first degree P1 (*Prostrate dwarf-shrub, herb tundra*) is a dry tundra with scattered prostrate shrubs no more than 5 cm high (*Salix* sp., *Dryas*), graminoids, and herbs. Lichens are often found in places without vascular plants. This is the zonal vegetation of bioclimatic zone B. P2 *(*prostrate/hemiprostrate dwarf-shrub tundra) is a dry to moist tundra with prostrate to dwarf-shrubs up to 15 cm tall (*Cassiope tetragona*).

Erect-shrub tundra also has two degrees. Degree S1 (erect dwarf-shrub tundra) is dominated by shrubs up to 40 cm tall, while degree S2 (*Low-shrub tundra*) is dominated by shrubs over 40 cm tall (*Betula* sp., *Vaccinium* sp., *Ledum palustre*, *Empetrum nigrum*, *Salix* sp., *Cassiope tetragona*). S1 is the vegetation of zone D, while S2 belongs to zone E. Scattered *Pinus pumila* can be found in S2 (in eastern Siberia).

The last vegetation type is *Wetlands,* which is divided into 3 degrees. W1 (*Sedge/grass, moss wetland*) are wetlands of the cooler parts of the Arctic with a dominance of grasses, sedges (*Carex* sp., *Eriphorum* sp.), and mosses. The wetlands of bioclimatic zone D are classified as W2 (*Sedge, moss, dwarf-shrub wetland*). Apart from grasses, non-tussocky sedges and mosses, shrubs up to 40 cm tall (*Ledum palustre*, *Salix* sp., *Empetrum nigrum*, *Betula nana* s.l., *Vaccinium* sp.) grow here. In the wetlands of zone E, degree W3 (*Sedge, moss, low-shrub wetland*) contains shrubs over 40 cm in height (in addition to the above-mentioned, *Rubus chamaemorus*, *Oxycoccus microphyllum*).

As can be seen, the Arctic biome is very rich in terms of habitats. There is great variability in abiotic conditions, which influences local vegetation cover. We can find polar deserts without vegetation or with lichen and moss cover, as well as wetlands and developed shrub tundra.

Adaptation of Arctic plants to factors limiting plant growth in the Arctic

Adaptations are deeply imprinted in the genome of organisms through evolution. Plants in the Arctic have therefore mostly already arrived in the Arctic with specific adaptations to local conditions, otherwise they would not be able to establish viable populations there. Due to the very unique and harsh environmental conditions in the Arctic, plants must be adapted in many ways. The most important of these is adaptation to low temperatures, because temperature is a crucial factor for all physiological processes; Arctic plants have mastered this adaptation perfectly and low temperatures do not pose a barrier for them, as Chapin (1983) explains in his review. Nevertheless, low temperatures limit the growth and distribution of Arctic plants indirectly by affecting other biotic and abiotic factors necessary for plant growth (Chapin 1983).

Photosynthesis in Arctic

The most important physiological process for plants is photosynthesis, which enables plants to fix carbon into their tissues and grow. Under temperate conditions, the optimum temperature for photosynthesis is 25 °C; however, Arctic plants have been able to push the optimum to 15 °C (Chapin et Oechel 1983; Tieszen 1978) by increased concentrations of the enzyme RuBP carboxylase (Berry et Björkman 1980), which is responsible for photosynthetic efficiency. This innovation not only shifted the optimum for photosynthesis to lower temperatures, but even allowed photosynthesis to function at 0 °C (Chapin 1983).

Thus, photosynthetic efficiency is rather indirectly suppressed by other environmental factors including low temperatures. One factor, for example, is late snowmelt and vegetation exposure. Snow cover often does not melt in the high Arctic until late June, when solar activity is at its maximum, and plants therefore do not begin to photosynthesize until the second half of the polar day, when solar activity begins to decline (Chapin 1983). Photosynthesis (hence the entire growing season) therefore takes place for only a short period of time, limited at the beginning by snowmelt and at the end by the onset of the polar night.

Nutrients as a limiting factor

To grow, plants need other nutrients besides carbon, especially nitrogen and phosphorus, which are the main limiting factors in the Arctic (Bliss et al., 1984, Güsewell 2004, Olofsson et al. 2004, Shaver et al. 1992, Soudzilovskaia et al. 2007, Weintraub et Schimel 2005). Phosphorus uptake is limited by low temperatures in temperate areas; no such limitation occurs in the Arctic however (Chapin et Bloom 1976, McCown 1978). In this case, we do not observe a shift of the optimum, but a resistance to low temperatures. That is, the optimum temperature for phosphorus uptake is the same for both temperate and Arctic plants, but Arctic plants do not stop nutrient uptake at low temperatures (Chapin 1983). Specifically, Arctic plants are adapted to increased phosphorus uptake under all temperature conditions (Chapin 1974, McNaughton et al. 1974), including low ones. They manage this by increased respiration (Billings et al. 1971) to which they also need to increase nitrogen uptake. But because of the general limitation of nitrogen in the environment, abnormally high phosphorus uptake is not obvious and is only manifested by its presence at low temperatures.

Like photosynthesis or phosphorus uptake, nitrogen uptake is limited indirectly by factors other than temperature or the inability to accept nutrients (Chapin 1983). Indeed, Arctic soils are generally very poor in nitrogen due to slow chemical weathering at low temperatures (Ellis, 1980) and the locking of most nutrients in the permafrost (Chapin 1983). Therefore, nitrogen only enters the soil through atmospheric inputs and fixation (Atkin 1996, Chapin et al., 1980). The reason for limited fixation can be found in the permafrost lying shallow below the soil surface. Permafrost prevents the drainage of water and therefore creates an anaerobic environment in the soil (Chapin 1983). In an anaerobic environment, only bacteria, which are significantly less effective fixators than fungi, are retained (Flanagan and Bunnell 1980).

Adaptation for low temperatures

All the mentioned elements are required by plants for growth, either vegetative or for the production of reproductive organs. Unsurprisingly, optimum temperatures for Arctic plant growth are low (15-25 °C; Tieszen 1978); however, growth is severely limited by the above-mentioned factors. Slow growth produces the specific Arctic growth forms, a small stature and frequent cushion or tussock forms. These growth forms are suited to maintaining temperatures a few degrees warmer than ambient air temperature (Bliss 1962, Chapin et al. 1979, Mølgaard 1982, Warren Wilson 1957).

However, low temperature is not only a growth-limiting factor; under certain circumstances it can directly denature proteins or destroy the tissue of an unadapted plant by forming ice crystals in the intercellular space. Arctic plants defend against this with protein dehydrins (DHNs), which prevent cell dehydration in general (Tiwari et Chakrabarty 2021). Dehydration occurs from many causes, from a simple lack of water, soil salinity, exposure to heavy metals, or frost (summarized in Hanin et al. 2011; Hara 2010; Tiwari et Chakrabarty 2021). In frosts, the function of DHNs is to prevent denaturation of proteins that are sensitive to freezing (Hughes et Graether 2011, Rinne et al. 1999, Shi et al. 2016) and also can suppress ice crystal formation (Wisniewski et al. 1999).

Adaptations to Arctic conditions are essential for growth in the harsh climate; however, Arctic specialists have adapted very well. They are essentially limited in growth only by inadequate resources, which are limited by low temperatures.

Arctic vegetation and contemporary climate change: mutually reinforcing entities

Arctic amplification and other processes changing Arctic vegetation.

Climate change is a complex process dependent on many factors that influence each other, often in a positive loop. In the Arctic, climate change is more pronounced than at lower latitudes due to the phenomenon of 'Arctic amplification' (Serreze et Barry 2011). The main mechanism of this amplification is the disappearance of sea ice, thus reducing albedo which leads to increased warming, which in turn leads to further extensive sea ice melt. This is accompanied by many smaller-scale mechanisms including biological processes.

Changes in the composition and distribution of vegetation also contribute to Arctic amplification. A description of all the processes so far known to be associated with vegetation change in a changing climate is given in detail by Wookey et al. (2009). The most prominent changes in vegetation associated with climate change are the so-called "greening" and "shrubification" (Chapin et al. 2005, Elmendorf et al. 2012, Epstein et al. 2004, Myneni et al. 1997, Sturm et al. 2001, Tape et al. 2006) that occur due to many combined factors.

Increase of bushes and decrease of bryophytes.

Plant height is the first and most visible manifestation of change in vegetation. With warming, vegetation height increases. To reach greater heights, a plant often needs a strong, woody stem. Therefore, we observe an increase in shrubs with increasing vegetation height (Wahren et al., 2005). With taller vegetation, mosses and lichens decline due to shading and increased competition for resources (Cornelissen et al. 2001, Jägerbrand et al. 2006, Klanderud et Totland 2005, Olofsson 2006, Walker et al. 2006). Lichens and bryophytes not only suffer from competition, but also, they may suffer from changes in abiotic conditions (e.g. desiccation) in open habitats typical for them due to warming (Cornelissen et al. 2001, Walker et al. 2006). Due to the loss of lichens and bryophytes, more unused nutrients remain in the soil, and in addition with dead bryophytes and lichens, the nutrients stored in their tissues return to the soil. All these unused and decomposed nutrients can be used by vascular plants in a positive feedback loop (Wookey et al. 2009).

The disappearance of mosses results in faster melting of the permafrost and an increase in the active layer (Wookey et al. 2009). Indeed, mosses act as an insulating layer for the soil and reduce the exchange of thermal energy between the atmosphere and the soil (Gornall et al. 2007). The more active soil layer is also influenced by the taller vegetation itself, which better traps and maintains snow cover (Elberling 2007, Goetz et al. 2007, Körner 1999). With a higher snow cover, the soil is better protected from temperature fluctuations, the soil climate is more stable, microbial activity in the soil increases and there is higher nitrogen mineralization (Bardgett et al. 2005, Schimel et al. 2004, 2006, Sturm et al. 2005a, b, Walsh et al. 2005).

Change in mycorrhizal communities.

Higher soil temperatures are also associated with higher activity and growth of ecto-mycorrhizal hyphae (Clemmensen et al. 2006). Therefore, there is a change in the proportion of mycorrhizal symbionts in the soil. Since shrubs make associations with ecto-mycorrhizae or ericoid mycorrhizae, while herbs and graminoids have arbuscular mycorrhizae (Read et al. 2004), the change in mycorrhizal symbionts goes hand in hand with the change in vegetation in favour of shrubs. Non-arbuscular symbionts, which are more efficient in fixing nitrogen from the soil, start to dominate (Leake et al. 2004).

Although all of the changes and positive feedback loops described so far lead to an increase in available soil N, the shift from graminoids and forbs to shrubs also leads to an increased C:N ratio of the vegetation. Non-woody plants have a lower C:N ratio than woody plants due to the dominance of green photosynthetic tissues over woody ones (Shaver et al. 2001), meaning that woody-dominated vegetation can afford to generate more biomass per unit N (Wookey et al. 2009). As an example, a study from Alaska found that a non-deciduous heath tundra contained 23-25% more biomass than a wet tundra dominated by graminoids (Shaver et Chapin 1991).

Short-term fluctuations in the environment.

In addition to greening and shrub encroachment, a number of other events occur, but these depend on other climatic, biological and baseline vegetation conditions. They are therefore highly site- and time-specific, often contradictory, and we cannot consider these changes to be generic to the warming Arctic (Beck et Goetz, 2011, Elmendorf et al. 2012, Huang et al. 2017, Myers-Smith et al. 2015). Moreover, these factors often act only for short periods of time and their effect on vegetation is therefore (in contrast to long-term increases in mean temperature) rather destructive.

An important site-specific event is the change caused by the increasing frequency of warm events during winter (winter warming events; Bonsal et al. 2001; Liu et al. 2006; Shabbar et Bonsal 2003). Cases have been recorded where temperatures changed from -20 °C to +5 °C within 24 hours (Callaghan et al. 2004, Phoenix et Lee 2004). During these events, snow melts and vegetation is exposed to a warm climate, which triggers various physiological processes leading to initiation of growth (Bokhorst et al. 2010). However, growth is then abruptly stopped by the onset of frost again, but this time the plants are unprotected by snow cover. This damages both the belowground parts (roots) and above-ground parts (shoots, leaf and flower buds), resulting in reduced growth and fruit production (Bjerke et al. 2017, Bokhorst et al. 2008, 2009, 2011, Milner et al. 2016). So far, all studies were made on shrubs only, and none indicate the extent of damage to herbs, graminoids or bryophytes. At the same time, most of the studies were conducted in the low Arctic and only two present data from the high Arctic. In the high Arctic, rain showers falling on snow cover (rain-on-snow events, Ravolainen et al. 2020) can often be observed in association with warm winter events, causing ice crust formation in addition to snow melt.

In addition to abiotic factors acting on a short-term and irregular basis, a number of biotic factors can be observed. For example, sudden fluctuations in rodent population sizes can interfere with vegetation structure to a large extent, and with climate change these sudden events may become more frequent and occur in new locations (Bilodeau et al. 2014, Johnson et al. 2011, Olofsson et al. 2012, Ravolainen et al, 2011). No rodents occur naturally in Svalbard, our model system, but there is a small and non-expanding population of the vole *Microtus rossiaemeridionalis* (current valid name *Microtus levis*, see chapters 14, 15 and 16) (Markova et al. 2016), which could expand and impact local vegetation under favourable conditions.

Herbivore pressure, however, may not be only short-term. It can also be a long-term disturbance or a combination of both. Short-term action can cause increased growth, as has been observed with reindeer pasture on willow (Ravolainen et al. 2014), while long-term action suppresses willow in areas with increased herbivore pressure (Bråthen et al. 2017). Geese also have a major impact on vegetation in the High Arctic, especially the pink-footed goose *Anser brachyrhynchus* in Svalbard, whose feeding can create areas of bare ground (Ravolainen et al. 2020). Bare soil has a different moisture regime and responds differently to other abiotic factors than soil with vegetation, so we can expect a consequent impact of this change on the ecosystem (Ravolainen et al. 2020).

Conversely, other short-term and irregular events may include fires (Mack et al. 2011); however, their real impact has not yet been documented. Similarly, there are no studies documenting increased nutrient inputs with increasing populations of reindeer, geese, as well as land-nesting seabirds (Ravolainen et al. 2020).

Although climate change is well documented in many places in the Arctic, and there are long-term observational data, we cannot conclusively summarize the direction in which the Arctic tundra will change. This is due to the high heterogeneity of the environment and the combination of long-term and short-term climatic pressures and fluctuations. Emerging drivers (such as fires) and biotic interactions (such as herbivore pressure) are still poorly understood, so we cannot predict their influence on Arctic tundra change. In order to better understand climate change in the tundra, we need to continue to monitor the situation, develop realistic models, and draw on the historical record of past warming events.

13. Ecology of birds of polar regions and important species of birds living in Svalbard

Václav Pavel

Of the total number of bird species found on Earth (over 10,000 species of birds are known today; of which approx. 6,000 species are passerines and approx. 4,000 species are birds from other orders), only a small fraction lives in the polar regions. For example, only about 40 species of bird nest in the Antarctic region (Antarctica, including the subantarctic islands and the Southern Ocean), and a few dozen other species rarely wander into the vicinity of Antarctica. Only 16 nests of bird species have been recorded on the Antarctic continent itself; in addition to penguins (order Sphenisciformes), there are also some albatrosses and petrels (order Procellariiformes), cormorants (order Pelecaniformes) and shorebirds (order Charadriiformes).

Near the north geographic pole in the Arctic, the composition of bird communities is slightly more diverse than in Antarctica, but still falls far short of the species diversity of temperate, subtropical or tropical regions. So far, 203 bird species have been recorded in and around Svalbard, but of these, only 28 species are considered to be regular breeders, 13 species are rare breeders, 12 species have nested at least once, and 150 bird species are rare vagrants that are unlikely to breed in the cold northern regions. These 203 bird species of the high north taxonomically belong to 17 orders and 43 genera, the orders Procellariiformes, waterfowl Anseriformes and long-winged Charadriiformes being the most represented.

An obvious disparity can be observed in the polar regions in the representation of individual taxonomic groups of birds. While songbirds represent about 60% of bird species worldwide, they are almost non-existent in Antarctica and the Arctic. In the Antarctic region or on the adjacent islands within the Antarctic Convergence (the circumpolar sea belt surrounding Antarctica, where the cold waters of the Southern Ocean meet and mix with the relatively warm waters of the Atlantic, Indian and Pacific Oceans), passerines do not breed at all, and some species (for example, the pipit *Anthus* and true thrushes of the genus *Turdus*) are observed only as vagrants in the marginal warmest parts of Antarctica, for example on the South Shetland archipelago. This absence of passerines can easily be explained by the unavailability of suitable food. In the Antarctic region, there is a minimum of terrestrial food sources usable for birds. Apart from a few species of springtails and mites, we do not find insects, arachnids or other invertebrates, and, apart from two types of grass, there are no higher plants, i.e. nor their seeds, buds or other essential energy-rich food sources for herbivorous or omnivorous birds. These are nesting warblers in the high Arctic, but they are only individual species, for example, only one, the northern snow bunting *Plectrophenax nivalis*, nests in Svalbard.

In addition to the small number of passerines in polar regions, there is also a limited representation of Falconiformes and owls, which are also limited by the availability of suitable food. While these apex bird predators do not occur at all in Antarctica, we do find a few representatives in the high Arctic (the gyrfalcon *Falco rusticollus* and the snowy owl *Bubo scandiacus* occur far to the north in the regions of Greenland and on the islands in northern Canada), but, for example, in Svalbard neither Falconiformes nor owls nest on the eternally frozen islands north of the Russian mainland. The role of top bird predators in the coldest regions is then taken over by long-winged birds, and in Antarctica and the Arctic we can meet, for example, skuas from the *Stercorarius* genus (Fig. 1.13), which specialize not only in picking nests (including killing young) and stealing food from other bird species, but can also actively hunt adults, for example smaller ones like the cape petrel *Daption capense* in the south or the arctic terns *Sterna paradisaea* in the north.

Fig. 1.13: The arctic skua *Stercorarius parasiticus* replaces predatory birds in the food chains of the inhospitable Arctic. Cape Hotellneset, Svalbard (Pavel).

Most of the birds in the polar regions are migrants who come to high latitudes only for the summer season to take advantage of the local high production and abundance of food to raise their young. The midnight sun also allows them to search for food 24 hours a day. Another added value of polar regions for nesting birds is a lower incidence of parasites (parasites generally do worse in cold conditions and after the departure of the migrants, permanent parasites have to spend most of the year without a host) and limited predation (permanent predators, for example arctic foxes *Vulpes lagopus* (Fig. 2.13). In the north, these predators experience periods of food abundance during the birds' nesting season, but for the rest of the year they must survive on more modest permanent local resources and supplies).

Fig. 2.13: Arctic foxes (*Vulpes lagopus*) together with polar bears are the top land mammal predators on Svalbard (Pavel).

To make the long migration to the Earth's poles worthwhile, the abundance of food that the Arctic and Antarctic offer birds during the astral summer must be optimally used. The polar summer is short, and therefore every long day that the birds spend actively here is important. At the end of the short summer season, young migratory birds must be large enough to make the long journey to their wintering grounds. Polar birds therefore move to their nesting grounds as soon as the weather permits, and immediately upon arrival they build nests and lay eggs. They often line the nests with down to additionally insulate the eggs. For example, some waterfowl (brent geese of the genus *Branta*, geese of the genus *Anser* or eiders of the genus *Somateria*; Fig. 3.13) cover their eggs directly with feathers and, when leaving the nest, cover them with feathers so that the incubated eggs do not get cold. Incubating polar birds reduce leaving their nests to a minimum and, overall, during nesting they invest all their energy in rapid nesting. In most species, both parents take turns in caring for the eggs and young, and in many species, the adult birds live on reserves and starve during nesting. The young usually hatch at the time of greatest food abundance: in herbivorous birds, when grasses and other energy-useful plants are sprouting, in insectivorous birds at the time when insects are most abundant, and in seabirds, the feeding of young is coordinated with the greatest abundance of marine invertebrates (krill) and small fish. This necessity of the ideal timing of the hatching of the young with an abundance of suitable food has been causing more and more problems in recent years for birds, especially in northern latitudes, because ofclimate change the astral summer in the north comes earlier and earlier and the birds are not capable of such a rapid response to change the nesting times by adjusting their migration habits. Therefore, some species of birds do not find enough food during nesting, they produce fewer and fewer young, and their populations have decreased significantly in recent years. A typical example of a northern passerine, whose populations in the tundra decreased significantly at the beginning of the 21st century and almost disappeared from relict nesting sites in Central Europe, is the Bluethroat *Luscinia svecica.*

Most of the nutrients and energy in the regions around the Earth's poles come from the sea, which freezes during the winter months, so birds from these regions disappear for the winter to the open (non-freezing) sea or to warmer lands closer to the equator. The emperor penguin *Aptenodytes forsteri* is the only bird species that occurs in the frozen parts of Antarctica on the ice shelf during the winter. This largest species of penguin has such a long egg incubation and chick development time that nesting must begin at the beginning of the winter season and the chicks hatch in the middle of the polar winter so that they are sufficiently developed, molted and ready to become independent in the abundance period during the following polar summer.

Fig. 3.13: The pink footed goose *Anser brachyrhynchus* nests in large numbers on Svalbard, but most of the eggs and chicks are lost as food for arctic foxes (Pavel).

An important and often discussed phenomenon is the role of birds in the transfer of energy and nutrients in polar ecosystems. A number of studies have shown that seabirds, however impressive their numbers on the breeding grounds may appear, consume only a small part of the production of the polar seas compared to cetaceans, pinnipeds and other higher animals. However, their non-negligible importance may lie in the transfer of nutrients and energy from the sea to the land. Colonial seabirds divide their time during nesting between foraging at sea and tending nests on land. The remains of food and droppings of both adults and young remain on the nesting grounds in the vicinity of the nests, which they "fertilize". Extreme concentrations of nutrient-rich substrate (guano – a layer of accumulated excrement, food remains and dead individuals) can then be found, for example, on a narrow strip of land below the bird bazaars (cliffs on which colonies of seabirds nest; Fig. 4.13). If we compare the vegetation growing under the bird bazaars in the far north with the surrounding vegetation, we find that it is much lusher under the nesting cliffs. Scientists have calculated that the 70,000 pairs of the little auks *Alle alle* that nest on Svalbard fertilize the terrestrial ecosystem below the nesting cliffs with 60 tons of guano in dry weight each year. This is a non-negligible amount of "quality fertilizer" in the nutrient-poor polar terrestrial ecosystem, although its spatial distribution is quite uneven.

Fig. 4.13: Among the bird species that nest in bird bazars on Svalbard is the Brünnich's guillemot *Uria lomvia* (Pavel).

In the high north of Svalbard, the only bird species that remains on the islands year-round is the endemic Svalbard ptarmigan *Lagopus mutta hyperborea*, which is able to feed during the polar winter on the sparse vegetation on the wind-blown exposed parts of the tundra, otherwise covered by a continuous layer of snow and ice. A few other species of birds (for example, the long-tailed duck *Clangula hyemalis*, the ivory gull *Pagophila eburnea* or the black guillemot *Cepphus grylle*) winter in the open sea near Svalbard along the edges of the winter freeze, while other bird species fly south to winter. One of the most distant migrants is the already mentioned snow bunting and, paradoxically, one of the smallest birds found on Svalbard, namely the snow bunting *Plecopterax nivalis* which winters from Svalbard probably as far as the Asian steppes.

The Arctic tern *Sterna paradisea* is the bird that undertakes the longest recorded migration journeys during its lifetime and flies annually to the Arctic to breed and to the Antarctic to winter (Fig. 5.13). This excellent aviator spends about half of the year traveling between the north and south polar regions over the oceans every year, covering more than 50,000 km. Its life is also unique in that it experiences two polar summers every year – one during nesting in the Arctic and the other during wintering on the seas in the fringes of the frozen summer Antarctica.

Fig. 5.13: The arctic terns *Sterna paradisea* from Svalbard fly to Antarctica every year to spend the winter (Pavel).

This ability of birds to undertake long migratory journeys and visit different terrestrial and aquatic ecosystems during them seems to play a significant role in the spread of other organisms. It is a well-known fact that birds carry various microorganisms, cyanobacteria and algae, or even small animals, for example molluscs, in their feathers, on their feet and inside their bodies. Some of these organisms are bound to their hosts/vectors (parasites in particular), but others accidentally use birds only for transport and, after transfer, settle in a new environment without problems, independent of the feathered means of transport that brought them there. In this way, birds can involuntarily contribute to the settlement of new territories (in polar landscapes, such territories are often formed in freshly thawed areas during the retreat of glaciers or in places that emerge above sea level for various reasons). An extreme example of the transfer of organisms over huge distances is the colonization of deglaciated areas within Antarctica. The long-tailed tern is one of the few known natural "means of transport" that has been regularly creating a direct link between the Arctic and Antarctica every year for thousands of years.

Although the bird communities of polar regions are disproportionately poorer in species than communities in the tropics or even the temperate zone, the total numbers of individuals of some species are so large that polar birds are among the most numerous bird species on earth. According to a census carried out in the 2020s, there are about 50 billion birds in the world, with the most widespread species being the house sparrow *Passer domesticus*, with a global population of 1.6 billion individuals. But, among the most numerous bird species, is the glaucous gull *Larus hyperboreus*, which lives in the Arctic and has a worldwide population of almost 1 billion individuals, and the black-legged kittiwake *Rissa tridactyla* with a global population of 815 million individuals. Bird species that nest in typical colonies in climatically cold regions have relatively large populations. In the Antarctic region, the most numerous penguins are the Adélie penguin *Pygoscelis adeliae* /probably over 10 million individuals) or the chinstrap penguin *Pygoscelis antarcticus* (over 15 million individuals), which nest in huge colonies of up to several tens of thousands of pairs. In the bird bazars in the far north, the already mentioned three-toed gull and also the atlantic puffin *Fratercula arctica* (around 14 million individuals) or the Svalbard ptarmigan *Lagopus mutta hyperborea* (20 million individuals) are among the most numerous species.

Many bird species in the polar regions are endemic and have developed unique ecological adaptations that have enabled them to inhabit these inhospitable places. Of the group of Nordic land birds, the white-tailed grouse has come the farthest in their adaptations to cold conditions independent of food sources from the sea. The endemic Svalbard ptarmigan *Lagopus muta hyperborea* (Fig. 6.13) is the only bird that remains on the frozen land in the high north during the frosty and cold winter. Even during the polar winter, they are able to survive on the remains of scanty vegetation and survive the worst frosts by being buried under an insulating layer of snow. As an anti-predation strategy, they have developed a seasonal color change, so in the summer season the inconspicuous grey-brown and white chickens blend into the stony tundra but change to a pure white dress for the winter, which is disturbed only by the black-coloured beak, eye and end of the tail, and the red crest above the eye. The tiny black and red markings on the winter plumage seem to have a signalling function in this social bird species, and if a white-coloured individual crouches in a snow-covered landscape, it blends in perfectly with its surroundings. Other adaptations are feathered legs, including toes (which improves not only the insulation ability of runners, but also their load-bearing capacity in soft snow by acting as natural snowshoes) and feathered nostrils (which helps limit heat loss during breathing). The external adaptations are supplemented by strong runners with claws, which help the white chickens to dig into ice and snow or dig out food under ice and snow. The digestive tract of these nordic chickens is also adapted to the harsh nordic conditions, which is enlarged (guts, stomachs) and elongated (intestines) in order to be able to accommodate a large amount of energy-poor vegetation that they already consume, and to make maximum use of it with the help of symbiotic microorganisms. Adaptations to the cold also include adjustments to the vascular system: the arteries bringing oxygenated blood to the peripheral parts of the body are already intertwined deep inside the body with the vessels taking the cooled deoxygenated blood back to the body, which creates a perfect heat exchange that limits heat loss through runners, for example. In addition, white chickens are able to reduce blood flow in the legs, and as a result reduce heat loss even more. If even this is not enough, they stand on one leg while protecting the other deep in feathers, close to the body.

Fig. 6.13: The Svalbard ptarmigan *Lagopus muta hyperborea* changes its inconspicuous summer clothes for winter with a white covering coloration (Pavel).

Ptarmigans are also an important part of the food chain in the high Arctic in Svalbard. As the only resident bird species, they represent one of the few food sources available in winter for resident predators, such as arctic foxes.

The ability of the resident animal species to create reserves for this cold and dark period is also important. Most species create such reserves in the form of fat (for example, the aforementioned white grouse "puts on a lot of weight" for the winter), however, some species, such as the just-mentioned arctic foxes, also make "external reserves", and in the summer we can observe scenes of bleeding, when the hunting fox slaughters entire flocks of growing young Nordic birds (for example, geese or waders) and then buries the caught prey in this way in a series of stores prepared for the "hungry" season.

An interesting dietary adaptation of some nordic species of birds (but also arctic foxes) is the "accompanying" of polar bears. A typical example of a saprophagus (scavenger) is, for example, the Ivory gull *Pagophila eburnea* nesting on Svalbard (Fig. 7.13). Found in ice-covered areas of the Arctic Sea, this beautiful pure white gull normally feeds on marine invertebrates and fish, but can also feast on the remains of polar bear prey and may also eat bear faeces. After all, the saprophytic way of obtaining food is quite common in polar regions, and this food strategy is occasionally used by most species of seagulls and skuas or fulmars. We can therefore observe groups of these birds gathering, for example, on cetacean carcasses or near colonies of seabirds and pinnipeds. Recently, with the increasing number of people coming to the Arctic and Antarctica either to work or as tourists, saprophytic bird species are also beginning to specialize in human waste as "dump" species. Around polar stations and northern towns we can find, for example, a larger amount of nesting skuas and seagulls (Fig. 8.13) than in the surrounding natural landscape.

Fig. 7.13: The ivory gull *Pagophila eburnea* in Svalbard often accompanies polar bears and feeds on the remains of their prey (Pavel).

Fig. 8.13: The glaucous gull *Larus hyperboreus* often specializes in eating their garbage in the presence of people (Pavel).

This phenomenon, that is, that birds seek the neighborhood of people, is not limited to saprophytic species in Antarctica and the Arctic. "Anthropogenic" colonies can also be observed in other bird species. For example, it is common in terns, which often nest right along streets and around buildings inside human settlements/bases. "Urban" colonies of long-tailed terns can be found in the towns of Longyearbyen and Ny-Alesund on Svalbard, and similar colonies are also created by the Antarctic tern *Sterna vittata*, for example, in the immediate vicinity of bases on King George Island in South Shetland, Antarctica. Terns can seek protection from predators inside human settlements and take advantage of the fact that people create new suitable nesting sites (gravel areas) for them during construction activities. But it may also be just a coincidence, in that people build their bases in places where terns have traditionally nested, and if suitable conditions remain in these places, terns continue to coexist there with humans. Terns are able to compensate for the slight disadvantage of more frequent nest disturbance by getting used to human disturbance, returning to the nests faster after being frightened, thus the total time spent incubating is not significantly reduced.

Another interesting example of the adaptation of birds to a human-shaped landscape is the nesting colony of black-legged kittiwakes on houses in the abandoned settlement of Pyramiden in Svalbard. This Russian mining town was abandoned in 1998 and the residents were evacuated so quickly that most of the furniture remained intact on the site. The windows, alcoves and ledges of depopulated multi-storey apartment buildings and former coal mine buildings were occupied by three-toed gulls over the next few years, and today there is a thriving colony of hundreds of these birds in Pyramiden, which have quickly adapted to nesting on the unusual "artificial cliffs".

Human settlements in the high north are also a widely used nesting habitat for the northernmost songbird, the snow bunting *Plecopterax nivalis* (Fig. 9.13). Snowbirds nest in the natural landscape of the Nordic tundra in crevices and cavities in rubble. In Nordic settlements, where, due to permafrost, houses and technical installations (pipes, cables) are built on piles above the ground, a large number of well-covered artificial semi-cavities and crevices are created inside these installations, which have been occupied by nesting snowbirds. These "urban" populations are again more numerous than the natural populations in the untouched tundra and have recently been the subject of intensive studies by polar ornithologists (an extensive long-term study of the snow bunting *Plectrophenax nivalis* in Longyearbyen and Ny-Alesund in Svalbard is being conducted by ornithologists from the Norwegian Technical University in Trondheim).

Fig. 9.13: The snow bunting *Plectrophenax nivalis* in Svalbard abundantly inhabits artificial cavities in human settlements (Pavel).

14. Invertebrates and vertebrates in the terrestrial habitats of Svalbard.

Oleg Ditrich

In terrestrial habitats, the extreme conditions in the polar regions are much more pronounced than in the seas. This is also significantly reflected in the low number of species of invertebrates and terrestrial vertebrates. This phenomenon is extremely evident mainly on the Antarctic continent, but it is also found in the High Arctic. In Svalbard and other islands far from the mainland, the consequences of the balance rule of island theory approach this: the number of species on an island is determined by the balance between immigration and extinction, and this balance is dynamic, that is, species die out and come in all the time. Biodiversity is therefore lower on an island remote from immigration sources (MacArthur et Wilson 1963). The known number of terrestrial and freshwater faunal species of Svalbard now slightly exceeds one thousand (Coulson 2007). Some large groups (e.g. terrestrial and freshwater molluscs) are completely absent from the Svalbard fauna. Others are represented in low numbers (Fig. 1.14).

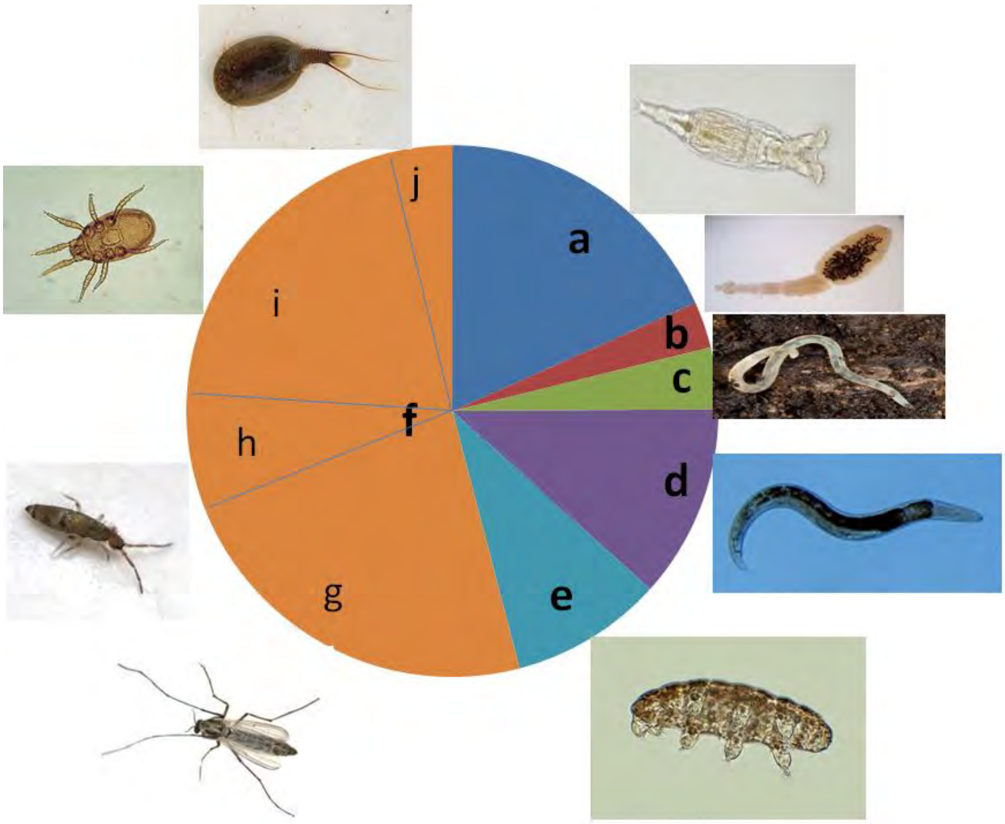


Fig. 1.14: Species representation of individual invertebrate phyla found in terrestrial and freshwater biotopes of Svalbard: (a) Rotifera 176; (b) Platyhelminthes 27; (c) Annelida 36; (d) Nematode 113; (e) Tardigrada 89; (f) Arthropoda 519; of which: (g) Insecta 252; (h) Collembola 64; (i) Chelicerata 170; (j) Crustacea 33 (Ditrich, data source Coulson 2013).

Insects are the most abundant. The latter is mainly represented by dipteran species, followed by Hymenoptera, while the world's most widespread orders are poorly represented (20 species of beetles and 3 species of butterflies, if we do not count species on islands accidentally blown by the wind).

As can be seen from the overview, dominant terrestrial invertebrates are animals living in soil, moss and similar moist substrates (rotifers, tardigrades, nematodes, annelids and a significant number of arthropods; see also Chapter 10). Some groups of insects are dependent on the primary production of vascular plants. Predatory arthropods (arachnids, beetles) are relatively poorly represented, while parasitoids (wasps) and parasites (some nematodes, some mites and flatworms; see also chapter 17) are more abundant. Crustaceans and numerous types of Diptera larvae can be found in fresh waters, where they play an important role in food chains (see also chapter 12). Conversely, the role of terrestrial invertebrates in food chains is much less significant.

The ability to survive extremely low temperatures and the mechanisms for adapting to freezing are different for individual groups. Larvae of some Diptera, e.g. *Heleomyza borealis*, can survive in a frozen state even at temperatures reaching -60 °C (Worland et al., 2000). Larvae of this species use desiccation resistance to survive, while larvae of the Antarctic fly *Eretmoptera murphyi* use desiccation tolerance (Everrat et al., 2014). The warmth of the decomposing substrate in which they live helps them to survive the extremely low temperatures in winter in the larval state. In the case of *H. borealis*, it is the soil under bird cliffs: the dropings-enriched soil under colonies of the black-legged kittiwake *Rissa tridactyla* has an average temperature of -10 °C even in severe winters (Ávila-Jiménezet al 2010)Springtails (*Hypogastrura tullbergi* and *Folsomia quadrioculata*), nematodes, soil mites (*Diapterobates notatus* and *Ameronothrus lineatus*) and enchytraeid (*Henlea perpusilla*) can survive frozen at -22 °C for at least 4 years (Coulson et Birkemoe 2000). An example of a successful strategy is the oribatid mite *Camisia anomia*, a ubiquitous species found in many soil animal communities on Svalbard. Adults of *C. anomia* have developed a very strong exoskeleton that protects them from extreme conditions: they are active at sub-zero temperatures down to -27 °C and survive short exposure to a high temperature of 42.5 °C. They are highly resistant to desiccation, can withstand submersion in water for 10 weeks and survive several months of winter in the ice in a state of rest. The price for these advantages is an extremely slow rate of reproduction (Hodkinson 2005). Another example is the Svalbard aphid *Acyrthosiphon svalbardicum*, specialized on *Dryas octopetala* (Fig. 2.14). Female founders hatching from overwintering eggs give rise to the sexual generation, which is an unusual phenomenon, as in temperate zones the cycle begins with several parthenogenic generations, and the sexual generation only occurs at the end of the season. The entire life cycle of this aphid, which adapts to external conditions, includes viviparous and oviparous generations with the aim of laying as many eggs as possible, at least some of which overwinter (Strathdee et al. 1993). Even this effective adaptation of the life cycle does not allow the Svalbard aphid to occupy the entire range of the dryad in Svalbard; it permanently inhabits warmer locations and uses climatically favourable periods to expand its range. Therefore, it is a suitable indicator organism of climate change (Hodkinson et Bird 1998).

Fig. 2.14: The endemic Svalbard aphid *Acyrthosiphon svalbardicum* sucking on a *Dryas octopetala* flower (Coulson 2013).

In vertebrates, the low biodiversity in polar regions is even more striking than in invertebrates. Some groups of vertebrates, such as amphibians and reptiles, did not adapt to the extreme conditions and are absent in the High Arctic. Other groups are found there, but in very limited numbers of species. The two species of freshwater fish currently living on Svalbard are mentioned in Chapter 10. Birds are covered in Chapter 12.

The mammals living on Svalbard are an ideal example for documenting the general ecological biogeographic rules: Foster, Allen and Bergmann. Animals living on Earth look or behave according to certain principles. They are most often adapted to the climatic conditions that prevail in the area in which a particular species lives. These rules can be often only applied to warm-blooded (homoiothermic) animals and their management of heat. Cold-blooded (poikilothermic) animals do not maintain a constant body temperature, with the temperature fluctuating with that of the surrounding environment. While this applies to a limited extent in birds (the size and shape of the body in birds are not significantly affected by the individual rules due to insulation by means of feathers and the generally smaller body size of birds) the autochthonous Svalbard land mammals are textbook examples and we will clarify these in the individual species.

Before the arrival of man, only two species of terrestrial mammals lived on Svalbard. The only herbivorous mammal is the Svalbard reindeer, *Rangifer tarandus platyrhynchus*. It is the smallest subspecies of all reindeer. The typical feature of this species is its relatively short legs with wide claws, which facilitates movement in wet or snowy terrain (Fig. 3.14).

Fig. 3.14: Svalbard reindeer, *Rangifer tarandus platyrhynchus* (CPE archive).

The origin of this island population has been disputed. At one time it was thought to have a western (Canadian and Greenlandic) origin, due to its similarity with the now extinct East Greenlandic subspecies *Rangifer tarandus eogroenlandicus* and the still living West Greenlandic *Rangifer tarandus groenlandicus*. However, more recent mitochondrial analyses confirmed the original hypothesis of a common origin of reindeer on the Eurasian mainland and archipelagos, including the Svalbard reindeer *R. t. platyrhynchus* (Kvie et al. 2016). Circumpolar occurrence of individual reindeer subspecies is shown in a schematic map (Fig. 4.14). It is worth noting that on the Eurasian continent practically all reindeer are domesticated (if you can call it domestication; reindeer herders basically follow the herds migrating along the original migration routes and interfere with their lives minimally), while the American subspecies have not been domesticated. Island reindeer populations are not domesticated, and people have not attempted to domesticate them.

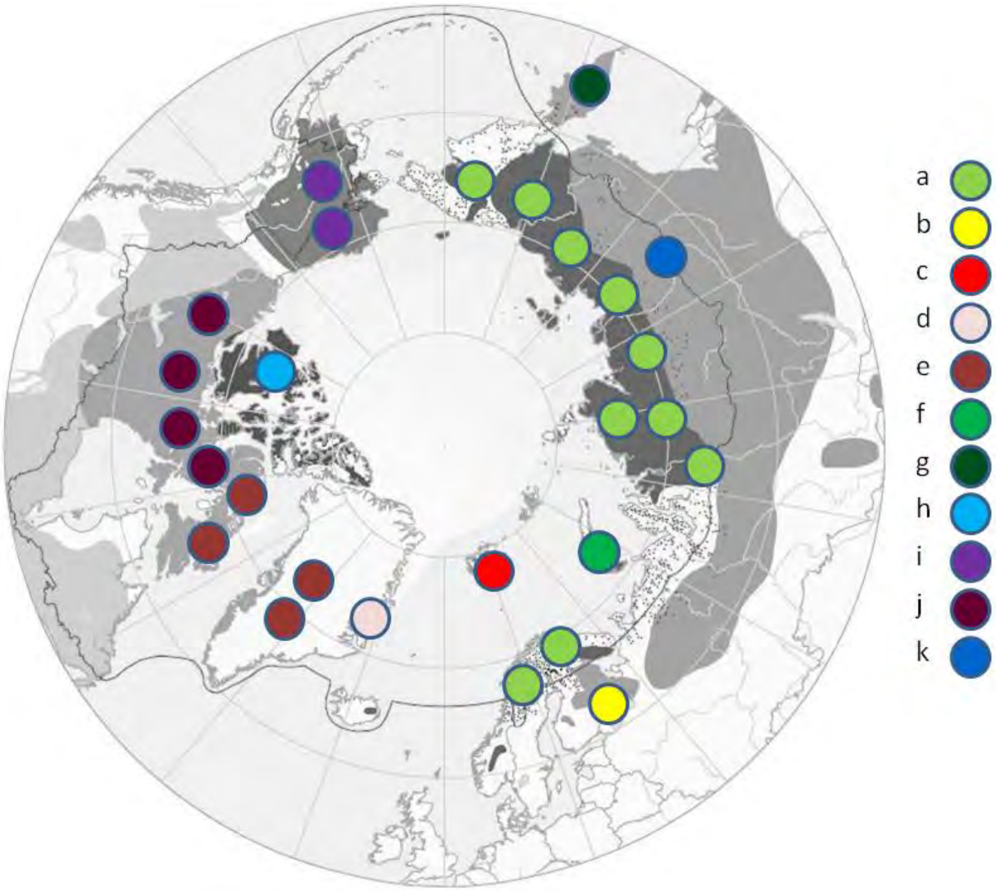


Fig. 4.14: Geographical distribution of individual subspecies of arctic reindeer *Rangifer tarandus*: (a) *R. t. tarandus*; (b) *R. t. fennicus*; (c) *R. t. platyrhynchus*; (d) *R. t. eogroenlandicus*; (e) *R. t. groenlandicus*; (f) *R. t. pearsoni*; (g) *R. t. phylarchus*; (h) *R. t. pearyi*; (i) *R. t. granti*; (j) *R. t. caribou*; (k) *R. t. valentinae* (Ditrich).

Due to intensive hunting, the Svalbard reindeer was threatened with extinction, leading to its hunting being completely prohibited in 1925. The population has recovered and since 1983 it has been hunted to a limited extent only in some areas. In places where it is not hunted, it has a very short escape distance. The Svalbard reindeer population thus lives without predators (predation of cubs by foxes and predation of reindeer by polar bears has been proven, but their influence is negligible). The reindeer population affects the vegetation of Svalbard to a large extent and is an ideal model for studying the influence of herbivores (Hansen et al. 2007).

The example of the Svalbard arctic reindeer *Rangifer tarandus platyrhynchus* can illustrate Foster's island rule, which deals with the emergence of dwarf forms of animals in isolated places. It is likely that, in addition to geographic isolation, adverse climatic influences also played a role in the emergence of dwarf forms (Foster 1964; Fig. 5.14).

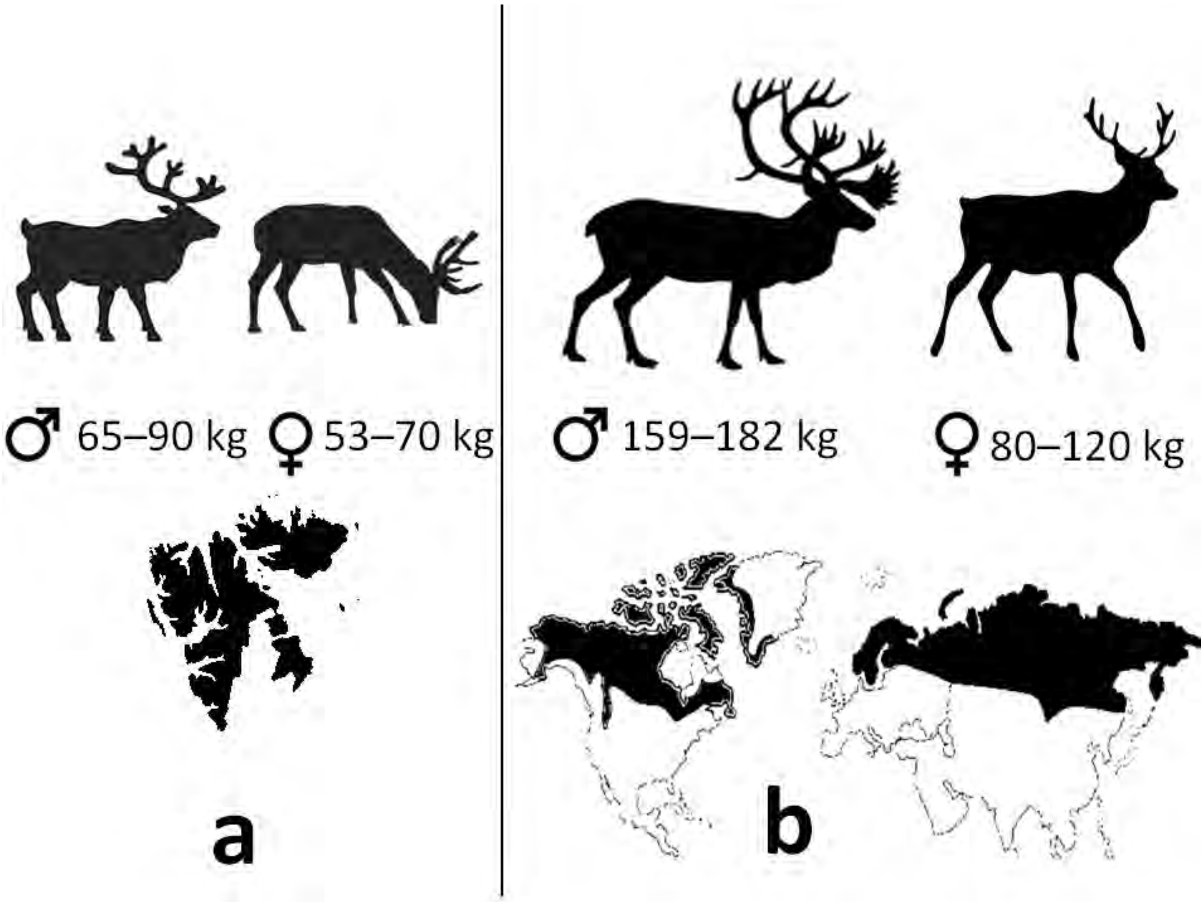


Fig. 5.14: Subspecies of arctic reindeer *Rangifer tarandus* illustrating Foster's island rule: (a) *R. tarandus platyrhynchus*; (b) *R. tarandus* ssp. (Ditrich).

The only truly terrestrial carnivorous mammal in Svalbard is the arctic fox, *Vulpes lagopus* (Fig. 6.14). Although the Svalbard populations used to be referred to as a subspecies, *Vulpes lagopus spitzbergenensis*, it has recently been shown, for instance by the study of fox parasites, that arctic fox populations still migrate within their circumboreal distribution and are able to overcome even huge distances between landmasses. To do this, they use floating ice and the ability to starve for a long time. This ability of arctic foxes to migrate between continents using sea ice and glaciers was confirmed by satellite tracking of marked animals (Fuglei et Tarroux 2019).

Fig. 6.14: Arctic fox *Vulpes lagopus* (CPE archive)

Continental arctic foxes inland mainly hunt small rodents. In many places, foxes are food specialists, focused on certain species of lemmings, and their numbers in a given area fluctuate with a yearly delay depending on the population waves of lemmings (Angerbjorn et al. 1999). Autochthonous rodents do not live on Svalbard and introduced ones (*Microtus levis*) are found only in some locations and in limited fluctuating numbers. It is primarily for this reason that arctic foxes in Svalbard are dietary generalists. Coastal foxes feed on bird eggs, chicks, carrion, including those thrown up by the sea, and the remains of polar bear prey. Inland foxes are primarily dependent on hunting the Svalbard rock ptarmigan (*Lagopus muta hyperborea*) and eating reindeer carcasses. Even in Svalbard, the number of foxes fluctuates, and their dependence on the number of reindeer carcasses and the number of nests of the barnacle goose *Branta leucopsis* has been traced (Fuglei et al. 2003). Fox pelts were the main prey of Svalbard trappers in past centuries: with the exception of reservations, foxes are still hunted today, and Norwegian trapper stations are maintained as part of the cultural heritage.

Foxes of the genus *Vulpes* are a very suitable example for documenting Allen's ecological rule (Allen 1877; Fig. 7.14). This rule deals with the body structure of warm-blooded animals related to each other. It indicates that animals living at higher latitudes have smaller body projections (beaks, ears, tails) and limbs than their relatives living closer to the equator. The reason for this morphological adaptation is the prevention of heat loss in cold areas and, on the contrary, faster cooling of the blood in animals living in hot areas.

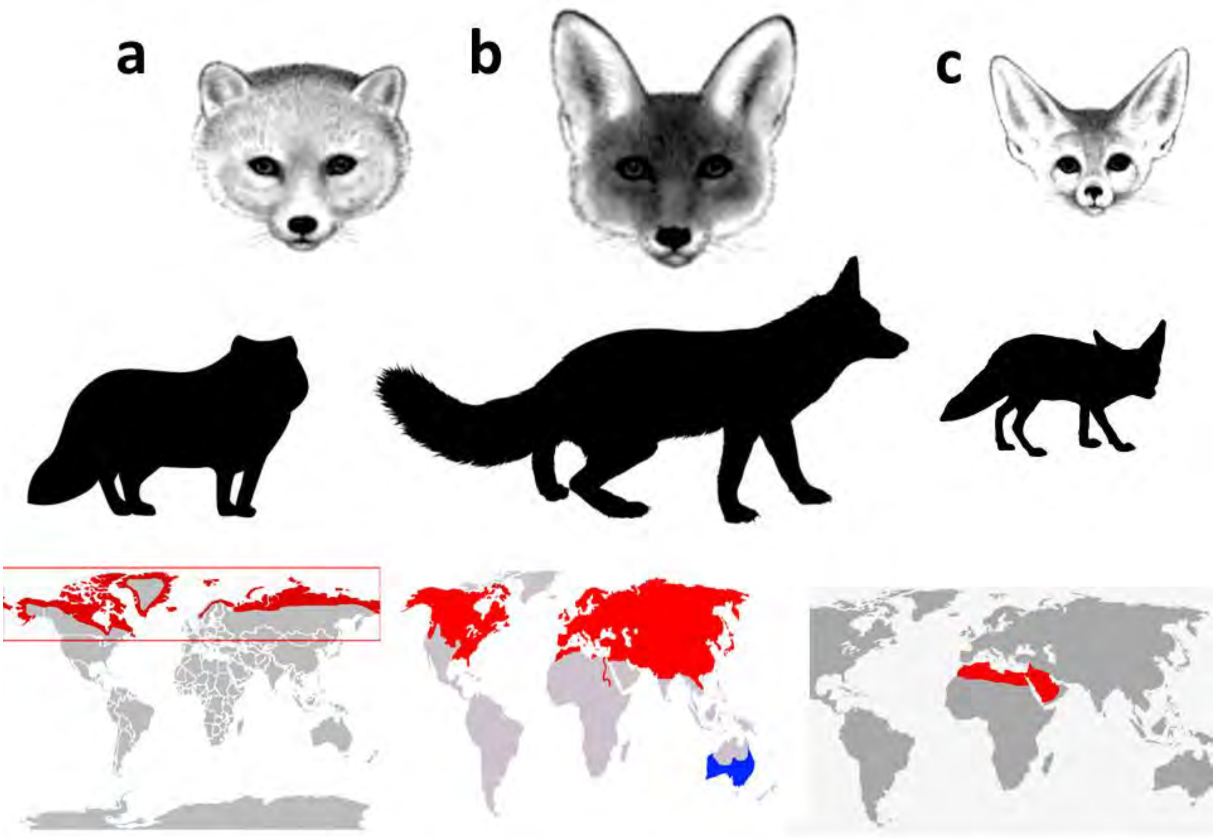


Fig. 7.14: Allen's rule - length of limbs and ears of foxes decreases with increasing northern latitude: (a) *Vulpes lagopus*; (b) *Vulpes vulpes*; (c) *Vulpes zerda* (Ditrich).

The top predator and the tip of the food pyramid in the Arctic, including Svalbard, is the polar bear, *Ursus maritimus* (Fig. 8.14).

Fig. 8.14: Polar bear (*Ursus maritimus*) in Svalbard (CPE archive).

As its scientific name suggests, it is basically not a terrestrial mammal, but a marine one. However, it split from the line of terrestrial brown bears only 150,000 years ago (Lan et al. 2022). Thus, it is not unreasonable to expect that it will partially return to land due to global warming. In the recent past, the polar bears' almost exclusive food was some species of seals, especially *Pussa hispida* and *Erignathus barbatus* in Svalbard. However, with the retreat of sea ice, hunting for this prey is becoming more and more difficult in some places. More and more often, polar bears are observed hunting and eating reindeer, freshwater and marine fish, plundering bird nests, eating carrion (especially whales) and even consuming plant food (Dyck et Romver 2007, Stirling et Derocher 2012, Gomezano et Rockwell 2013, Iversen et al. 2013, Stempniewicz et al. 2021). Polar bears can climb almost vertical ridges and can jump over four-meter holes in the ice. They are also very good swimmers, the best of all bears. They swim at a speed of about 10 km/h. They can also dive, staying under water for up to two minutes. The position at the top of the food pyramid brings the risk of exposure to foreign substances (pesticides, heavy metals, radioactive isotopes, etc.) (Fig. 9.14).

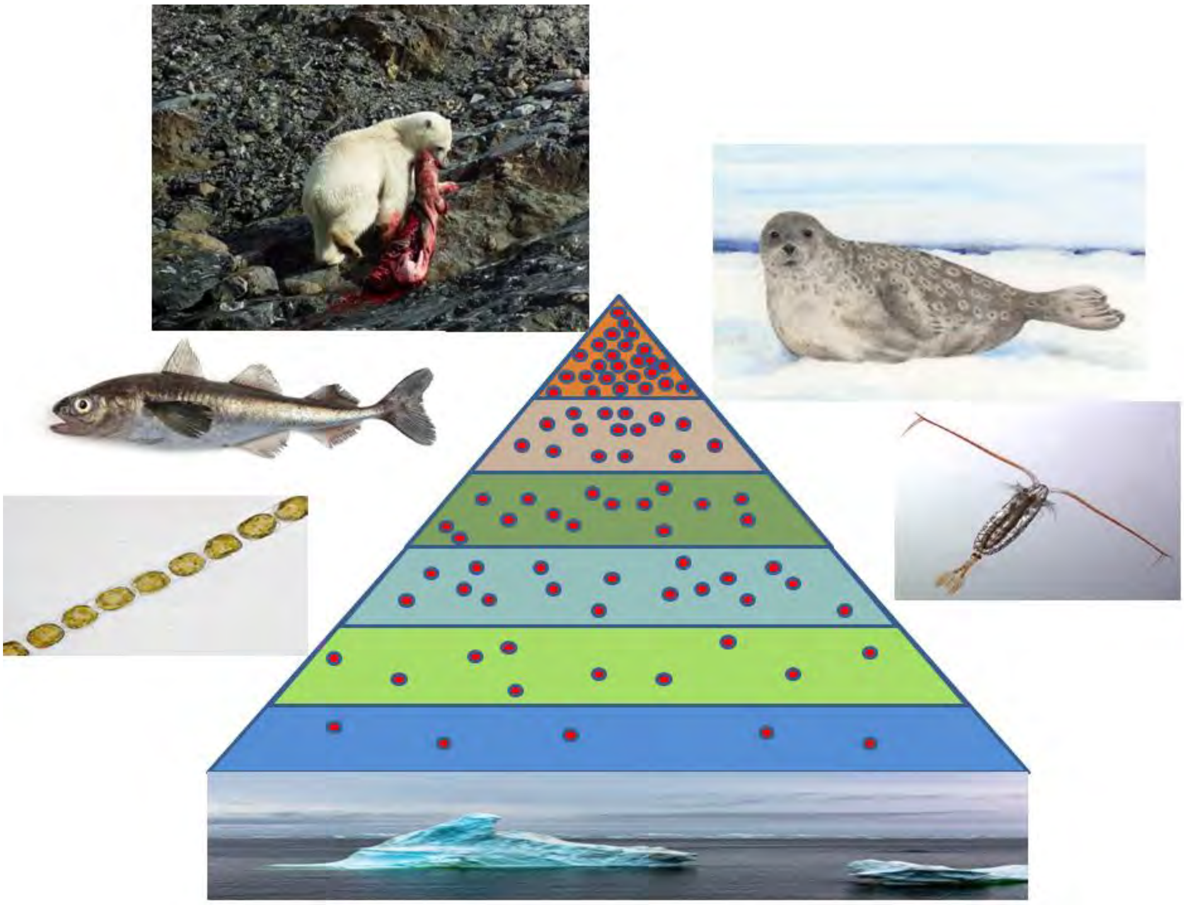


Fig. 9. 14: Scheme of the accumulation of foreign substances pollution in the food chain from primary producers to planktonic crustaceans, fish, seals, to polar bears (Ditrich).

Bergman's rule, which describes the body structure of related warm-blooded vertebrates living in different climatic conditions, can be very vividly demonstrated using bears. Species and subspecies living in colder regions are usually larger and more robust than their relatives from lower latitudes. The reason for the difference in size is the surface area to volume ratio of the body. A larger animal has a smaller body surface-to-volume ratio and thus less heat loss per unit mass (Bergmann 1847; Fig. 10.14).

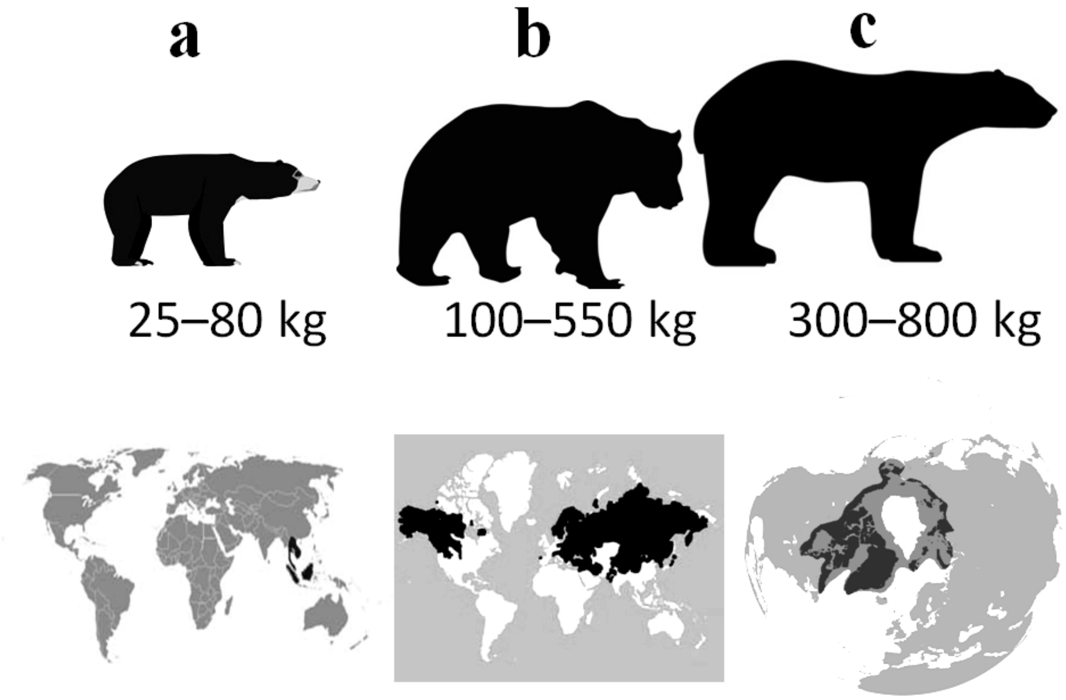


Fig. 10.14: Body weight of bears depending on northern latitude (Ditrich).

Like other areas of the High Arctic, Svalbard has not avoided the introduction of mammals. In the past, fortunately, an attempt to introduce the muskox *Ovibos moschatus* near Longyearbyen and Ny Alesund failed (Roberts et Jørgensen 2016). On the contrary, the unintentional introduction of the sibling vole (*Microtus levis*) was surprisingly successful, in contrast to the unintentional introduction of the house mouse *Mus musculus*, which is only found in small numbers in Barentsburg. The sibling vole was introduced from Russia with fodder for livestock that was reared near mining settlements in the Colesbukta and Grumantbyen area in the 1960s and 1970s (Nyholm 1966). Not only did it survive in these localities, but it spread as far as Longyearbyen, where it is commonly encountered, especially around the stations where sled dogs are kept (Fig. 11.14).

Fig 11.14: Sibling vole *Microtus levis* caught in Longyearbyen (CPE archive).

However, it has also reached places untouched by humans, away from the vicinity of human settlements, and found a favorable microclimate in the stone debris on the coastal slopes (Fig. 12.14). The vole population in Svalbard is subject to significant numerical fluctuation (Yoccoz et Ims 1999). The introduction of this rodent to Svalbard is also important for the spread of parasites that threaten humans (see chapter 15).

Fig. 12.14: Abandoned settlement of Grumantbyen and screes near it: habitat of *Microtus levis* (CPE archive).

15. Symbiotic relationships in Arctic habitats: mutualism, commensalism, parasitism – examples from Svalbard

Oleg Ditrich

One of the most interesting parts of ecology is the study of mutual interactions between organisms. These interactions are complex networks, including intraspecific and interspecific levels, neutralism, competition, predation, etc. In this chapter, we will focus on symbiotic relationships, i.e. the coexistence of two unrelated organisms.

Very often (but not always) one of the symbionts is larger (the host) and contains smaller symbiotes on or inside its body. Symbiotic interactions differ from each other not only in the degree of mutual benefit in regard to the participating organisms, but also in the degree of tightness of coexistence as well as many other parameters. Regarding mutual benefits, symbiotic relationships can be divided into **mutualism** (both organisms benefit from coexistence), **commensalism** (only one benefits - usually the smaller one, where its presence does not bother or benefit the host) and parasitism, where the smaller of the organisms lives on or in its host, uses either the host‘s food or directly its tissue and usually harms the host. There is no sharp line between these modes of symbiosis, since commensalism can turn into **parasitism** if the smaller of the symbionts overgrow or if the host does not have enough nutrients. A similar shift can also occur when the host's immune system is compromised. On the contrary, due to long-term coexistence during evolution, in some cases the parasite and the host have adapted to each other so much that the absence of the parasite can bring problems to the host. This example is best studied in humans, where the consistent extermination of intestinal helminths brings problems with the immune system, which expects them. This causes problems (some allergies and autoimmune diseases) when they are not received.

If we search the published data for examples of symbiotic relationships, we surprisingly find the fewest examples of mutualism, slightly more of commensalism, and a large amount of data on parasitism. However, this does not reflect the real situation, but the degree of attention that was paid to individual types of symbiosis. However, since the microbiomes (intestinal, skin mucosal and others) that all animals have, and where the relationship of most microorganisms with their host is undoubtedly mutualistic, have come to the attention of the professional public, this ratio will hopefully reverse in the future.

Mutualism

In general, the most well-known example of a mutalistic and long-term fixed symbiosis during evolution are lichens, composed of an originally saprophytic fungus (mycobiont) and green algae or cyanobacteria (photobiont). In the High Arctic, including Svalbard, we find a number of species of often very conspicuous lichens (Fig. 1.15).

Fig. 1.15: Lichen *Xanthoria elegans* on a rock in Petuniabukta, Svalbard. The mycobiont of this species is an ascomycete fungus and the photobiont is a green alga of the genus *Trebouxia* (CPE archive).

A very illustrative example of mutualism is the microbiome of the digestive tract of reindeer (*Rangifer tarandus*), especially the microbiome of the rumen and caecum (Salgado-Flores et al. 2016). In Svalbard, the intestinal microbiome changes depending on the season: in the winter, when reindeer do not have enough vascular plants and feed mainly on lichens, microorganisms capable of breaking down the lichen thallus increase in their rumen (Orphin et al. 1985), and similar seasonal changes also occur in the caecal microflora (Mathiesen et al. 1987). The gastrointestinal microbiomes differ in the nominate subspecies of reindeer (*Rangifer tarandus tarandus*) reared on the mainland and Svalbard's reindeer (*Rangifer tarandus platyrhynchus*) living wild in Svalbard (Sundset et al. 2007). The anatomy of the digestive system is also adapted to this symbiosis: in Svalbard reindeer, both the rumen and the caecum enlarge during the winter, in contrast to reindeer reared on the mainland (Staaland et al. 1979).

Commensalism

The relationship between a polar bear and an arctic fox is often referred to as commensalism, especially in the popular media, where the foxes' benefit from coexistence with the bears by feeding on their prey (when there are enough seals, the bears prefer the energy-rich subcutaneous blubber of the seals, while they leave the muscles and the rest of the body to the foxes). Also, the ivory gull often uses the remains of seals caught by polar bears as food (Hamilton et al. 2017) (Fig. 2.15).

Fig. 2.15: Ivory gull (*Pagophila eburnea*) on a sperm whale carcass, Petuniabukta, Svalbard. This endangered species of seagull lives in free commensalism with polar bears (CPE archive).

They are examples of a very loose symbiosis, like the fox-reindeer relationship. This type of mutualistic symbiosis has been observed in the continental tundra inhabited by rodents: in winter, foxes accompany reindeer digging lichens from the snow and use the exposed pieces of tundra to hunt lemmings more easily.

A number of examples of symbiosis can be found in the sea. Jellyfish or comb jellies near the shores of Svalbard often carry amphipod crustaceans (Amphipoda) of the Hyperiidae family. At a certain stage of life, it is probably only phoresis, i.e., the transport of a smaller organism (phoront) with the help of the host, which serves as a means of transport. Crustaceans feed mainly on zooplankton, which sticks to the host. However, in the case of the species *Hyperia galba* and the jellyfish *Cyanea capillata* (Fig. 3.15), it was proven that, during the life cycle of the crustacean, it is indeed a temporary but obligatory parasitism. Stinging cells (nematocytes) of host jellyfish have been found in the stomachs of *H. galba*, and crustacean larvae have been found not to mature unless they spend part of their lives in the gonads of the jellyfish, where they shelter and eat them (Dittrich 1988).

Fig. 3.15: The amphipode crustacean *Hyperia galba* on the jellyfish *Cyanea capillata* (CPE archive).

Another example is the so-called entocommensalism of some species of ribbon worms (Nemertea). More than half of the *Mya truncata* bivalves in the shallow waters of the Svalbard fjords host the larvae of the ribbon worm *Malacobdella grossa* in their mantle cavity; even adult ribbon worms can be found in large specimens (Fig. 4.15).

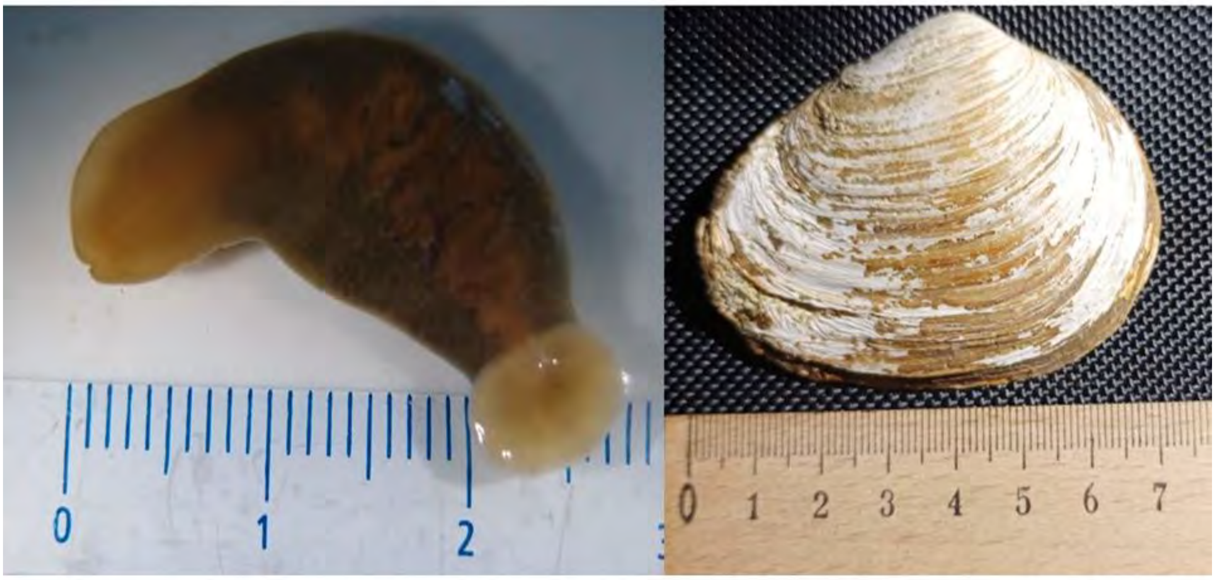


Fig 4.15: *Malacobdella grossa* ribbon worm and the *Mya truncata* bivalve shell in which it was found (CPE archive).

Unlike free-living ribbon worms, which are predators, the entocommensalistic Bdellonemerthea ribbon worms consume all particles and planktonic organisms filtered by the gills of the host bivalve (Gibson 1968; Gibson et Jenkins 1969). So, they take food away from their host, but due to its abundance (*Mya truncata* lives in sediments from glaciers and filters often very turbid water), it does no harm, and the relationship between the ribbon worm and the bivalve is consistently referred to as commensalism.

The absolute majority of cases of the relationship between so-called amphizoic amoebae (changelings) and their (random) host can be described as commensalism. These are free-living amoebae from mutually unrelated groups that feed on bacteria in water (fresh or marine) or in the soil. They thrive very well in the cavities of various aquatic invertebrates (hydrocoel of echinoderms, internal gills of crustaceans, etc.). Some amphizoic amoebae can parasitize warm-blooded animals, including humans. *Naegleria fowleri* causes primary amoebic encephalitis in humans, and amoebas of the genera *Acanthamoeba* and *Balamuthia* cause granulomatous amoebic encephalitis. Only amoebae can parasitize mammals with the ability to multiply at 37 °C, which fortunately the vast majority of them lack. From Skansbukta Bay in central Svalbard, *Vermistella arctica* Tyml et al., 2016 (Fig. 5.15) was described from the gills of the hermit crab *Pagurus pubescens*, which has a sister species in Antarctica: *Vermistella* *antarctica*. This is an example of bipolar occurrence, known in a number of microorganisms and marine invertebrates.

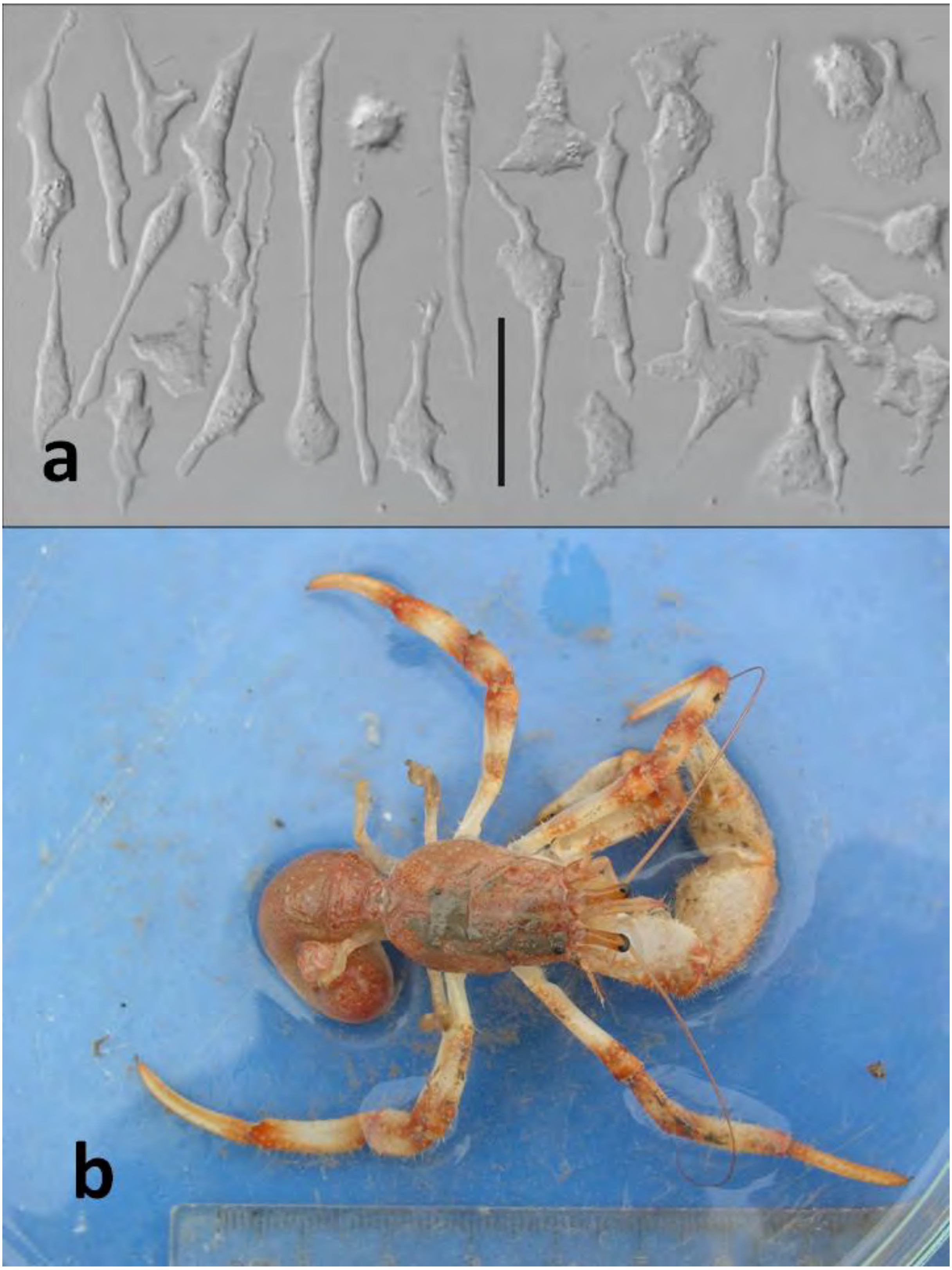


Fig. 5.15: Amoeba *Vermistella arctica* (a) isolated from the gills of the hermit crab *Pagurus pubescens* (b). Dash size 20 µm (CPE archive).

On the border between commensalism and parasitism are many species of trichodins (*Trichodina*), ciliates living on the skin or gills of fish. During research on the parasites of shorthorn sculpins (*Myoxocephalus scorpius*) in Petuniabukta on Svalbard, not a single specimen of fish was found that did not have these ciliates on the gills (Fig. 6.15).

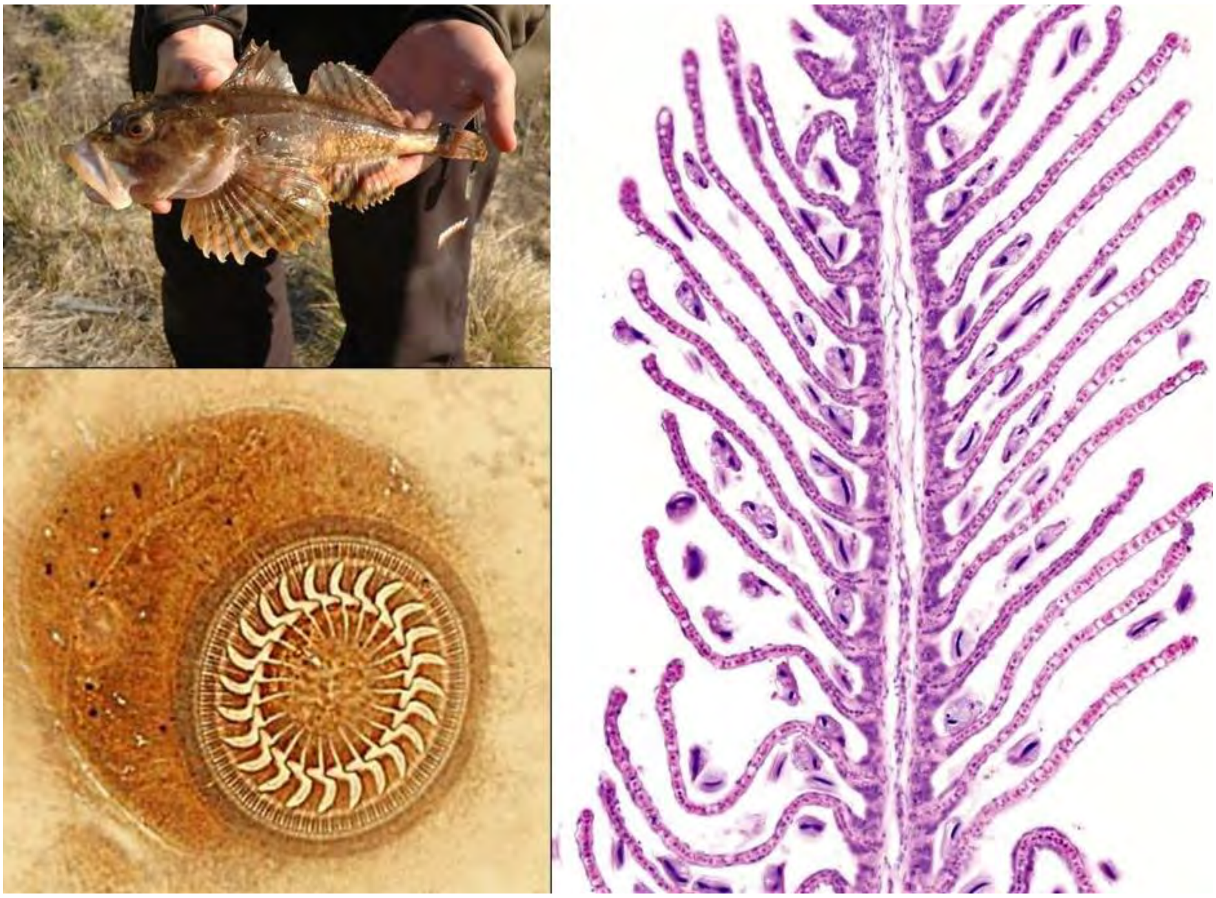


Fig. 6.15: Shorthorn sculpin *Myoxocephalus scorpius* and the commensal ciliate *Trichodina* sp. living on its gills. On the right, a histological section of a crow gill leaf (stained with hematoxylin-eosin) with numerous trichodines between the lamellae (CPE archive).

In some cases, the trichodines multiply so much that it is hard to believe that they are not affecting the host, but still their numbers have not affected the sculpins. (Komendová 2012).

Another parasitic organism, *Ïchthyophonus* sp., from the class of Mesomycetozoa, also lives in the gill tissue of crows. It was found in 35% of the sculpins caught in Petunia Bay, Svalbard, which in itself indicates that its pathogenicity is not high (Fig. 7.15). However, serious pathogens of fish, amphibians and warm-blooded animals can also be found in the highly heterogeneous group of fungi (Mendoza et al. 2002).

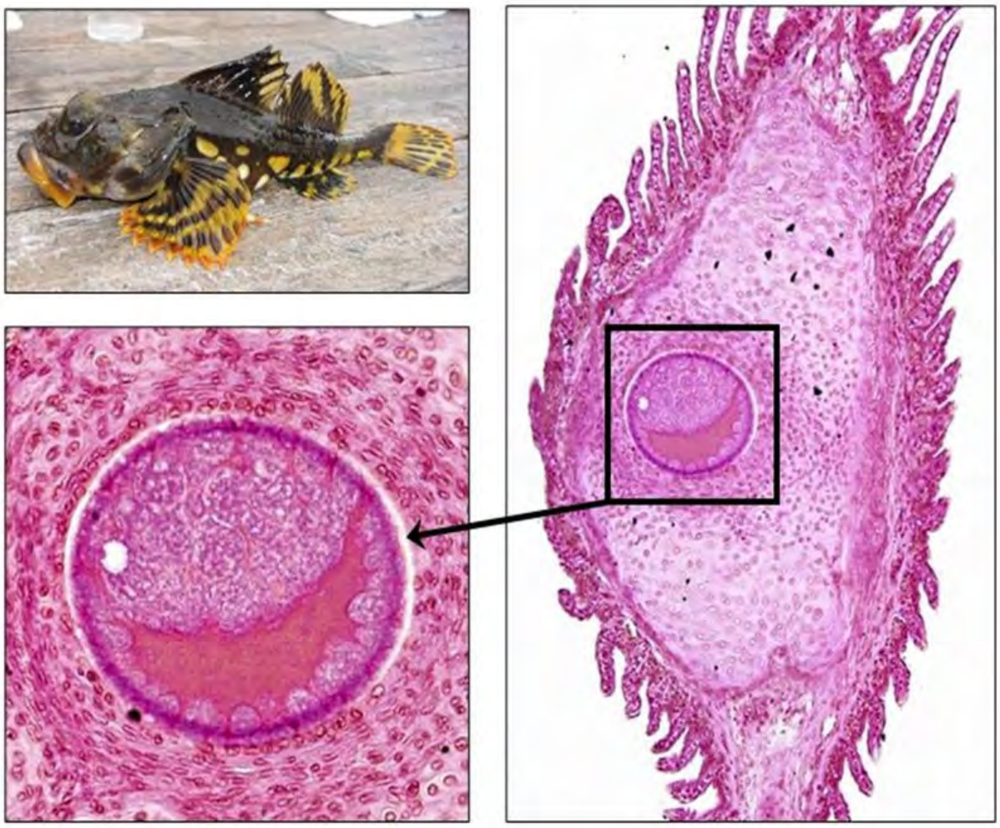


Fig. 7.15: A male sculpin *Myoxocephalus scorpius* and a mesomycetozoan *Ïchthyophonus* sp. in sculpin gill tissue (CPE archive).

Parasitism

True parasites, i.e. organisms that live at the expense of their host, can be found in many marine animals around the world, including arctic regions. Rather, it is difficult to find an animal without parasites in the sea, and even in that case it is not completely certain that some parasite, occurring in low intensity, was not found (a false negative result of a parasitological examination). In the following overview, we will list the most important groups of parasites occurring in the polar regions, which we encountered during parasitological research in Svalbard.

Apicomplexa

They are unicellular eukaryotic organisms (Protista) infecting almost all groups of animals from polychaetes and insects to fish, reptiles, birds and mammals. These include the causative agents of serious human infections (malaria, genus *Plasmodium*) and the most widespread human infections (toxoplasmosis, the causative agent is *Toxoplasma gondi*. Almost a third of the population is infected in our country while in some countries even the majority of the adult population). Among them we find the causative agents of opportunistic diseases (cryptosporidiosis, genus *Cryptosporidium*) and serious infections of farm animals (for example, coccidiosis, genus *Eimeria* and others). They are characterized by the presence of specific intracellular structures, such as the apical complex or the residual plastid. The spore plastid is surrounded by four cell membranes, which reveals that it was originally a eukaryotic alga that lived in endosymbiosis with the host protozoan (feeding itself and its host through photosynthesis). The host element retained the endosymbiotic alga even after it lost the ability to photosynthesize: it needs it for the synthesis of vital substances, as it itself lost the ability to synthesize them during evolution (Oborník 2020). Some representatives of spores are monoxenic (they can have only one type of host) and are spread by faecal-oral transport (for example, *Cryptosporidium* ssp. and *Eimeria* ssp.), while others alternate hosts in their life cycle (for example, the definitive host of the coccidia *Toxoplasma gondi* are felines and the intermediate host is all mammalian orders (including humans) and birds).

A number of spores infect blood cells; thus, we classify them as blood parasites. Often their definitive host is a blood-sucking arthropod while an intermediate host is a vertebrate; in epidemiology, these arthropods are referred to as vectors (for example, mosquitoes of the genus *Anopheles* are the vectors of malarial plasmodia). In the marine environment, leeches (Hirudinea) from the annelid group (Annelida) often serve as vectors of blood parasites. Some sea leeches (genera *Pontobdella*, *Acanthobdella*, *Calliobdella*, *Oceanobdella, Platybdella*, *Heptacyclus*) also live in arctic seas. The leech *Heptacyclus scorpii* (formerly listed as *Malmiana scorpii*) parasitizes sculpins of the genus *Myoxocephalus*. The occurrence of the sporogonic stages of *Desseria myoxocephali* was found in its suction system (Khan 1980). This coccidia was found in sea sculpins at several sites in Billefjorden (Svalbard); in addition to the type host *M. scorpius*, it was also found in the northern crow *Gymnocanthus tricuspis* (Pospíšilová 2014). Another coccidia found in Svalbard belongs to the genus *Haemogregarina*. This genus was already described in 1885, when the species *Haemogregarina stepanowi* was found parasitizing in the blood of the water turtle *Emys orbicularis*. Since then, more than 300 species of the genus *Haemogregarina* and nearly 100 species from three other genera of haemogregarins have been described (Desser 1993). Life cycles of these fish parasites are heteroxenous (requiring more than one host to complete the life cycle) although direct transmission occurs in some cases (Khan 1972). Haemogregarins are worm-shaped parasites living inside erythrocytes or leukocytes in blood. They have two hosts in their life cycle. While merogony and gamogony take place in vertebrate intermediate hosts, the sexual stages, sporogony and then merogony, take place in leeches or other invertebrates, which are therefore the definitive hosts (Davies 1995). Haemogregarines often infect skates (stingrays). The prevalence of *Haemogregarina delagei* in skates varies by season and reaches 77 to 91%. The prevalence of *H. delagei* infection in skates off the Canadian shores in Passamaquoddy Bay was higher than in skates in the North Atlantic, which the authors explained by different host species (Siddall et Desser 2001). Geographical differences in the occurrence of *H. delagei* are also described by other authors (Khan et al. 1980). Asexual reproduction (merogony) has been observed in skate blood exclusively in November (Khan 1972). Transmission of *H. delagei* occurs at the end of the breeding season of the thorny skate *Amblyraja radiata*, i.e. in autumn. The prevalence of sexual stages (gamonts) reaches its maximum in the winter months (Khan 1972). Different species of the genus *Haemogregarina* are transmitted by infected isopods (Isopoda) or leeches depending on the geographical location. While leeches have been recorded in the northern hemisphere, isopods are the vector in the south (Davies 1995). Different developmental stages of *H. delagei* have been found in the tissues of the leech *Oxytonostoma typica* (Siddall et Desser 1993), especially in their salivary glands (Khan et al. 1980).

Thorny skates *Amblyraja radiata* are dominant benthic vertebrates living at a depth of about 30 m off the coast of Adventfjorden near Longyearbyen. *Haemogregarina delagei* was detected in 90% of blood smears from their blood and the sexual stages (gamonts) were found in them already at the end of August (Fig. 8.15).

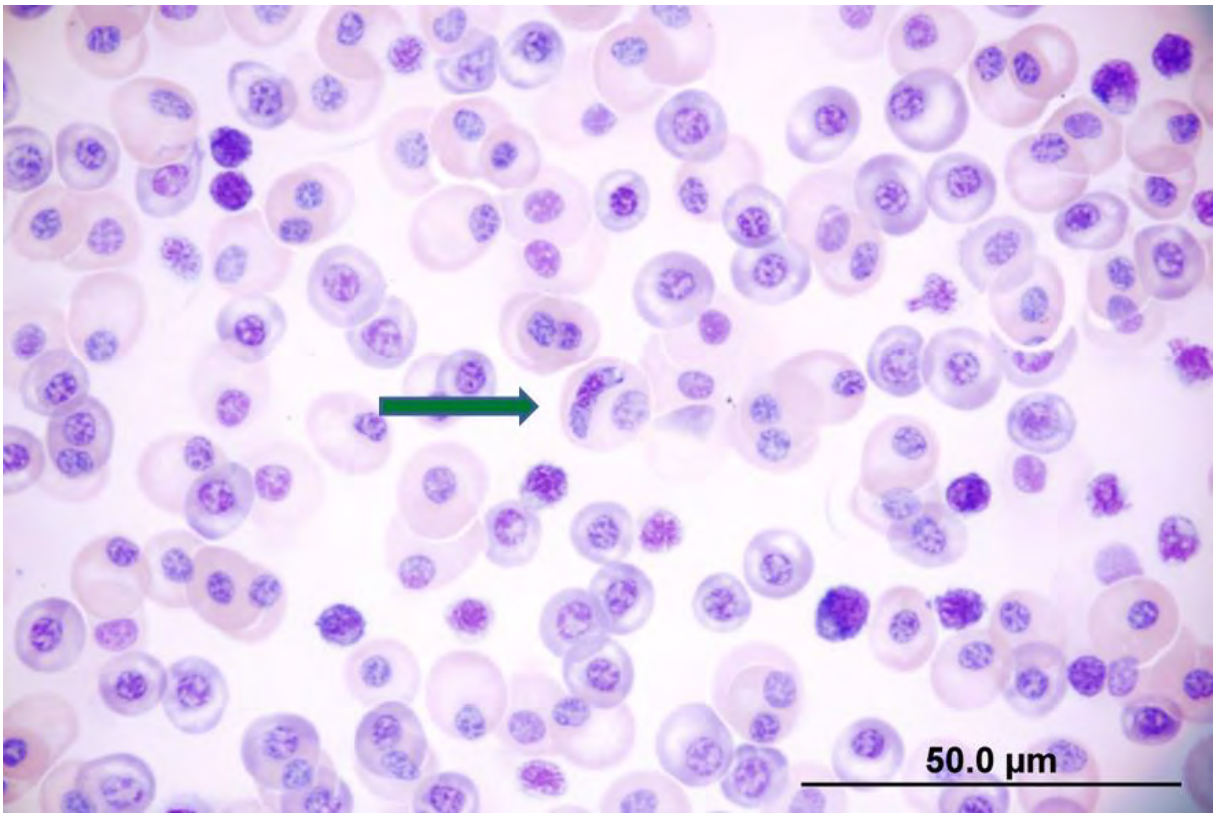


Fig. 8.15: Blood smear of the thorny skate *Amblyraja radiata*. In the erythrocyte in the middle (arrow) is the sexual stage (gamont) of *Haemogregarina delagei* (CPE archive).

Myxozoa

Parasites belonging to the phylum Myxozoa have also been recorded in Arctic regions. It is again an exclusively parasitic group of microscopic organisms, which for a long time were considered strange protozoa, although their multicellularity (typical feature: "cell within a cell") has been observed since their very description. They most likely appeared at the end of the Paleolithic, sometime in the Cryogen (about 600-700 million years ago). At this time, they separated from their free-living ancestors, the Cnidaria, which include the well-known groups of marine corals, jellyfish, tetrapods, polyps and calyces. They switched to a parasitic way of life in the Ediacaran period (the youngest period of the Paleozoic), when they found their hosts among annelids and bryozoans. In later periods, they successfully managed to survive even in the predators of these animals, and their life cycles, including vertebrates, expanded. They first infected cartilaginous fishes, i.e. chimeras, sharks and rays (Lisnerová et al. 2022), later they switched to bony fish and today they are also known from mammals (Dyková et al. 2011, Székely et al. 2015).

However, the vast majority of species are found in the aquatic environment, both in freshwater and marine fish, including arctic ones. In Svalbard, *Ceratomyxa porrecta* was identified in the sculpin *Myoxocephalus scorpius* (Kodádková et al. 2014). Parasites of the Ceratomyxidae family are transmitted in Arctic regions by polychaetes (Polychaeta), which belong to the Sabellidae family (Køie et al. 2008, Kodádková et al. 2014). *Parvicapsula petuniae* (Parvicapsulidae) was described in *Gymnocanthus tricuspis* in Svalbard (Kodádková et al 2014). *Zschokkella siegfriedi* (Myxidiidae) was found in the kidneys of Arctic cod *Boreogadus saida* in Svalbard. *Latyspora* sp. (Sinuolineidae), was identified in the herring *Clupea harengus*; these parasites were again localized in the kidneys (Kodádková et al. 2014).

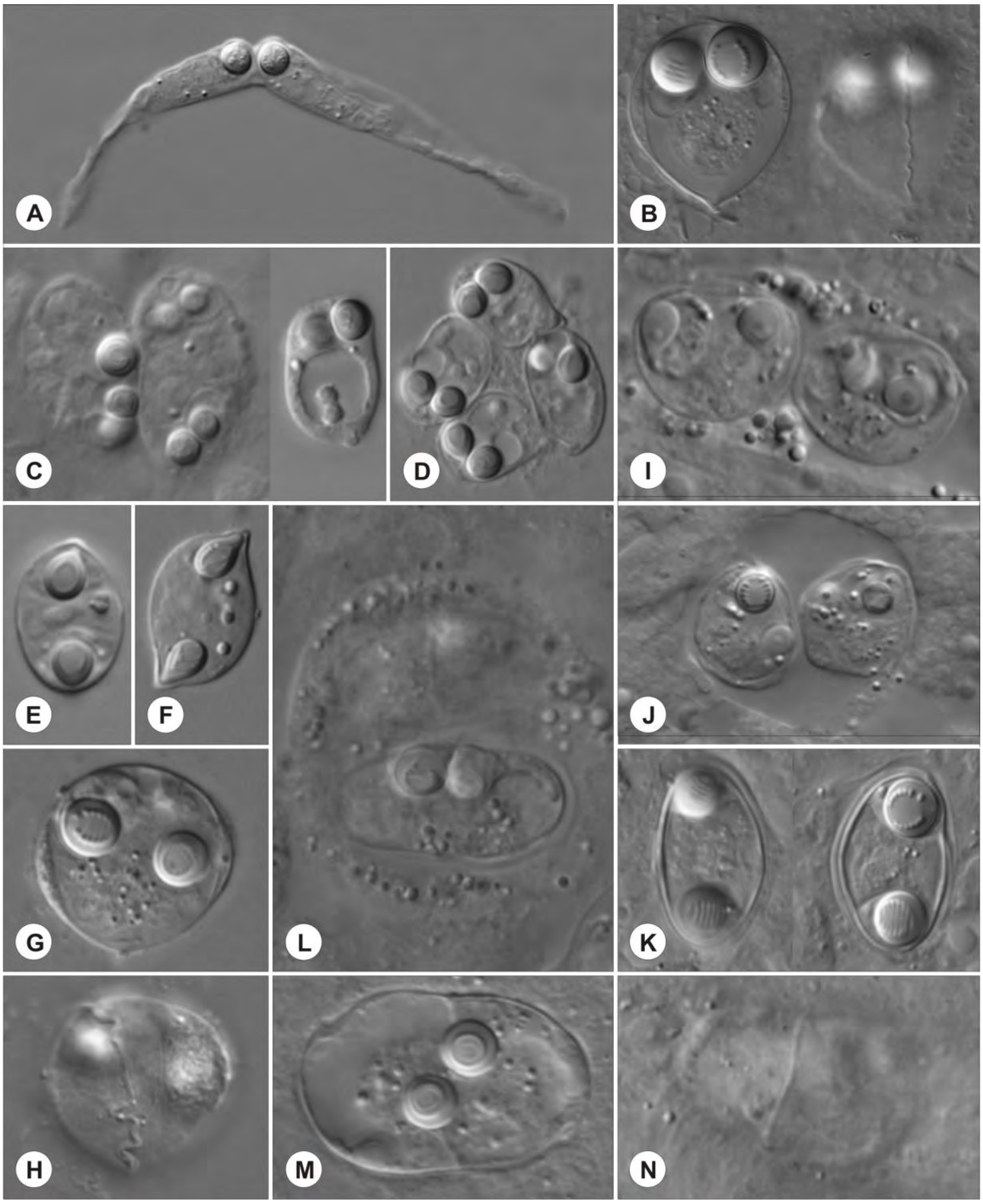


Fig. 9.15: Mature spores and plasmodia of myxozoans from Svalbard fish photographed using Nomarski contrast: A: spores of *Ceratomyxa porrecta* (gall bladder of *Myoxocephalus scorpius*); B: spores of *Schulmania aenigmatosa* (urinary bladder of the American plaice *Hippoglossoides platessoides*); C: plasmodium and spores of *Parvicapsula irregularis* (kidney and urinary bladder of the plaice *H.platessoides*). D: spore of *Parvicapsula petuniae* (kidney and bladder of an Arctic staghorn sculpin *Gymnocanthus tricuspis*; E: spore of *Myxidium gadi from* and *M. scorpius* gall bladder; F: spore of *Myxidium finnmarchicum* (gall bladder of M. scorpius); G, H: spores of *Sinuolinea arctica* (*M. scorpius* gall bladder); I.J: plasmodia of *Zschokkella siegfriedi* (kidney of the polar cod *Boreogadus saida*); K: spore of *Zschokkella siegfriedi* (kidney of the polar cod *Boreogadus saida*); L: plasmodia of *Latyspora* sp. (kidney of herring *Clupea harengus*); M, N: spores of the plasmodium of *Latyspora* sp. (kidney of the herring *Clupea harengus*) (Kodádková et al. 2014).

The cited publication is also proof of how little parasites in the Arctic have been studied so far. Parasitological research on several species of fish from a small part of only one of the many Svalbard fjords brought much new information: the description of three species new to science, new hosts for already described species, new insights into phylogeny and much more.

Helminths

Most multicellular parasites are classified as helminths. This term has no taxonomic value and includes several mutually unrelated groups of animals, which, in addition to multicellularity and the ability to live parasitically, are united in most cases by an elongated (worm-like) body shape. That is why they are popularly called "parasitic worms." Helminths mainly include tapeworms, hookworms, flukes, nematodes and acanthocepalans. The first 3 listed belongs to the phylum Platyhelminthes ("flatworms"), sub-phylum Neodermata. The name derives from the fact that, during the change of the first larval stage to the next, the surface of the skin is replaced: the ciliated surface of the first larval stage, which is free-living, is replaced by the skin formed as a syncytial (multinucleated) neodermis in the next, already parasitic stage.

Tapeworms (Cestoda)

Tapeworms (Cestoda) are an exclusively parasitic group of invertebrates, which are widely known mainly because of the representatives found in humans. Tapeworms are found in almost all groups of vertebrates and use a number of invertebrates as intermediate hosts (especially crustaceans, insects, less often also molluscs). So far, 6,000 species of tapeworms from more than 750 genera have been described, which are classified into 19 orders. Individual orders are mainly characterized by the shape of the scolex (front part of the body, also "head") and tend to be specific for a certain group of definitive hosts. The greatest boom in diversity was achieved by tapeworms in cartilaginous fish, probably due to the structure of their intestine, which is short, but the surface of which is greatly increased by a spiral valve called the typhlosolis.

In skates and sharks, we find representatives of almost half of the described orders (9 out of 19)! They are characterized by high host specificity (one species of tapeworm parasitizes only one species of fish) and considerable frequency – several species of tapeworms are found in almost every skate. As a rule, these are small representatives (the smallest known species reaches a length of only 200 µm, but most often around 2 cm). The most striking feature of these skate tapeworms is the presence of a differently shaped scolex – a necessary organ for attaching the parasite to the intestinal epithelium (or spiral valve) of the host (Fig. 10.15).

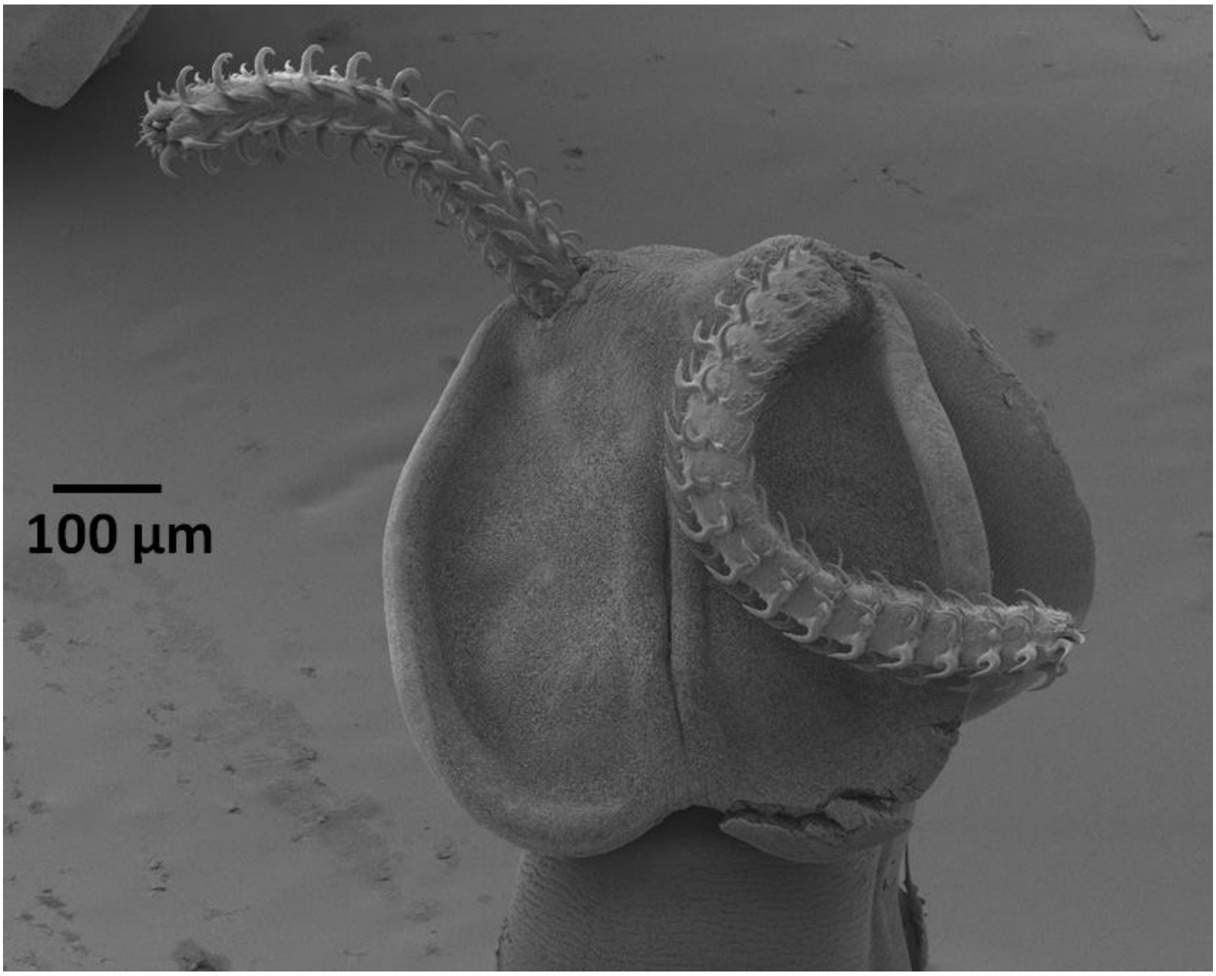


Fig. 10.15: SEM micrograph of scolex of the tapeworm *Grilotia* sp. from the spiral valve of the thorny skate *Amblyraja radiata* (CPE archive).

Tapeworms of the order Spathebothriidea, which have a circumboreal distribution, live in the gut of bony fish. The tapeworm Diplocotyle olriki (Kuchta et al. 2014) was found in the intestines of 5-20% (depending on the season) of the sculpin *Myoxocephalus scorpius* and, more rarely, *Gymnacanthus tricuspis* caught in the Billefjorden (Svalbard) fjord locations (Kuchta et al. 2014) (Fig. 11.15).

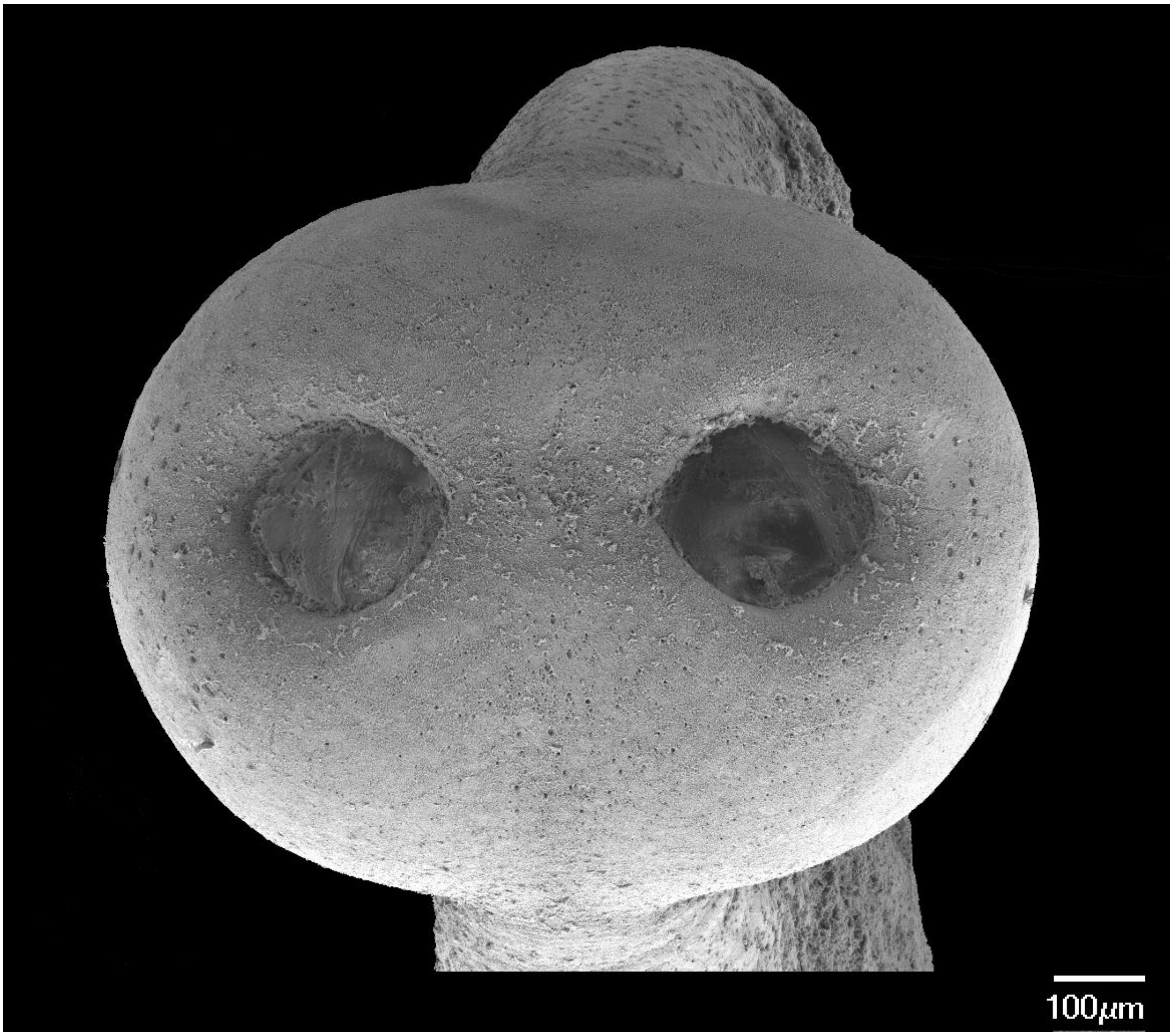


Fig. 11.15: SEM micrograph of scolex of the tapeworm *Diplocotyle olrikii* from the intestine of the sculpin *Myoxocephalus scorpius*. SEM image (Kuchta et al 2014)

A larva (plerocercoid) of the tapeworm *Pyramicocephalus phocarum* (Fig. 12a.15) was found in the body cavity of the sculpin *M. scorpius* in Billefjorden, while dozens of adult tapeworms of the same species were found in the intestine of a freshly dead ringed seal *Pusa hispida* found in the same location (Fig. 12b.15). (Schäffner et al 2018)

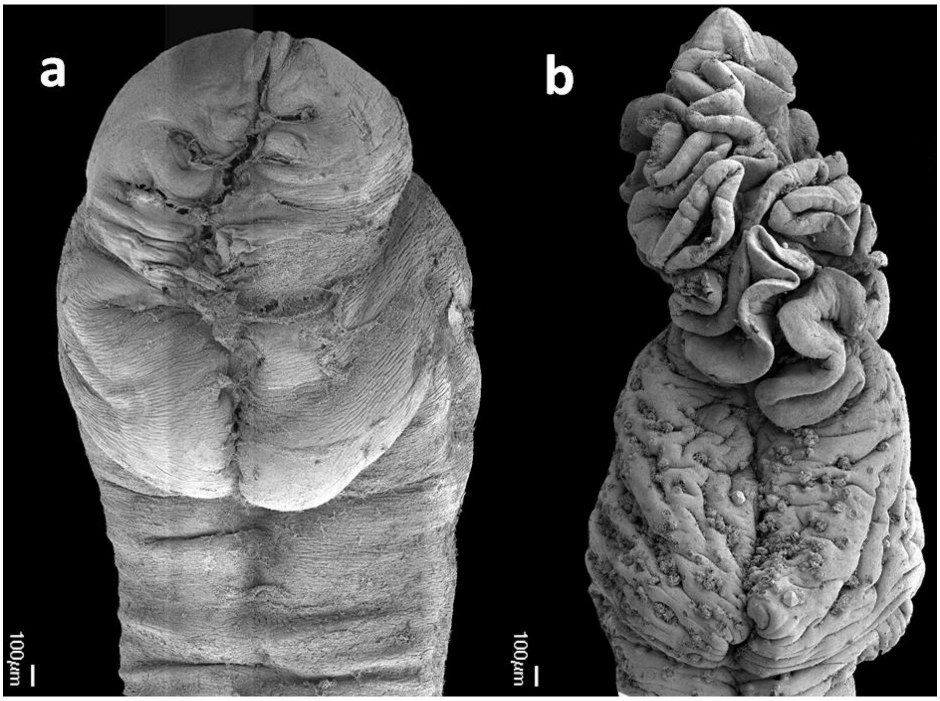


Fig. 12.15: Tapeworm *Pyramicocephalus phocarum*, SEM. A: plerocercoid from the body cavity of the sculpin *Myoxocephalus scorpius*. B: scolex of an adult tapeworm from the gut of the ringed seal *Pusa hispida*. (Schäffner et al 2018).

In the gut of the same seal, hundreds of adult tapeworms of *Diphyllobothrium schistochilos* (Fig. 13.15), a representative of an important genus parasitizing many species of mammals, including humans, were found.

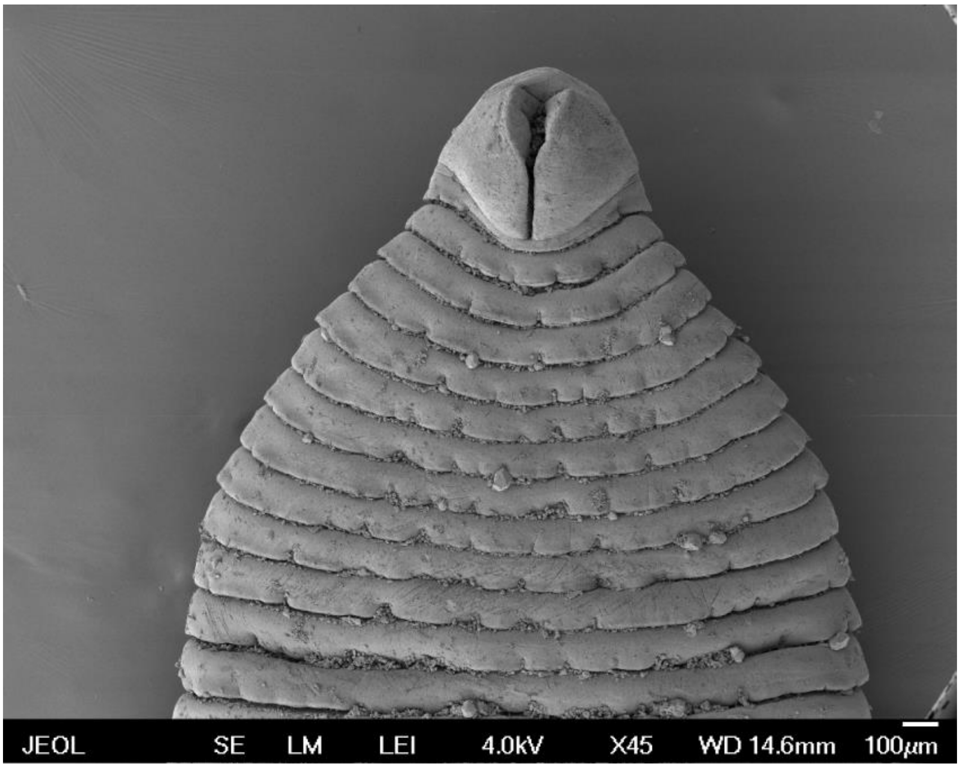


Fig. 13.15: SEM micrograph of scolex of the tapeworm *Diphyllobothrium schistochilos* from the gut of a seal *Pusa hispida*. SEM (Schäffner et al 2018).

Tapeworm larvae of the order Tetrabothriidea, which has a single family Tetrabothriidae with a cosmopolitan distribution, can also parasitize fish living in Arctic seas. The definitive hosts of the tapeworms of this family are mostly seabirds, and to a lesser extent cetaceans and pinnipeds. Hundreds of adult *Tetrabothrius macrocephalus* tapeworms were found in the gut of a dead loon *Gavia arctica*, found in Petunia Bay (Fig. 14.15).

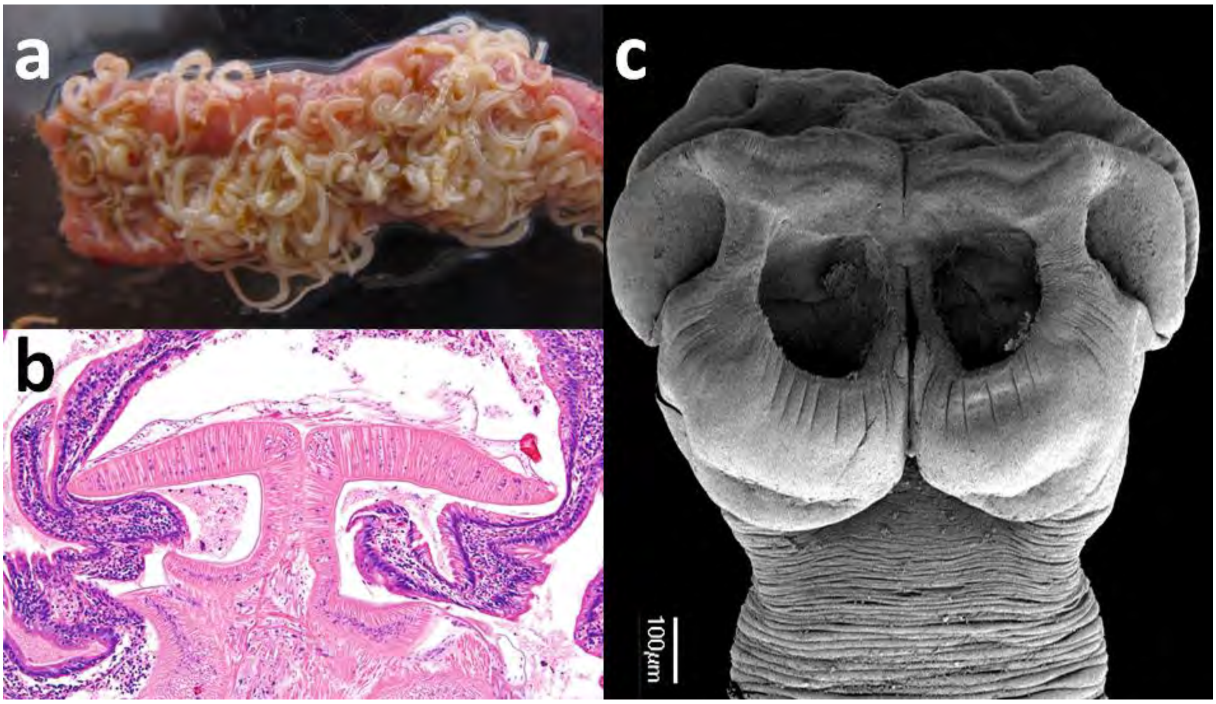


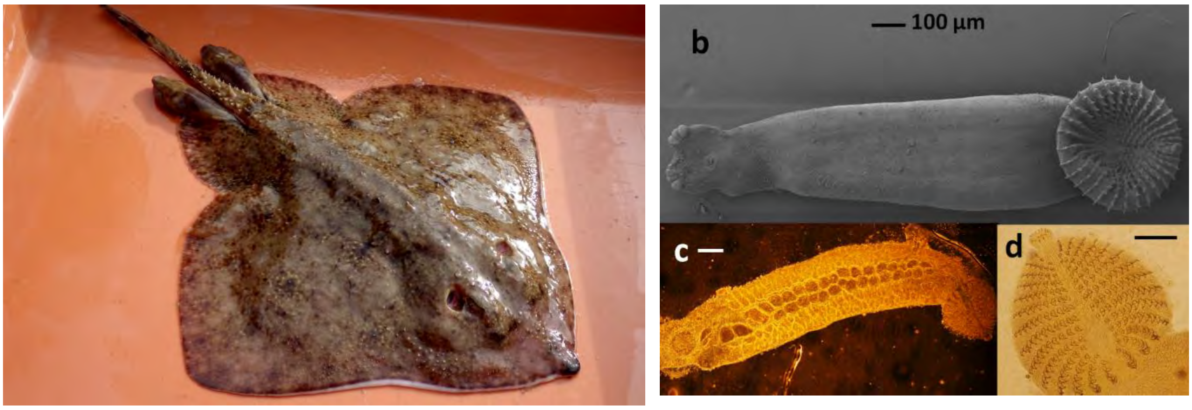
Fig. 14.15: Tapeworm *Tetrabothrius macrocephalus*. A: Dissected intestine of a loon *Gavia arctica*, with numerous tapeworms. B: Histological section of the intestine of a loon with the scolex of the tapeworm *T. macrocephalus* emerged in the intestinal mucosa. C: SEM image of the scolex (CPE archive).

There is still little information about the effect of tapeworms on the health of wild animals. According to Fig. 14.15 (number of tapeworms, extent of mucosal damage), it would be possible to assume that tapeworm infection contributed to the death of the host. However, in reality, similarly massive infections can be found in asymptomatic hosts.

Monogenea

Monogenea, a class from the phylum Platyhelminthes, is also an exclusively parasitic group. They get their name from their simple life cycles: they get by with one host. Previously, these helminths were classified as flukes (uniform flukes), but molecular analyses have shown that they are related to tapeworms.

Parasites of the Monogenea represent an important group of organisms, numbering up to 25,000 species. Their prevalence is often high in commercial fish farms and can thus lead to significant losses in the host population. Although representatives of monogeneans are cosmopolitan and some of them are important pathogens, knowledge of the biochemical or molecular nature of the parasite-host interaction is very limited. They infect a wide range of hosts that spend a significant part of their lives in water (fish, amphibians, hippos). However, the vast majority of them infect the gills, skin or fins of fish and cartilaginous fish, including arctic ones. As an example, from the Svalbard fjords, we present two species of monogeneans infecting the star skate *Amblyraja radiata* (Fig. 15a.15): *Acanthocotyle verrilli* (Fig. 15b.c.d.15), which lives on the skin and fins of skates, and *Rajonchocotyle emarginata* (Fig. 15e.f.15), parasitizing on their gills.



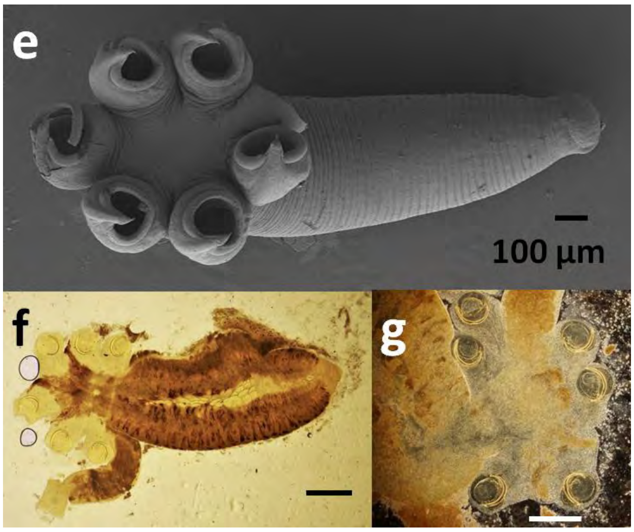


Fig. 15.15: Monogenea parasitizing skates. Thorny skate *Amblyraja radiata* (a), *Acanthocotyle verilli* from skin, SEM (b). *A. verilli* from a light microscope (c), Detail of a pseudohaptor (d), *Rajonchcotyle emarginata* from gills SEM (e), *R. emarginata* from a light microscope (f), detail of haptor (g). (CPE archive).

These species are very suitable for practical demonstration at a field station, especially due to their considerable size: A. verilli reaches up to 3 mm and the sclerites on the attachment organ (pseudohaptor) are already visible under a magnifying glass. *Rajonchcotyle emarginata* is even larger (over 7 mm) and the bizarre body shows a haptor with 6 suckers equipped with sclerotized hooks. The material of these parasites was also analysed molecularly, which made it possible to specify the phylogenetic position of both species within the class Monogenea (Hermans et al. 2021).

Flukes (Trematoda).

The last class from the sub-phylum Neodermata are flukes (Trematoda). Their life cycles are often even more complex than those of tapeworms, with the exception of basal representatives parasitizing bivalves. Adults of other flukes are parasites in the vast majority of vertebrates. The vast majority of species live endoparasitically in the intestine or liver, less often in the bloodstream, lungs, pancreas, etc., with the exceptions of ectoparasites, which live on the gills of fish (family Syncoeliidae) or under scales (Transversotrematidae). The first intermediate host, infected by a larva called a miracidium, is molluscs; we will mention one of the rare exceptions later. The miracidium moves in the water with the help of a ciliated surface and looks for a host mollusc. In some species, the egg hatches in the digestive tract of the gastropod, which has eaten the egg. In the first host, the miracidium develops into a sporocyst and reproduces asexually, resulting in daughter sporocysts or redia. Further asexual reproduction produces cercariae, which in most species leave the first intermediate host and seek out the second one. The second intermediate hosts, in which the cercaria encyst and develop into a resting stage - metacercaria, can be various types of invertebrates (most often molluscs or crustaceans) or even cold-blooded vertebrates. The second intermediate host may be absent and the cercariae may encyst on various surfaces (aquatic plants) and form the so-called adolescaria. Further development in the adult fluke occurs in the definitive host, into which the metacercaria usually enters by being ingested by a second intermediate host.

The life cycles of some groups of flukes may differ from this general scheme. For example, in schistosomes, the causative agents of serious host diseases, the cercariae penetrate directly into the definitive host and mature in its bloodstream. Unlike most other flukes, which are hermaphroditic, schistosomes are gonochoristic. In the High Arctic, where freshwater or terrestrial snails are mostly absent, most flukes use marine molluscs as their first intermediate host, while the adults are found mainly in fish, marine mammals or sea birds. Typical fish parasites are members of the cosmopolitan Opecoelidae family. Adults of this family parasitize mainly in the digestive tract of fish, both in the littoral and pelagic zones, but even in the bathyal and abyssal. On Svalbard, they can be found mainly among benthic sculpins: for example, in Petuniabukta, 48-85 % of the sculpin *Myoxocephalus scorpius* and 32-67 % of the northern sculpin *Gymnocanthus tricuapis* are infected with these flukes. In *M. scorpius* the fluke *Podocotyle atomon* predominates (Fig. 16.15), while in *G. tricuspis* the predominant fluke is the species *Anomalotrema koiae*. However, infections with both species in one fish are not rare either. Both species have a similar life cycle, the first intermediate host in this area is a gastropod of the Buccinidae family (*Buccinium undatum*, *B. polare*, *B. glaciale* and *Plicifusus kroyeri*) (Fig. 17.15) and the second intermediate host are amphipods (Amphipoda). These flukes use a not very common strategy of infecting the second host.

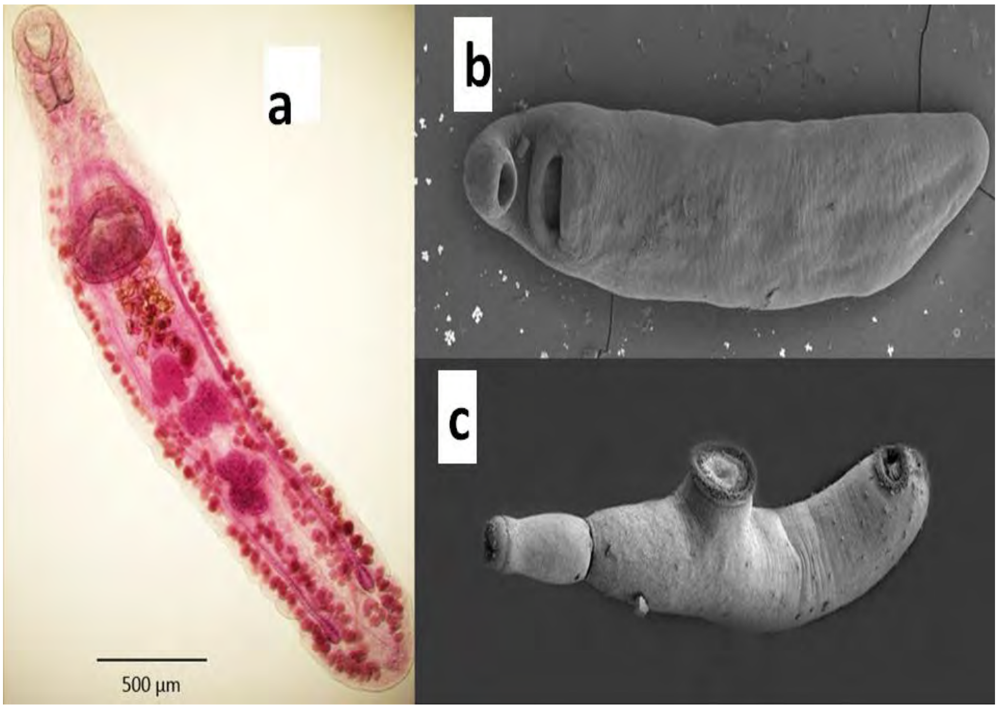


Fig. 16.15: *Podocotyle atomon* from the intestine of the sculpin *M.scorpius*. A: adult fluke stained with ferric acetocarmine. B: SEM adult fluke. C: cercariae from the whelk *B. undatum*, SEM (CPE archive).

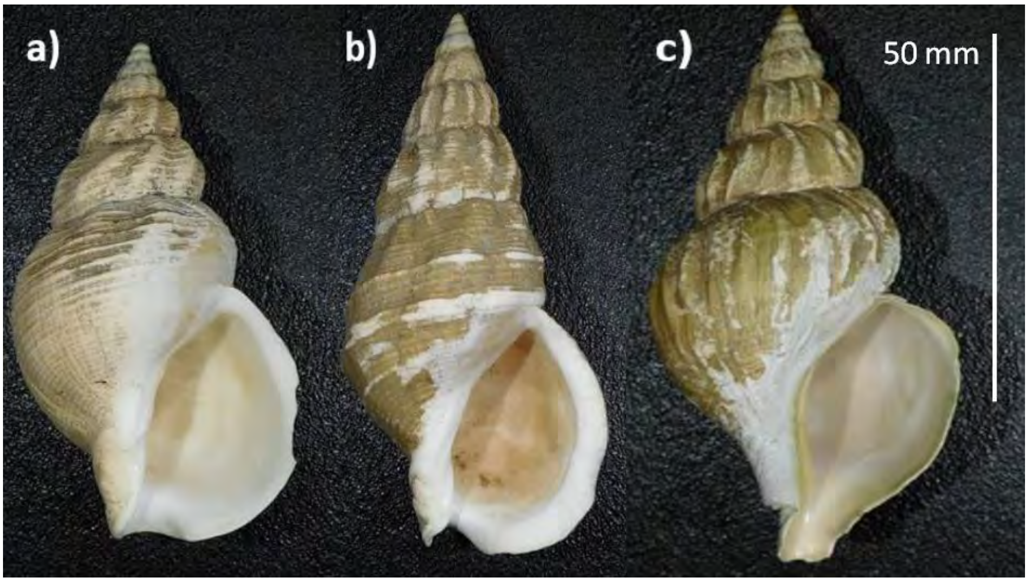


Fig. 17.15: Intermediate hosts of flukes of the Opecoelidae family from Petuniabukta: a) whelk *Buccinum undatum*, b) *B. glaciale*, c) *Plicifusus kroyeri* (CPE archive).

The vast majority of flukes try not to harm their first host much (apart from castration, which is common) in order for it to grow, survive as long as possible, and thus allow them to produce as many cercariae as possible, which emerge from the mollusc and actively search for a second intermediate host. However, the cercariae of *P. atomon* and *A. koiae* do not emerge from the host snails (the short tail does not even allow them to move effectively in open water (Fig. 18.15 and Fig. 19.15). They kill the host snail and wait for it to be actively eaten by scavenging crustaceans from the family Gammaridae.

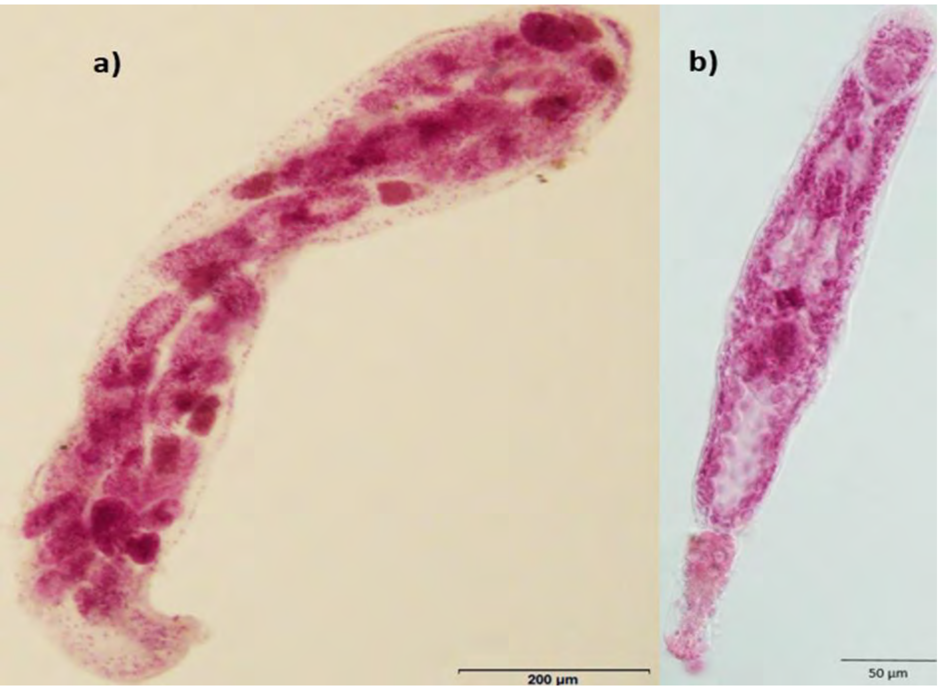


Fig. 18.15: Larval stages of *Anomalotrema koiae* obtained from the hepatopancreas of *Plicifusus kroyeri*. A: daughter sporocyst. B, C: cercariae. Stained with carmine (Novotný 2021).

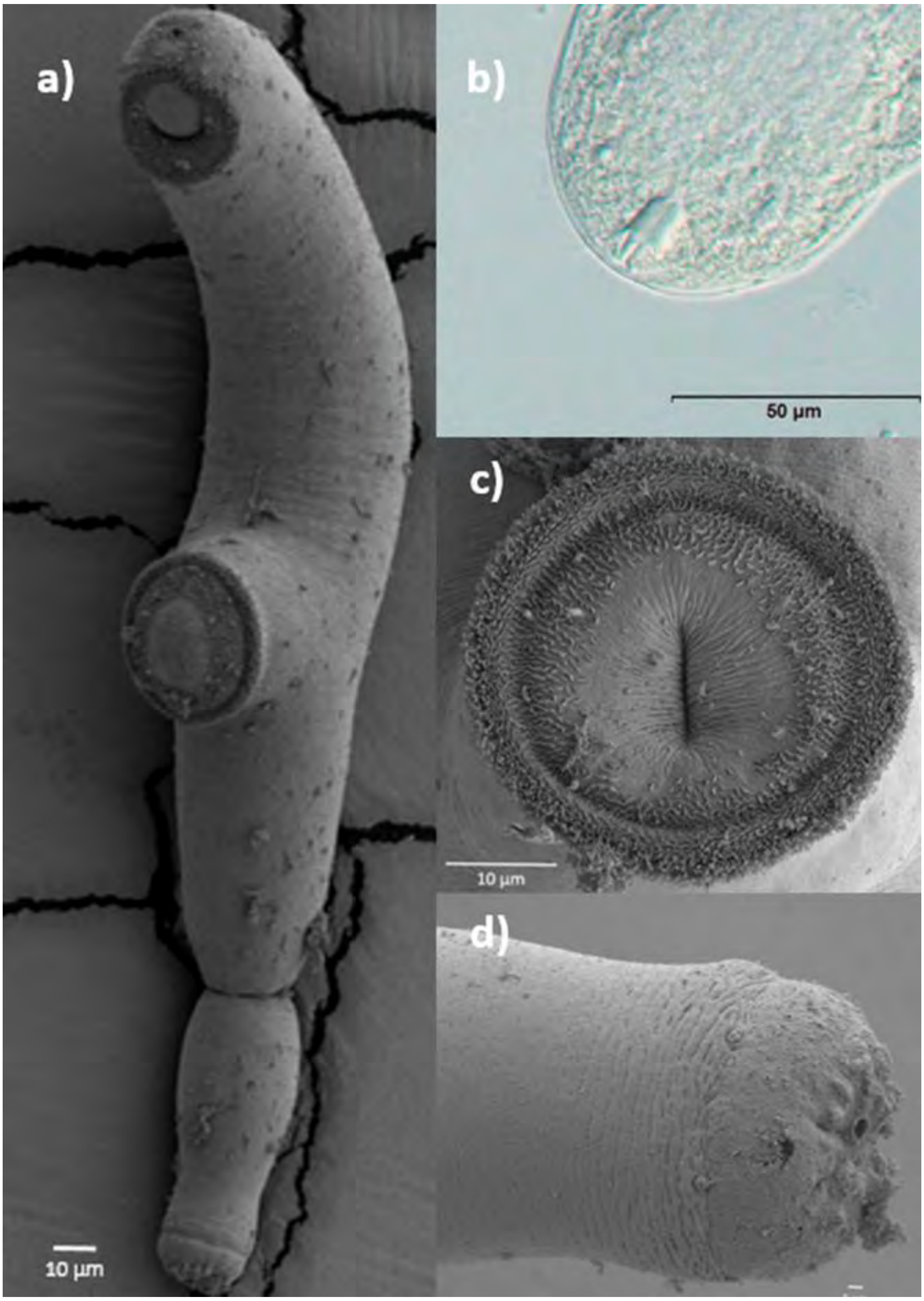


Fig. 19.15: Cercaria of *Anomalotrema koiae*, from the hepatopancreas of *Buccinum polare*. a: SEM image of the whole body, b: stylet (thorn at the anterior end of the body). c: abdominal sucker, d: posterior end of tail
(CPE archive).

After ingestion, they penetrate the muscle of Gammarus, encyst in the metacercaria, which has been repeatedly demonstrated experimentally (Fig. 20.15), and wait until the millipede is eaten by a fish, in whose intestine they mature and complete their life cycle (Ditrich et al., not yet published).

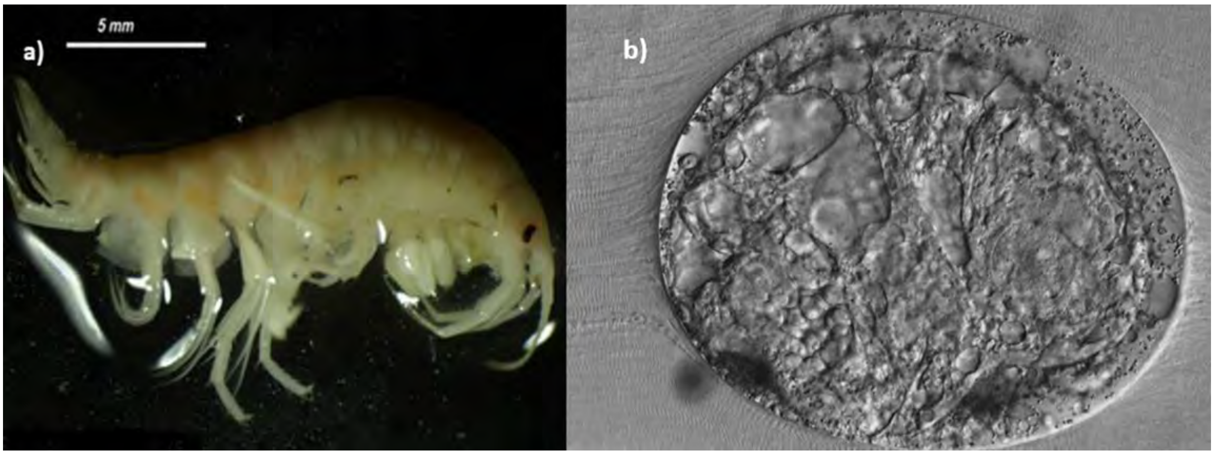


Fig. 20.15: *A. koiae* fluke in the second intermediate host. a: *Gammarus setosus* infected by ingesting the hepatopancreas of a parasitized whelk *Buccinum glaciale*. b) *A. koiae* metacercaria encapsulated in *G. setosus* muscle (CPE archive).

Flukes of the Heniuroidea superfamily are also abundant in the digestive system of fish off the coast of Svalbard. They occur abundantly in the stomach, gastric appendages and intestines of various fish species, especially the polar cod *Boreogadus saida* and the Atlantic cod *Gadus morhua* (Branišová 2020). The fluke *Derogenes varicus* has an interesting life cycle. The cercariae of this fluke emerge from the predatory gastropod *Euspira pallida* (Fig. 21.15).

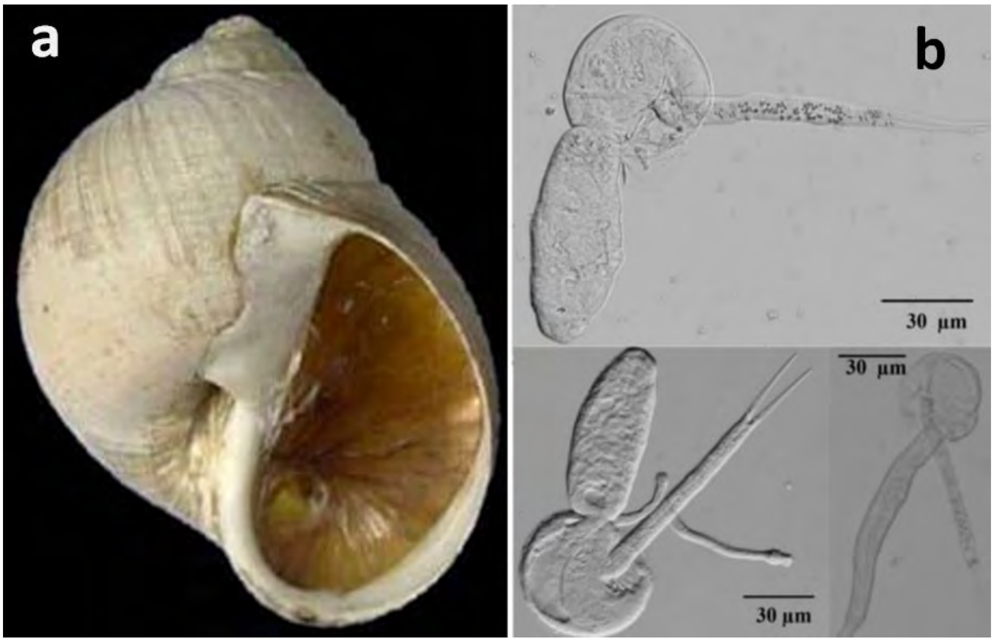


Fig. 21.15: The first intermediate host of the fluke *Derogenes varicus*. A: Host gastropod *Euspira pallida*. B: Cercariae of *D. varicus* emerging from its hepatopancreas (CPE archive).

The cercariae of this fluke are cystophorous, they float in the water and, with slow movements of their long tail, lure the second host (a planktonic crustacean) to eat it (Koie 1979). Along with it, another stage, the metacercariae, is then eaten by another host. A number of so-called paratenic hosts can enter the cycle, through which the metacercariae pass unchanged (Krupenko et al 2022). The definitive host is most often a pelagic fish (Fig. 22.15).

Fig. 22.15: *Derogenes varicus* fluke. A: Definitive host is the capelin (*Mallotus villosus*). B: adult fluke from the stomach appendage of a capelin (CPE archive).

In some cases, however, the metacercariae can already reach sexual maturity in the paratenic host, produce eggs and thus shorten the life cycle: this is the so-called progenetic cercariae. On Svalbard, in Adolfbukta Bay, the arrow worm *Eukrohnia* sp. can rarely be seen, but in huge amounts. Some of them are infected with progenetic metacercariae of *Derogenes varicus* (Fig. 23.15). Alternative paths in life cycles and their shortening can be considered as an adaptation of parasites to extreme living conditions.

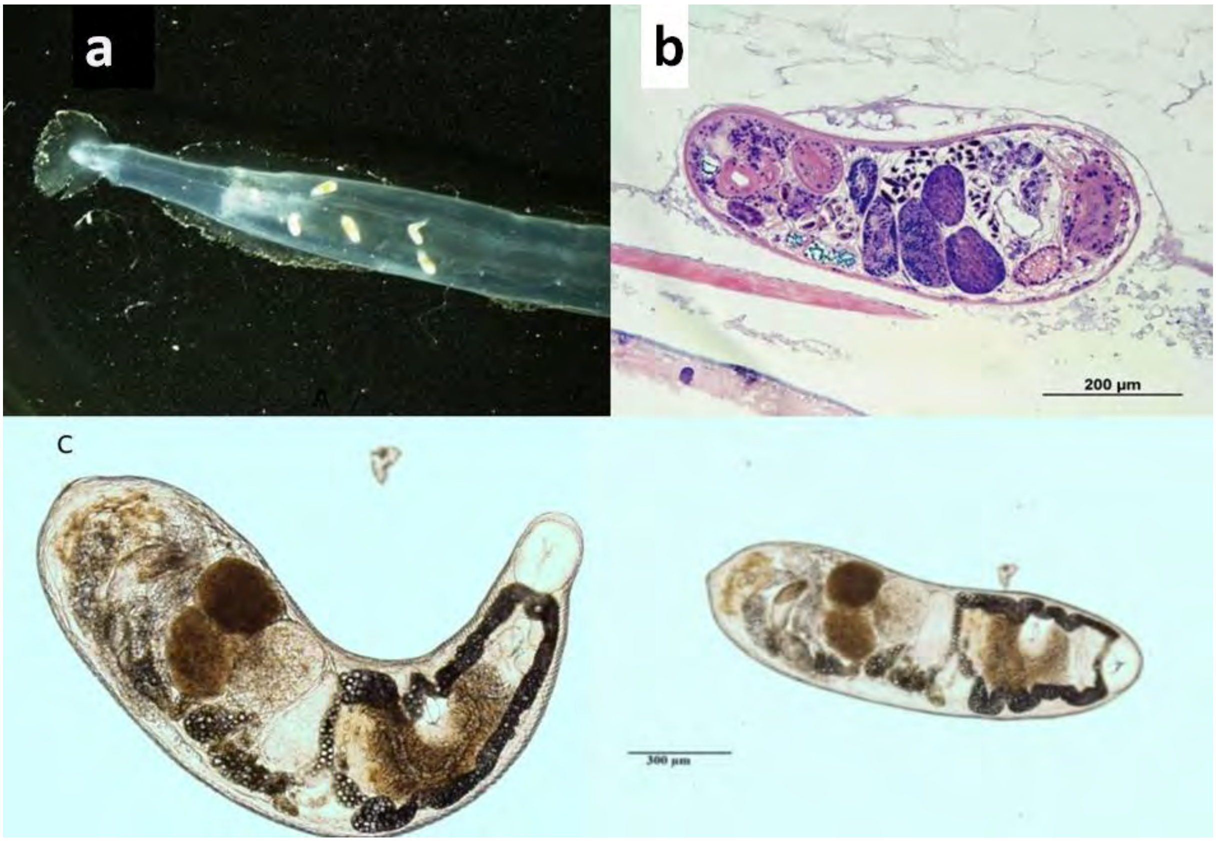


Fig. 23.15: Progenetic metacercariae of *Derogenes varicus*, A: Arrow worm with metacercariae in the body cavity, nativ. B: Histological section of an arrow worm with metacercariae, stained with hematoxylin-eosin. C: metacercariae from an arrow worm (CPE archive).

The fluke *Aporocotyle simplex* is a parasite in the bloodstream of flatfish. It is usually found in the heart chamber, abdominal aorta and gill arteries. In some cases, it can also be found behind the ocular orbit (Thulin, 1980). At a high intensity of infection, the eggs cause necrosis in the gill arteries and the heart muscle (Thulin, 1980). Its first intermediate host is the polychaete *Artacama proboscidea*. The larval stages of the fluke can induce defense reactions in the intermediate host that lead to sterility of the individual and muscle wasting. In such weakened individuals, severe infestations can cause the body wall to rupture, leading to the death of the individual (Koie 1982).

The main definitive host of *A. simplex* is the American plaice *Hippoglossoides platessoides*. The prevalence of *A. simplex* in this host exceeds 27% in the coastal waters of Svalbard near Longyearbyen (Fig. 24.15).

Fig. 24.15: American plaice *Hippoglossoides platessoides* and adult fluke *Aporocotyle simplex* from its gill artery (CPE archive).

The castration and muscle wasting of the *A. simplex* infected polychaete *A. proboscidea* described above can be considered as an example of manipulation of the host by the parasite. The castrated host does not invest energy in the offspring, leaving more energy for the parasite. The flaccid musculature does not allow the body to be pulled quickly into the sediment, and the host is thus exposed to predation. Like other manipulations, this increases the likelihood of closing the developmental cycle and ensuring the parasite's offspring.

An even more illustrative example of manipulation is the fluke *Gymnophalus* sp., a parasite of the sea eider *Somateria mollissima*. Its first and second intermediate host in the Svalbard fjords is the Arctic truncate softshell *Mya truncata*, which lives submerged in the sediment and brings water for breathing and filtering food into the mantle cavity with a siphon (Fig. 25.15).

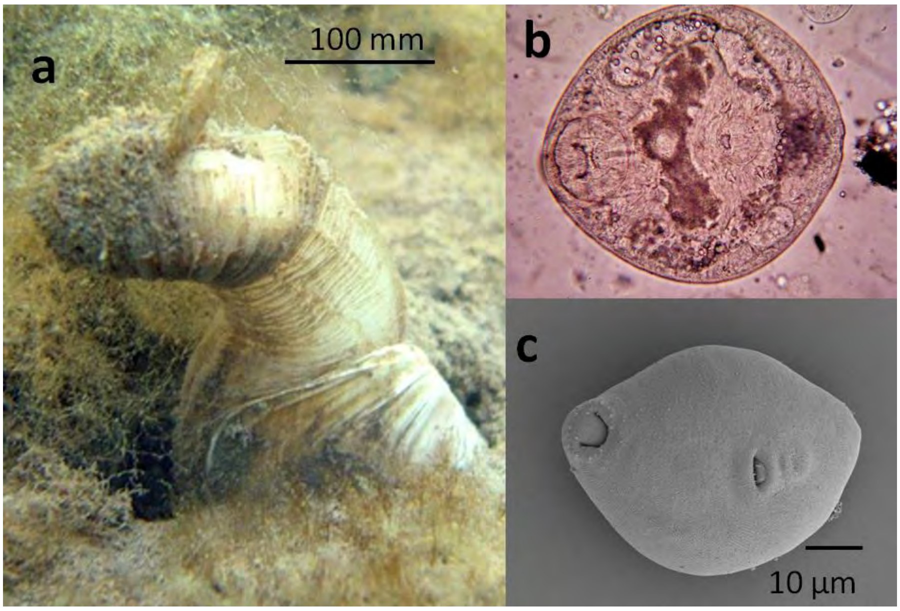


Fig. 25.15: (a) Arctic truncate softshell (*Mya truncata*) submerged in sediment (b) metacercaria of *Gymnophalus* sp. from its hepatopancreas (c) SEM micrograph of the metacercaria. (CPE Archive).

Once the metacercariae in the kelp have matured and are able to infect eiders, they cause the softshells to climb out of the sediment and expose themselves to predators, including eiders (Fig. 26.15). The result is again an increase in the probability of completing the development cycle.

Fig. 26.15: Arctic truncate softshell *Mya truncata* infected with the fluke *Gymnophalus* sp. on the surface of the sediment exposed to predation by predatory gastropods, walruses, starfish and eiders. (CPE archive)

Round worms (Nematoda)

Typical parasites of the Arctic region are nematodes of the Anisakidae family. Their first intermediate host are planktonic crustaceans, the second is fish, in which the larvae encyst and wait for the infected fish to be eaten by a fish-eating bird or mammalian host from the group of cetaceans or pinnipeds, which are the definitive hosts of these parasites. However, if the infected fish is eaten by a predatory fish, the larva is transferred to a new (ie paratenic) host. In places where pinnipeds live, such as Svalbard, it is not easy to find a fish that is not infected with anisakid larvae. Members of the genera *Contracaecum* and *Pseudoterranova* are often found in the muscle of fish in Svalbard, while representatives of the genus *Anisakis* are mainly found in the liver and other internal organs (Fig. 27.15).

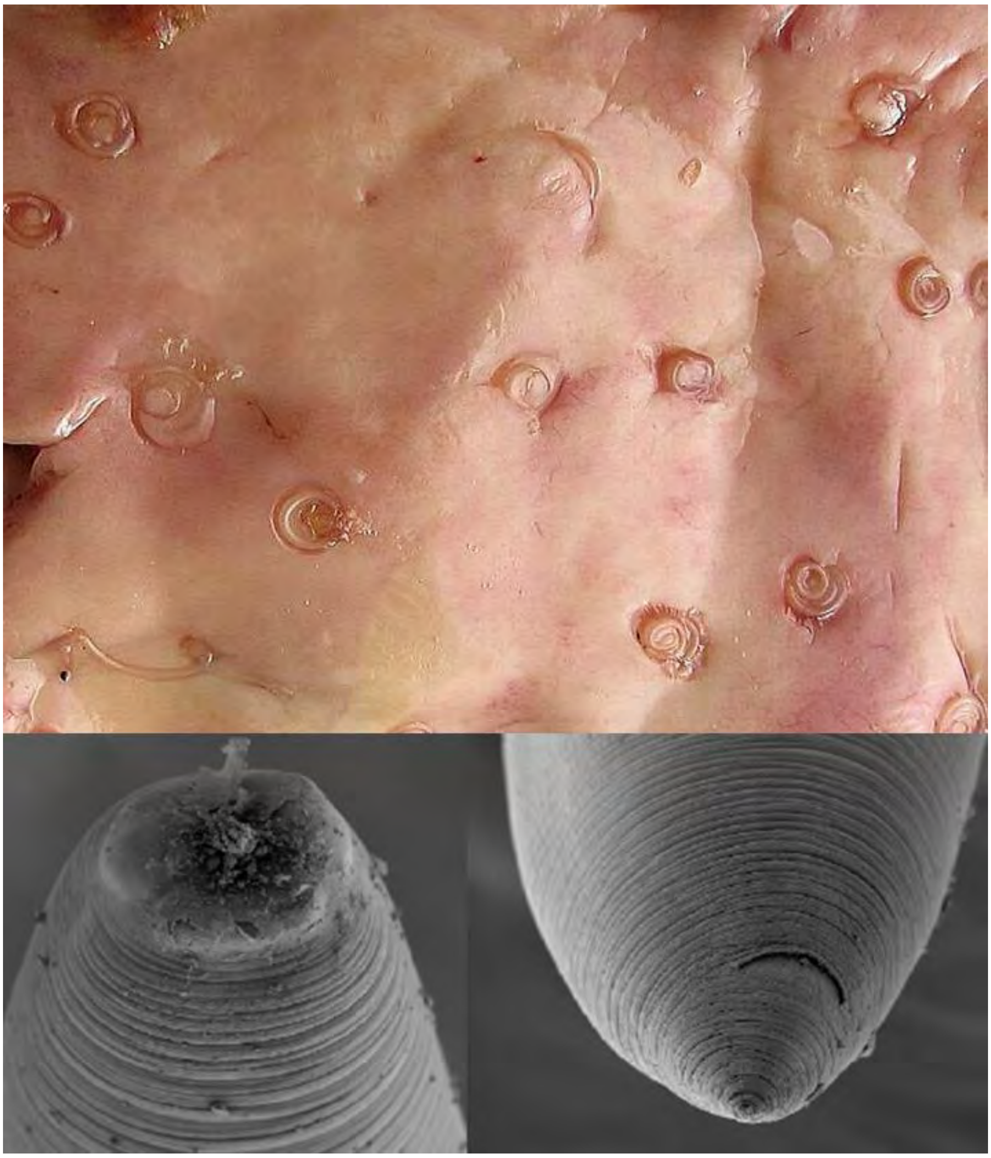


Fig. 27.15: Polar cod (*Boreogadus saida*) liver with *Anisakis* sp. nematode larvae and SEM micrograph of the larva; anterior and posterior ends (CPE archive).

Consumption of poorly prepared fish infected with anisakid larvae can be dangerous to humans. There is a risk of an unpleasant and sometimes even dangerous disease manifested by sharp stomach pains. These are caused by larvae that, after digestion, emerge from the attacked meat and try to burrow into the stomach wall of the host (Buchmann et Mehrdana 2016). Even consuming heat-treated or frozen and thawed fish is not without danger. Dead *Anisakis* and *Pseudoterranova* nematodes can be a source of dangerous substances that can stimulate the human immune system and cause an allergic reaction in the form of mild urticaria to anaphylactic shock (Nieuwenhuizen et Lopata 2013).

Crustaceans (Crustacea)

A number of parasitic crustaceans are found in polar seas. They have adapted to the parasitic way of life so much that they have changed their appearance in a significant way and bear little resemblance to their free-living ancestors. As an example, from Svalbard, we present the parasitic copepod *Omnatokoita elongata*, parasitizing the eye of the smallhead shark *Somniosus microcephalus* (also called the Greenland shark). These sharks are abundant in coastal littoral waters at depths below 50 m. Infection by this parasite causes blindness in 1 or both eyes. (Fig. 28.15). However, this does not cause much trouble to the host, since smallhead sharks hardly use their sight. It was speculated that the copepod may be bioluminescent and thus form a mutualistic relationship with the shark by attracting prey (Bjørn 1961).

Fig. 28.15: Copepod *Omnatokoita elongata* on the eye of the shark *Somniosus microcephalus*, stuck in a gill net near Longyearbyen (CPE archive).

Another type of ectoparasitic copepod occurs on the skin of the polar cod (Fig. 29.15).

Fig. 29.15: Parasitic copepod *Clavella adunca* on the polar cod *Boreogadus saida* (CPE archive).

Crustaceans from the group Rhizocephala have a complicated life cycle and do not resemble crustaceans at all when mature. They produce small eggs that hatch into female larvae that search for crabs. On them, it turns into a stage called the kentrogon. It injects itself into the crab's tissue, castrates the crab and creates a tangle of fibres in its body that concentrate around its intestine. After the host carapace shedding, a sac-like structure, the so-called externa, protrudes from its body. This is sought after by the male kentrogon, which hatches from larger eggs. Again, he injects himself into the external and then impregnates her. The externa matures and produces fertilized eggs, large and small. In seawaters, we often meet the rhizocephalan *Peltogaster paguri*, which, unlike its relatives from the temperate zone, castrates only the females of its host, the hermit crab *Pagurus pubescens* (Reinhard 1942). *Peltogaster paguri* is commonly found in hermit crabs in the Svalbard fjords (Fig. 30.15).

Fig. 30.15: *Peltogaster paguri* on the hermit crab *Pagurus pubescens*. (CPE archive).

Arctic parasites of terrestrial animals

Terrestrial biotopes of polar regions are characterized by their relative simplicity, low diversity with short food chains and with a limited flexibility and capacity to adapt to climate change (Callaghan et al. 2004, Hoberg et al. 2012). Additionally, basic and long-term records of parasite diversity (abundance or host and geographic distribution) are often lacking in polar regions, even for very well-known animal host species (Hoberg et Kutz 2013). However, there are exceptions. For example, a lot of information can be found about parasites of the digestive system of reindeer, because material from both farmed and hunted animals is easily accessible for parasitological examination. This also applies to the parasitofauna of the arctic Svalbard reindeer *Rangifer tarandus platyrhynchos*. The Svalbard reindeer population is 100% parasitized by the nematode *Marshallagia marshalli*, which is very well adapted to transmission in the extreme conditions of the Arctic, as its eggs and larvae tolerate low temperatures well (Carlsson et al. 2013). Five other species of nematodes live in the abomasum of Svalbard reindeer, and it is possible that some of them were introduced by domesticated reindeer used by several expeditions to the North Pole (Bye et Halvorsen 1983). In addition to nematodes, the Svalbard reindeer population hosts the tapeworm *Moniezia benedini* (Bye 1985), several species of coccidia (Fig. 31.15) and the microsporidium *Enterocytozoon bieneusi* (Myšková 2014).

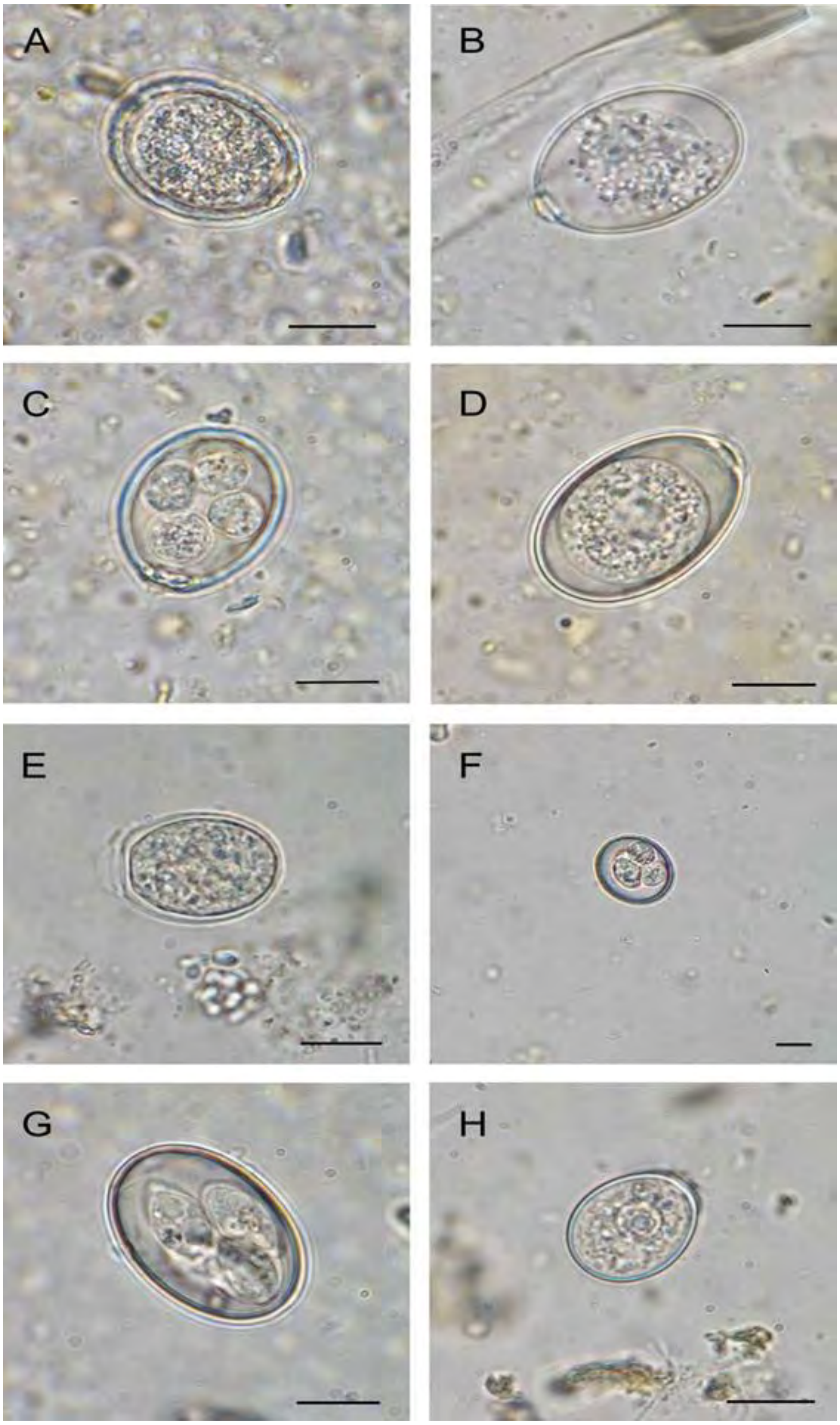


Fig. 31.15: Coccidia oocysts from reindeer droppings, flotation. A: *Eimeria polaris* B: *Eimeria* sp. C: *Eimeria* sp., D: *E. arctica*, E- *Eimeria* sp., F: *E. tarandina*, G: *E. rheindyria* H: *E. mayeri* (Scale = 10 µm). (CPE archive, Myšková 2014).

The parasitofauna of the arctic fox *Vulpes lagopus* is much less researched, because the material is less accessible and most of the information is obtained from coprological analyzes

(Myšková et al. 2019). The history of the fox tapeworm *Echinococcus multilocularis* in Svalbard is remarkable. As already mentioned in chapter 14, rodents did not live on the archipelago in the past, and the life cycle of this parasite, which can be very dangerous even for humans, could not take place there. However, the introduction of the vole *Microtus levis* enabled its progress (Henttonen et al. 2001), and infected foxes can occur mainly in localities where the vole population has been maintained (Fig. 32.15).

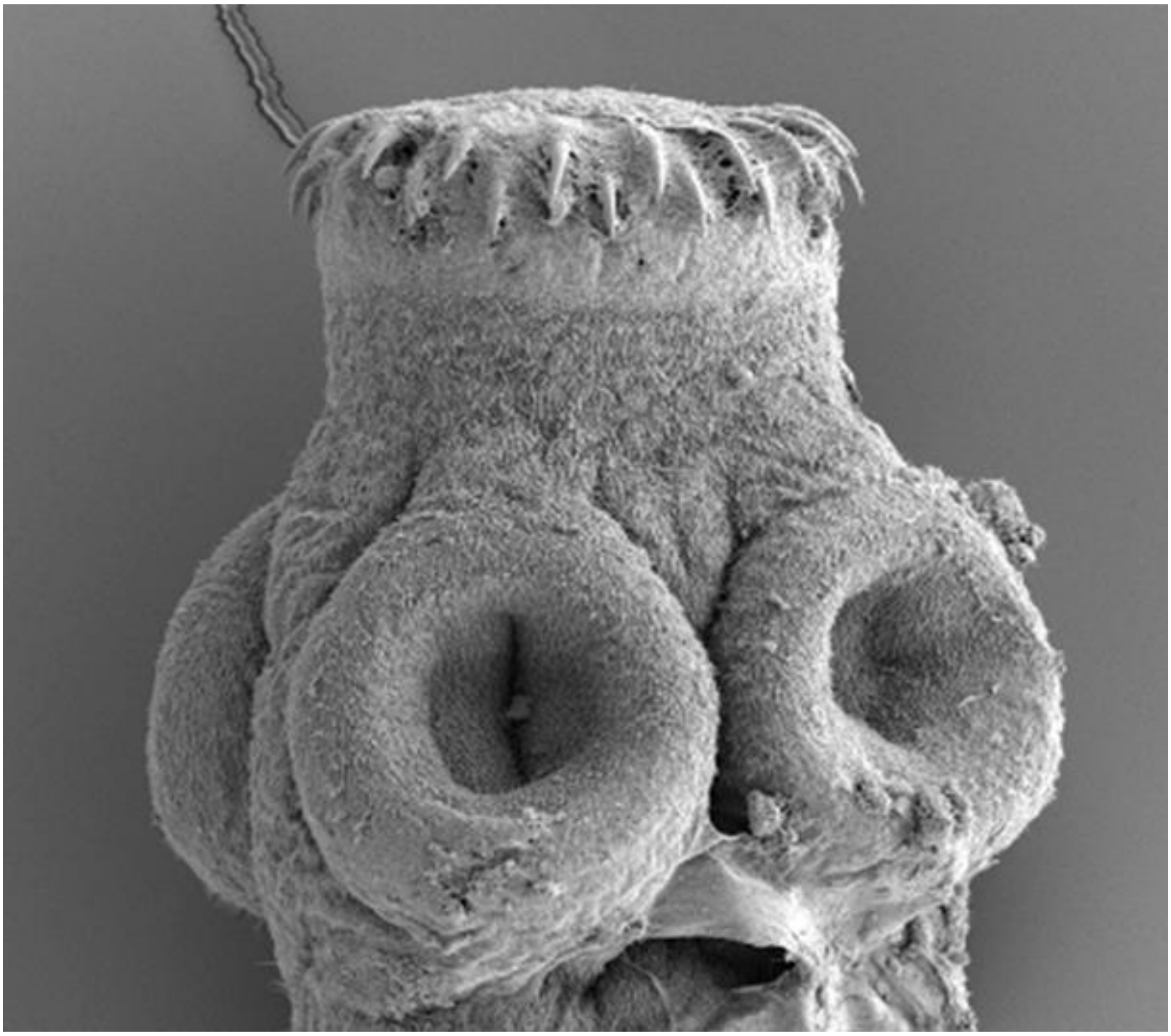


Fig. 32.15: Scolex of a tapeworm *(Echinococcus multilocularis*) from the gut of an arctic fox (*Vulpes lagopus*) hit by a car near the settlement of Nybyen near Longyearbyen. SEM. (CPE archive)

Based on similar findings, visitors to Svalbard are warned not to drink untreated surface water due to possible contamination from the eggs of this parasite. Although the probability of human infection is not high in Svalbard compared to, for example, Central Europe, precautionary measures are in order.

Another arctic parasite potentially threatening to humans is the nematode *Trichinella* spp. In the Arctic, the species *Trichinella nativa* is mainly found in foxes (*V. lagopus*) and polar bears (*U. maritimus*), but pinnipeds and paratenic hosts from several invertebrate groups are also involved in the life cycle (Oksanen et al. 2022, Fig. 33.15). In adult foxes, Trichinella infection on Svalbard reaches up to 36% due to scavenging (Prestrud et al. 1993).

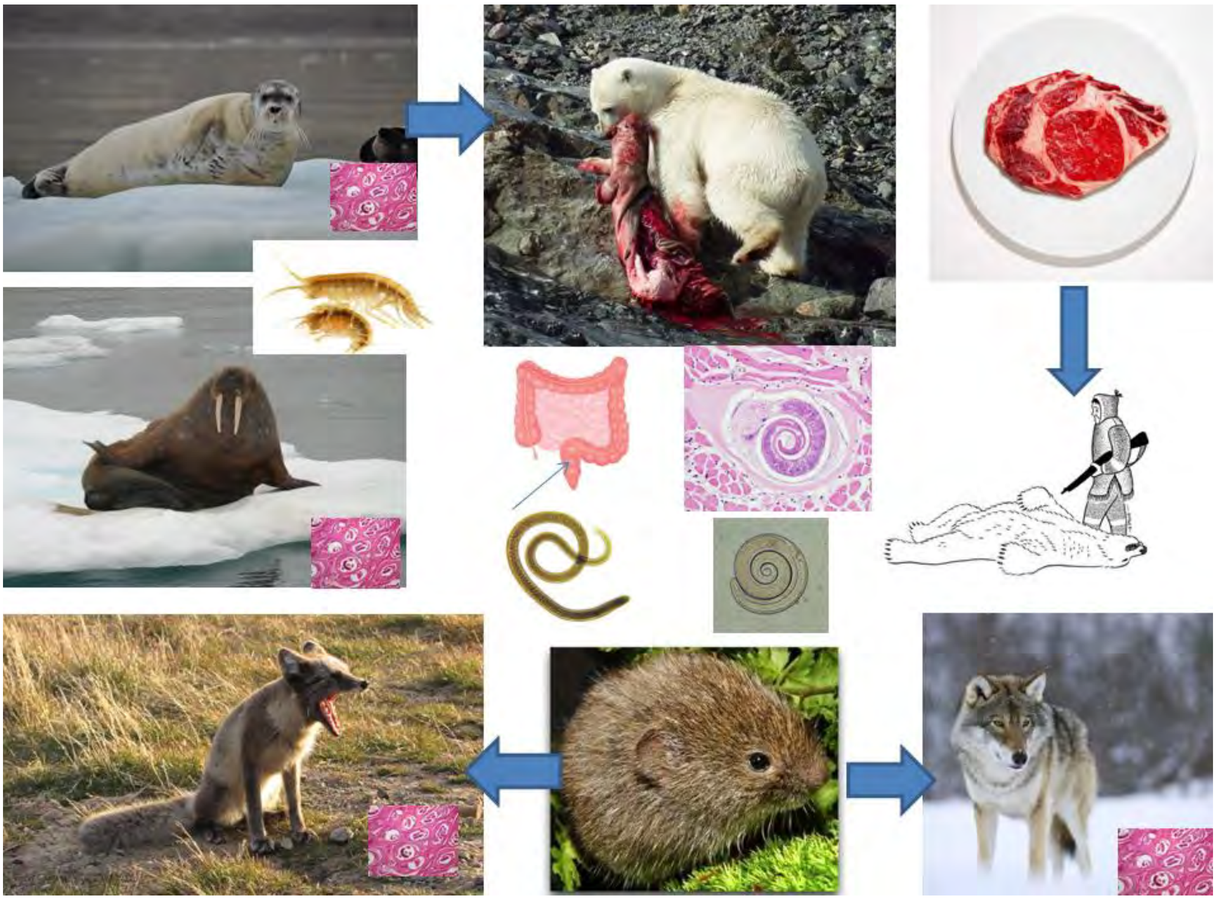


Fig. 33.15: Scheme of the life cycle of *Trichinella* spp. in Arctic conditions. (According to Oksanen et al. 2022, modified).

Although in the past human infections were recorded after eating polar bear meat, and at least 1 expedition to the North Pole died after eating undercooked bear meat (Akuratov 1964), today the risk of human infection from these sources is low (Dupouy-Camet 2017).

Blood sucking ectoparasites

While in the subarctic regions blood-sucking dipterans (mainly black flies from the family Simuliidae and midges from the family Ceratopogonidae) are found in such quantities that, in the past, this prevented their settlement by humans, in the High Arctic blood-sucking arthropods are found in limited numbers of species and individuals. For example, in Svalbard there is only one species of the blood-sucking mosquito, *Aëdes nigripes*, which mainly feeds on birds and reindeer. Although they can trouble even visitors to Svalbard on windless, sunny days (Fig. 34.16), this species is more troublesome than dangerous.

Fig. 34.15: *Aëdes nigripes* mosquito sucking on a visitor to Svalbard. (CPE archive).

The situation is similar for blood sucking mites. In Svalbard, there is only one species of tick, *Ixodes uriae* (Fig. 35.15), found in colonies of the Brünnich's guillemot Uria lomvia and to a lesser extent in colonies of the black-legged kittiwake Rissa tridactyla. More than 70% of the gulls at Pyramiden also host the ectoparasitic feathery Gull head louse *Saemundssonia lari*.

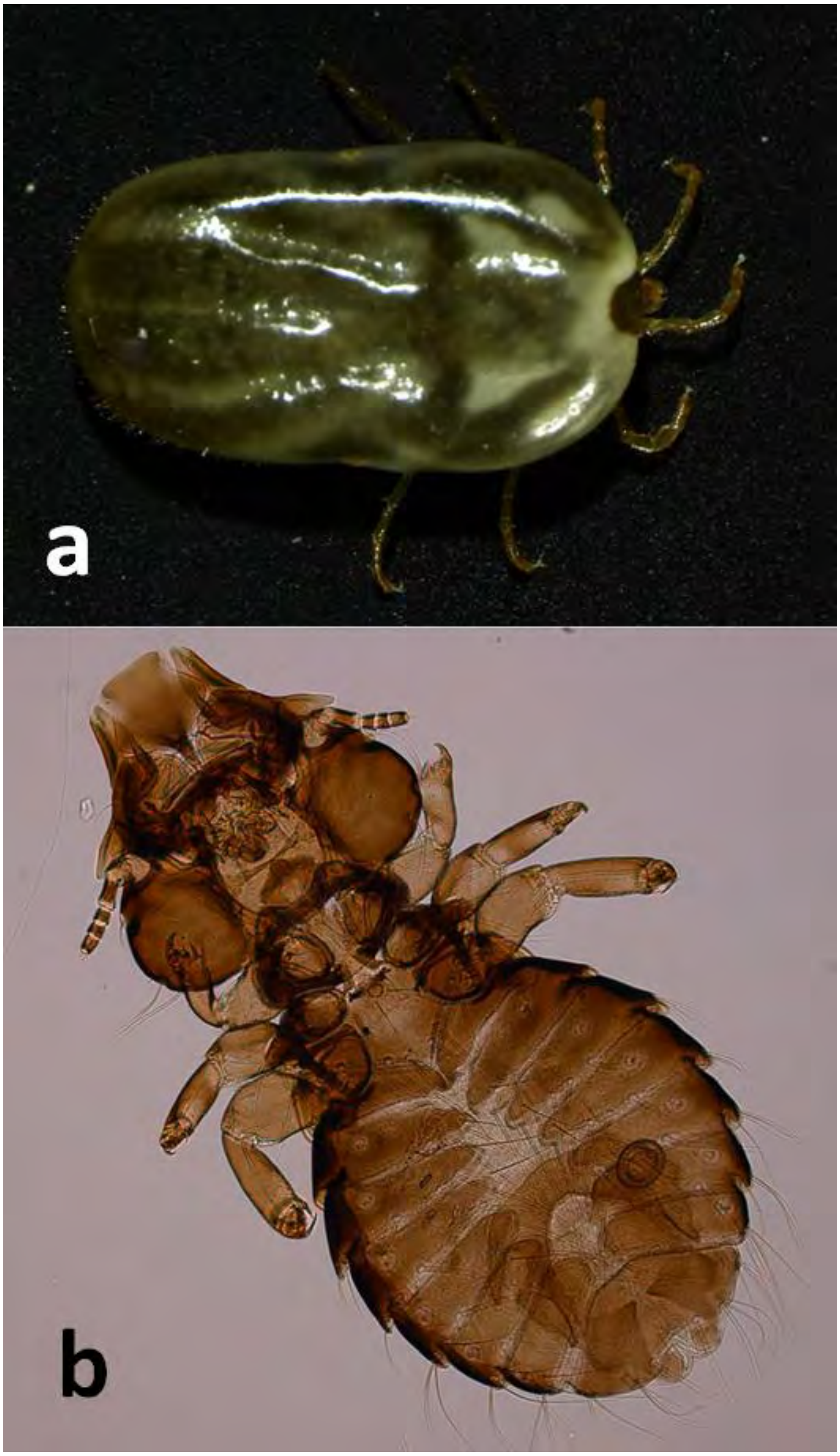


Fig. 35.15: (a) Tick *Ixodes uriae* from the Brünnich's guillemot *Uria lomvia* and goll head louse *Saemundssonia lari* from black-legged kittiwake *Rissa tridactyla*(CPE archive).

In arctic conditions, the role of blood-sucking arthropods as vectors of vertebrate infections, including viruses, is very limited. An intensive search for arboviruses (*arthropod born virus*) in the potential vectors on Svalbard described above ended with a negative result (Müllerová et al. 2018, Černý et al. 2021).

16. Anthropogenic influences on Svalbard in the past and now. Use of nature. Pollution. Invasiveness of organisms.

Josef Elster

The general perception of the Arctic is that it is a harsh, isolated region, minimally populated and minimally used by humans. Due to the geographic diversity of the Arctic, it is an area whose central and largest part is still the ice-covered Arctic Ocean, and around the ocean and local seas, the Eurasian and North American landmasses with a number of islands adjoin it. Thanks to the circulation of sea and air currents and the proximity of the industrial areas of the northern hemisphere of our Earth, the Arctic is an open and relatively accessible area. We provide the following overview of climate development in the Arctic region based on the report of the United Nations Environment Program from 2019 (Schoolmeester et al. 2019).

What anthropogenic influences are responsible for the warming of the Arctic?

Carbon dioxide (CO_2), methane (CH_4), tropospheric ozone (O_3) and micro-particles of carbon (Black Carbon - produced during combustion) are "greenhouse gases", or so-called "short-term sources of pollution" of the atmosphere (Fig. 1a.16) They enter the atmosphere in connection with a wide range of human activities and are directly or indirectly responsible for the anthropogenic warming of our entire planet, including the Arctic region. Their concentration in the Earth's atmosphere has been increasing since the beginning of agriculture, but especially since the beginning of the industrial revolution. In addition to warming, these substances also have a negative effect on all components of nature, including a negative effect on human health. With the help of air currents, they also reach the Arctic region. While carbon dioxide remains in the atmosphere for very long periods (thousands of years), the concentration of methane, ozone and the number of micro-particles of carbon change rapidly. Due to its production and environmental factors that influence its chemical composition, methane remains in the atmosphere for a period of several years. However, its effect on warming is many times greater compared to carbon dioxide. Methane, in addition to directly affecting warming, also simultaneously affects the formation of tropospheric ozone, which also directly contributes to warming. Micro-particles of carbon remain in the atmosphere only for a short period. However, industrial areas adjacent to the Arctic region with a high intensity of emissions contribute significantly to the warming of the (Fig. 1b.16) Micro-particles of carbon deposited on snow and ice absorb solar radiation and thus accelerate the melting of the snow and ice. For example, the countries of the Arctic Council agreed at their meeting in 2017 to reduce the emission of micro-particles of carbon by 25 to 33% in the period from 2013 to 2025.

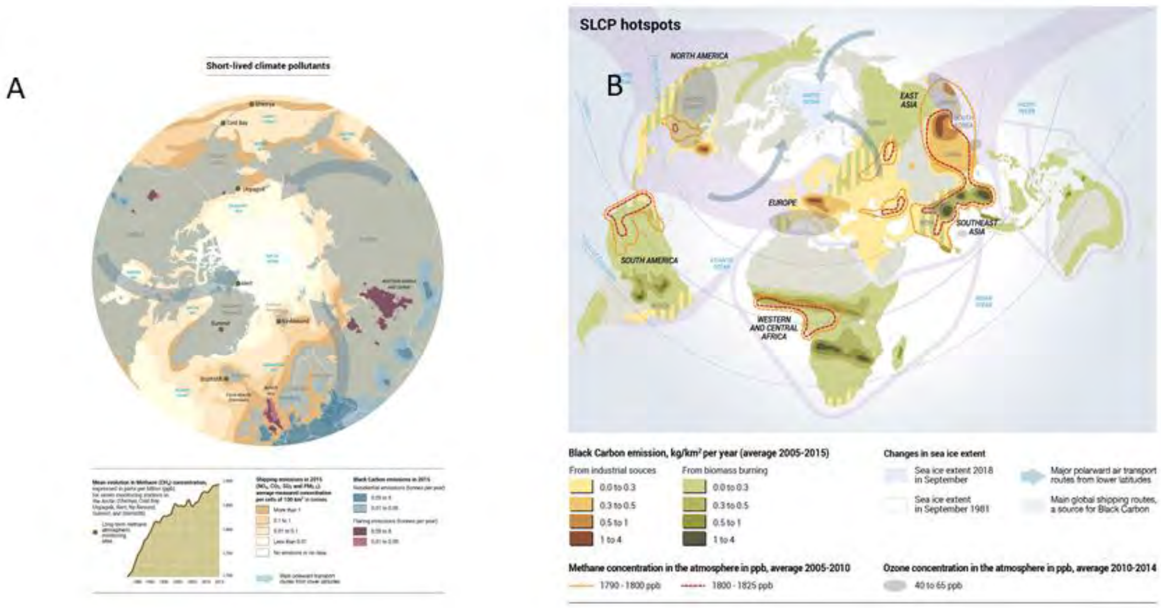


Fig. 1.16: (a) Source and spread of short-term atmospheric pollution in the Arctic; (b) sources and areas from which carbon microparticles reach the Arctic (Schoolmeester et al. 2019).

Inhabitants of the Arctic

About 4 million people live in the Arctic, and only about 10% are indigenous. About 70% of the population lives in the Russian Arctic region, while the largest representation of indigenous people is in Greenland and northern Canada. The original inhabitants of the Arctic are represented by a variety of peoples who speak different languages. The inhabitants of individual regions of the Arctic are grouped into regional areas. Due to the great distance from the inhabited continents to the islands of Norway, including the Svalbard archipelago, as well as the Barents, Kara, Laptev and the East Siberian Seas, the original inhabitants do not live here.Fig. 2.16 documents the distribution of people in the Arctic, including the size of human settlements in the different geographical parts. From an economic perspective, the extraction of raw materials (diamonds, iron, zinc, oil and natural gas), together with industrial fishing and logging, are the most important industries. Based on the geographical distribution and the social composition of the population, the impact of climate change is very different for the inhabitants of the Arctic.

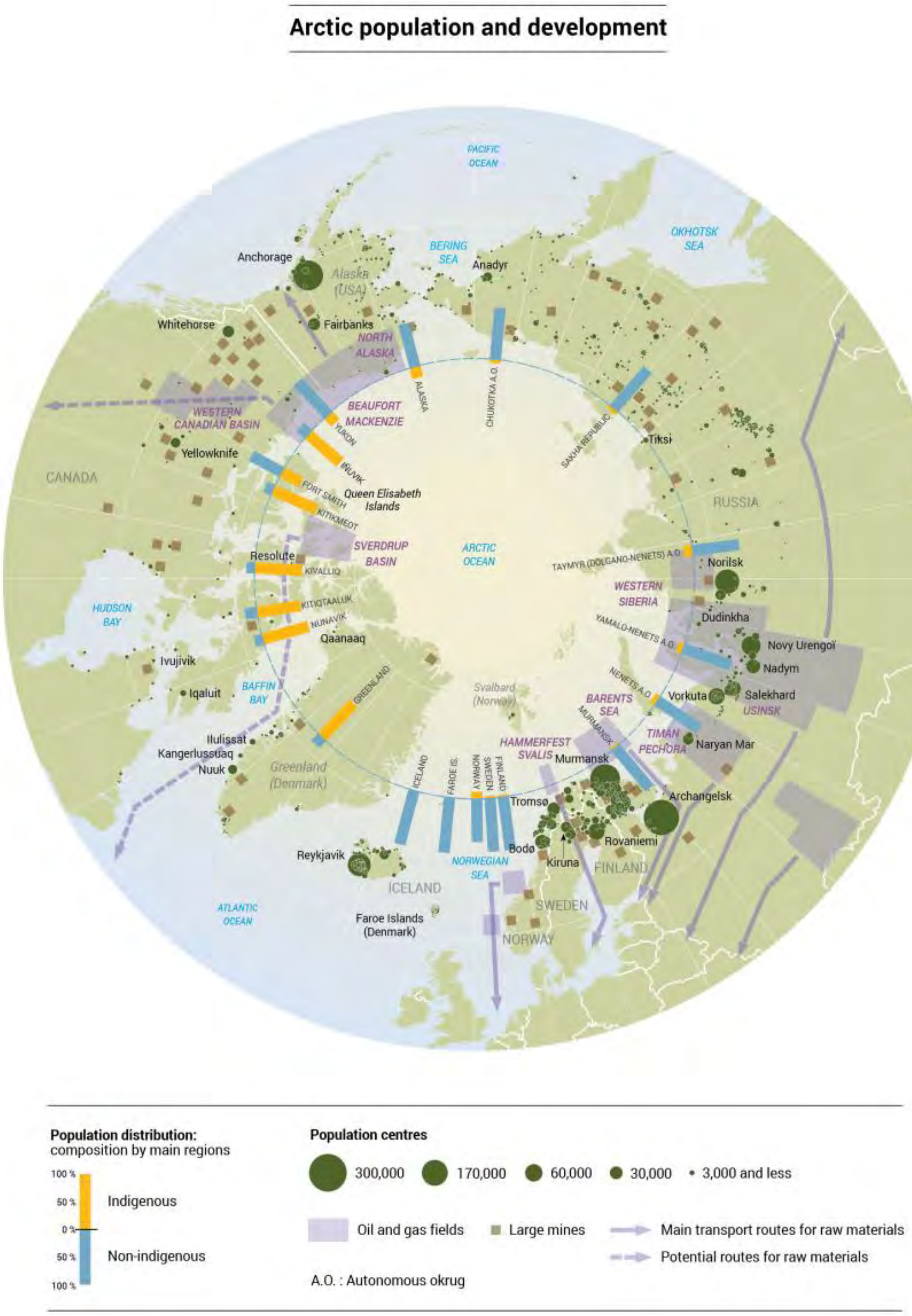


Fig. 2.16: Geographical distribution of people in the Arctic, including non-indigenous peoples concentrated in industrial areas (Schoolmeester et al. 2019).

Life in Svalbard

The Svalbard Treaty, signed in Paris in 1920 and entered into force in 1925, guaranteed a level playing field for the first 40 states in the commercial exploitation of the archipelago and surrounding territorial waters. Since the beginning of the 20th century, the main economic activity has consisted of coal mining, which began to be significantly reduced only at the beginning of this century. Today's employment structure in Svalbard consists, in addition to "Store Norske" coal mining workers, mainly of employment in services, including tourism (Svalbard is visited annually by around 80,000 tourists). Fig. 3.16 ocuments the locations visited by tourists and their annual frequency. A significant component of employment in Svalbard is also made up of workers in the academic sector (around NOK 350 million is invested in research every year). Other countries that are intensively involved in Svalbard research are Germany and Poland. The largest part of the research is focused on physical geography and biology.

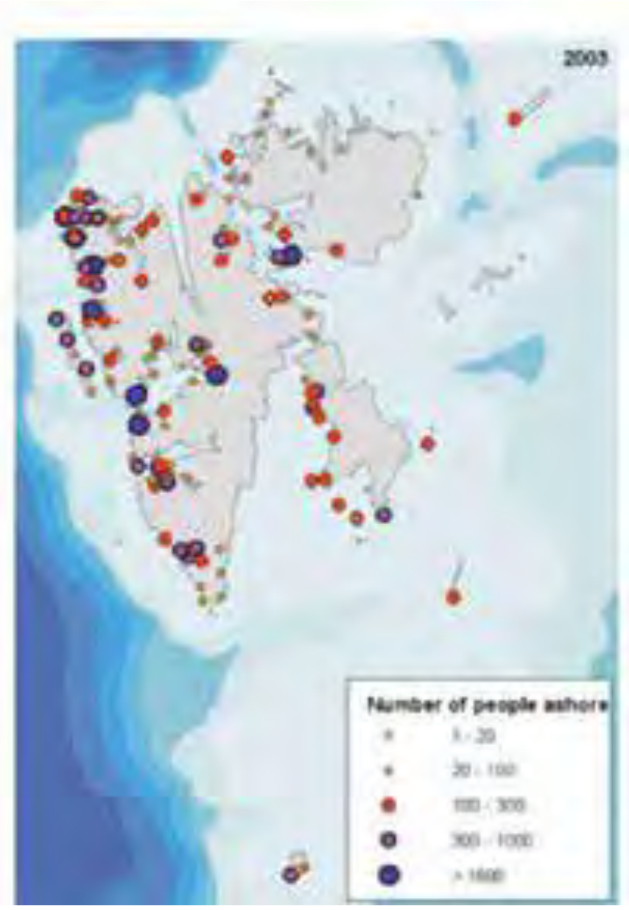


Fig. 3.16: Map of Svalbard showing the number of tourists visiting different locations (source Geitz et al. 2004).

In addition to the Norwegian mining (Store Norske) company, the Russian company "Trust Arktikugol" also operates in Svalbard, which operates mines near Barentsburg, where around 400 miners work. Around 2,500 inhabitants currently live in the whole of Svalbard. The number of employees often varies, depending on the season. In addition to Longyearbyen and Barentsburg, about 25 residents also live permanently in the science town of Ny-Ålesund. Several Polish scientists work year-round at the science base in Hornsund. We drew data on social conditions in Svalbard from publications published by Statistics Norway (Statistics Norway, www.ssb.no).

Climate change and its effect on the Arctic ecosystem

At the 2017 Arctic Council Intergovernmental Conference in Fairbanks, it was stated that all industrialized countries are responsible for climate change and pollution in the Arctic. The final declaration states that the production of greenhouse gases with consequent warming and pollution reaching the Arctic through long-range transport is significantly affecting the Arctic ecosystem, including rapid changes in its biodiversity. As can be seen from Fig. 4.16 and Fig. 4.16;the impact of the local Svalbard population and economic activities on the archipelago are negligible. On the contrary, the whole area is mainly affected by global processes and long-range transport of pollution.

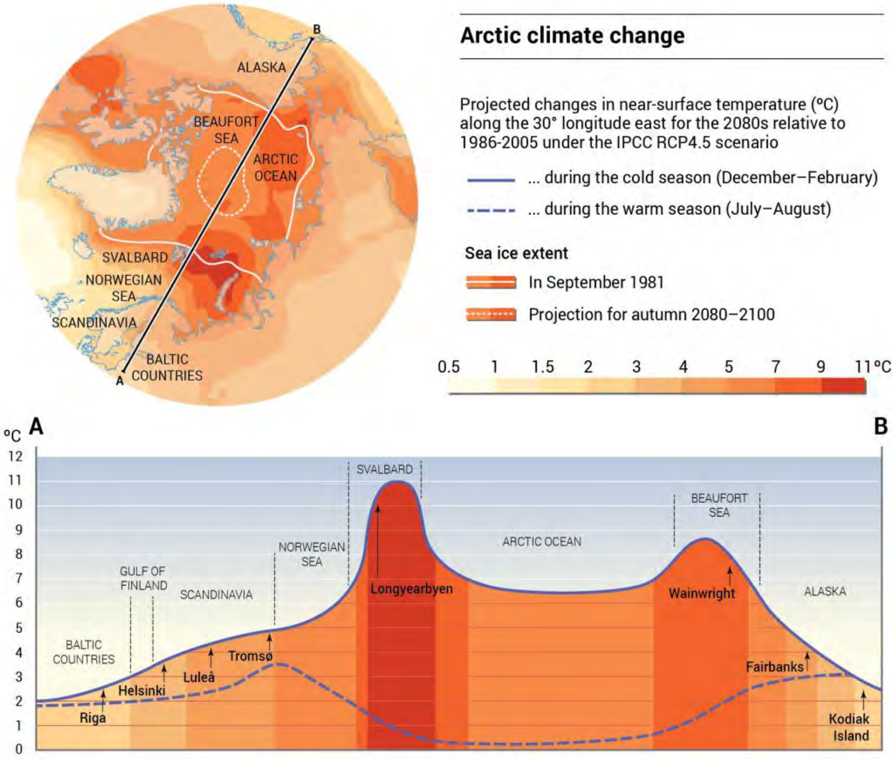


Fig. 4.16: Predicted Arctic ground surface warming by 2080 compared to 1986-2005 according to the RCP4.5 climate model (Schoolmeester et al. 2019).

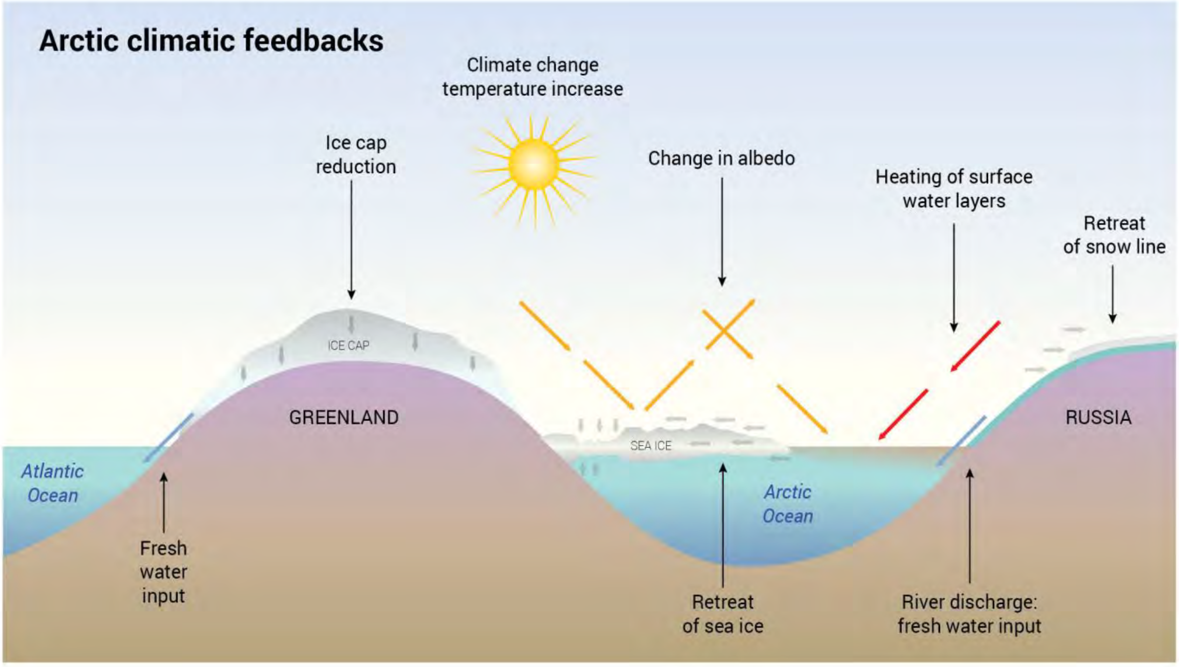


Fig. 5.16: Schematic behaviour of individual ecosystem types in the Arctic region under the influence of climate change (Schoolmeester et al. 2019).

Global warming, which is mainly caused by anthropogenic emissions of carbon dioxide and other greenhouse gases, is a long-term process that very intensively affects the marine and terrestrial ecosystems of the Arctic. This process is very gradual and the response to this change is very diverse and often difficult to document. The most frequent manifestations of warming in the Arctic are, for example, the occurrence of climatic extremes, such as the formation of local hurricanes. Another easily observable manifestation of warming is the shortening of the winter seasons, the occurrence of winter frosts and other extremes during the annual weather cycle. In the subarctic part of the Arctic, for example, large-scale fires occur, which are a consequence of long-term droughts in large continental areas. The term "Browning of the Arctic" was used for the changes in the sub-Arctic region. In the high Arctic, on the other hand, the "Greening of the Arctic" occurs due to the melting of glaciers and the development of vegetation. The Intergovernmental Climate Panel analyses and predicts the response to climate change using several climate scenarios. One of the scenarios that we consider the most realistic is the RCP4.5 forecast for the period from September 1981 to September 2080-2100. Fig.4.16 documents the increase in temperature across the Arctic region in winter and summer, and the decrease in Arctic Ocean sea ice cover.

The complexity and interconnectedness of individual events associated with climate change in the Arctic is well documented in Fig. 5.16. As the temperature of the atmosphere increases, glaciers melt on land (primarily in Greenland), and the area and thickness of the Arctic Ocean ice cover decreases. At the same time, the area and time that the land is covered by snow decreases (shortening of winter periods and increase of winter snowfall, as we have already mentioned). This reduces the albedo, the part of solar radiation that is reflected from the land and sea covered with ice and snow (80 to 90% of the incident solar radiation is reflected from sea - land covered with snow and ice, while water surface - land without snow and ice absorbs 80 to 90% of solar energy). The absence of ice and snow results in the absorption of a large amount of solar radiation into the environment. Albedo and the reflection or absorption of solar energy is a fundamental physical factor that significantly affects the flow of energy through the Arctic ecosystem. A diagram of the albedo principle is documented in Fig.5.16

Climate change and its effect on the Svalbard ecosystem

As was already presented in the previous chapter (Fig.4.16). Svalbard archipelago is the area most affected by warming (there was a temperature increase of 3 to 5°C in the period from 1997 to 2017), with all the consequences of the process which accompany warming. We drew information on climate change in Svalbard from the publication "Climate in Svalbard 2100 – a knowledge base for climate adaptation (Hanssen-Bauer et al. Ed. 2019).

We have taken the data on the basis of the milder RCP4.5 climate model already presented, which assumes that it will be possible to reduce greenhouse gas emissions after 2040. Based on this model, the average annual temperature in Svalbard between the years 1971-2000 and 2071-2100 is predicted to increase by 7°C (Fig. 6a.16). At the same time, precipitation will increase by 45%, which will occur as frequent heavy downpours Fig. 6b.16. his will result in a dramatic increase in river flows Fig. 6c.16 and melting of glaciers. There will also be a shortening of the period when the landscape of Svalbard is covered with snow and an increase in the occurrence of winter glaciations.

As a result of the increasing air temperature, the temperature of the sea water will also increase by 1°C around Svalbard and the salinity will decrease. An increase in temperature and precipitation will significantly lengthen the growing season (from 3 to 6 months) and shorten the winter period (from 9 to 6 months).

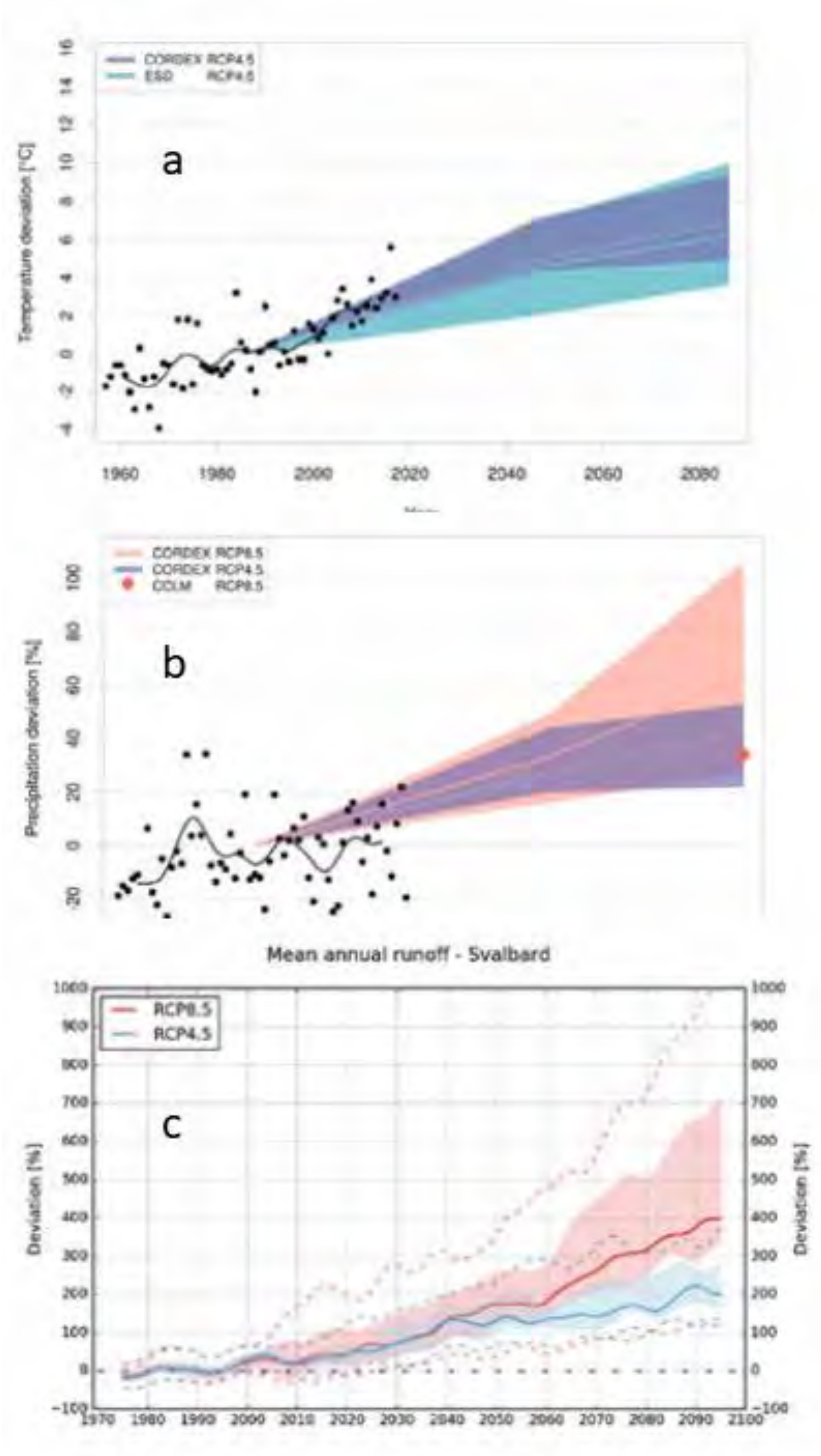


Fig. 6.16: Data projected from the most likely climate model RCP4.5: (a) increase in average temperature in the Svalbard archipelago; (b) an increase in average rainfall, with an estimated increase of 45 %; (c) Dramatic increases in river flows and the rate of melting of glaciers as a result of an increase in average rainfall (Hanssen-Bauer et al. Eds. 2019).

The melting cryosphere of the Arctic

Land and sea glaciers, together with the thickness and length of the snow cover, respond quickly to warming (Fig. 7.16). The melting of ice and snow significantly affects all physical, chemical and biological processes that take place in the terrestrial and marine parts of the

Arctic. Based on long-term satellite monitoring, the extent of sea ice has decreased by 40% since 1979. Even some mathematical models predict that the Arctic Ocean will already be free of sea ice in some summer periods in the second half of this century. Also, the rate of loss of land glaciers, especially the Greenland continental glacier, is very alarming. The melting of land ice is also closely related to the rising level of the world's oceans, which manifests itself in overall coastal erosion and damage to urbanized coastal areas. The reduction of the Arctic Ocean ice cover and the expansion of economic activities into the Arctic also simultaneously affects the circulation of sea currents and the geographic exchange of seawater of different properties (dense, more salty and cold deep seawater with less dense, less salty, brackish warmer water). This affects the intensity of energy exchange between marine and then air geographic circulations, such as the weakening of the influence of the Gulf Stream in the northern part of the Atlantic Ocean. Another rapid change concerns the behaviour of the seasonal snow cover of the landscape. From 1982 to 2011, the number of days with snow cover in the Eurasian Arctic region decreased by 12.6, and in North America by 6.2 days. Changes in the cryosphere associated with the intensity of water inflows from large river mouths document the effect of melting of the cryosphere on the Arctic (Fig. 7.16).

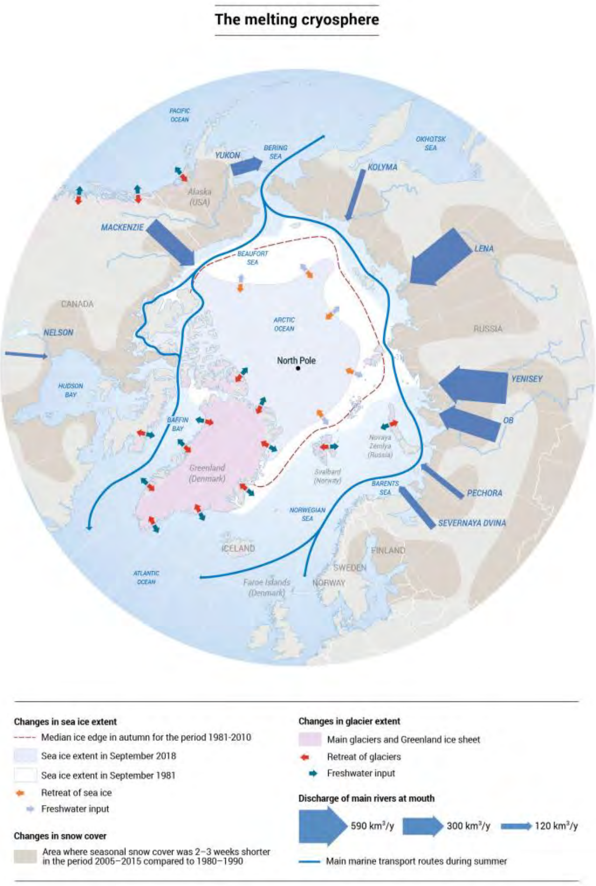


Fig. 7.16: Diagram characterizing the loss of land and sea glaciers together with the typical thickness and length of snow cover in the Arctic region (Schoolmeester et al. 2019).

Svalbard's melting cryosphere

Continental glaciers are a very complicated system and their long-term behaviour is conditioned by interaction with the climate. In Svalbard, the behaviour of the mainland glaciers has been monitored since the second half of the nineteenth century and, with the help of a number of methods, the glacial development has been reconstructed for the period since the beginning of the Holocene, that is, for the period of the last approximately 11,700 years. Reconstruction of glacial development is conducted using various geomorphological methods focused on the development of glacial moraines combined with the dating of vegetation, substrate and lake sediments. Using these methods, it has been shown that the displacement of glacier edges does not always correspond to the total mass balance of the glaciers, as there are periodic displacements of the ice. Nevertheless, these measurements contribute to clarifying the overall balance of the glaciers in Svalbard, where approximately 7% of the mainland glaciers have melted in the last 32 years, with an average of 0.2% per year (Fig. 8.16). There are currently no land glaciers in the entire Svalbard archipelago that would increase their glaciation area. Also based on geodetic measurement of the mass balance of the glaciers, it was shown that the mass of land ice in Svalbard is decreasing; generally, the glaciers in the southern part of the archipelago are shrinking faster than in the northern part. The trend in the behaviour of the Svalbard glaciers expressed on the basis of mathematical models in the period from 1957 to 2014 is documented in Fig. 8.16.

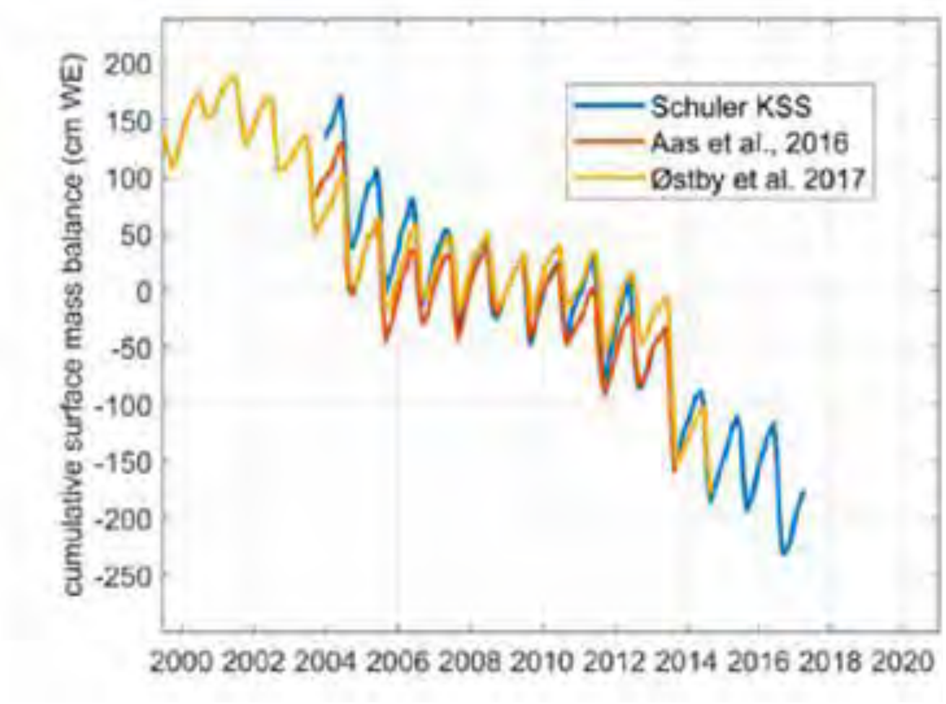


Fig. 8.16: . Decrease of the cumulative monthly mass balance of glaciers on Svalbard expressed on the basis of 3 climate models (Hanssen-Bauer et al. Eds. 2019).

Melting permafrost in the Arctic

Permafrost (ground that is frozen for at least a period of two years) is still widespread in the Arctic, including some parts of the sea shelf. Permafrost is spread over 22% of our planet's surface (in the Northern Hemisphere it covers 15 million km2) in which 1,500 trillion tons of carbon are frozen, twice as much as is contained in the earth's atmosphere. Processes associated with physical, chemical and biological changes in permafrost caused by warming are being intensively studied and monitored in all parts of the Arctic. Although the release of greenhouse gases from melting permafrost has not been high recently, it is expected that, with the increase in temperature, the process of releasing greenhouse gases from melting permafrost will become many times higher. The concentration of greenhouse gases in the atmosphere, the rate of warming and the melting of permafrost with the subsequent release of greenhouse gases are processes that are interconnected; therefore, the melting of permafrost is a very dangerous process globally. At the same time, the melting of permafrost contributes to the changes in Arctic biotopes (drying of wetlands, occurrence of fires, degradation of tundra) and very significantly disrupts the urbanized part of the Arctic, including disruption of the social structure (Fig. 9a.16). Thermokarst lakes, which form in terrain depressions after permafrost melts, can act as conductors of higher temperature into deeper layers of permafrost and can cause melting of permafrost and emissions of greenhouse gases from older and deeper layers of permafrost. Under the more optimistic climate model RCP4, permafrost would be preserved over much of the Canadian Arctic Archipelago and much of the Siberian region (Fig. 9b.16).

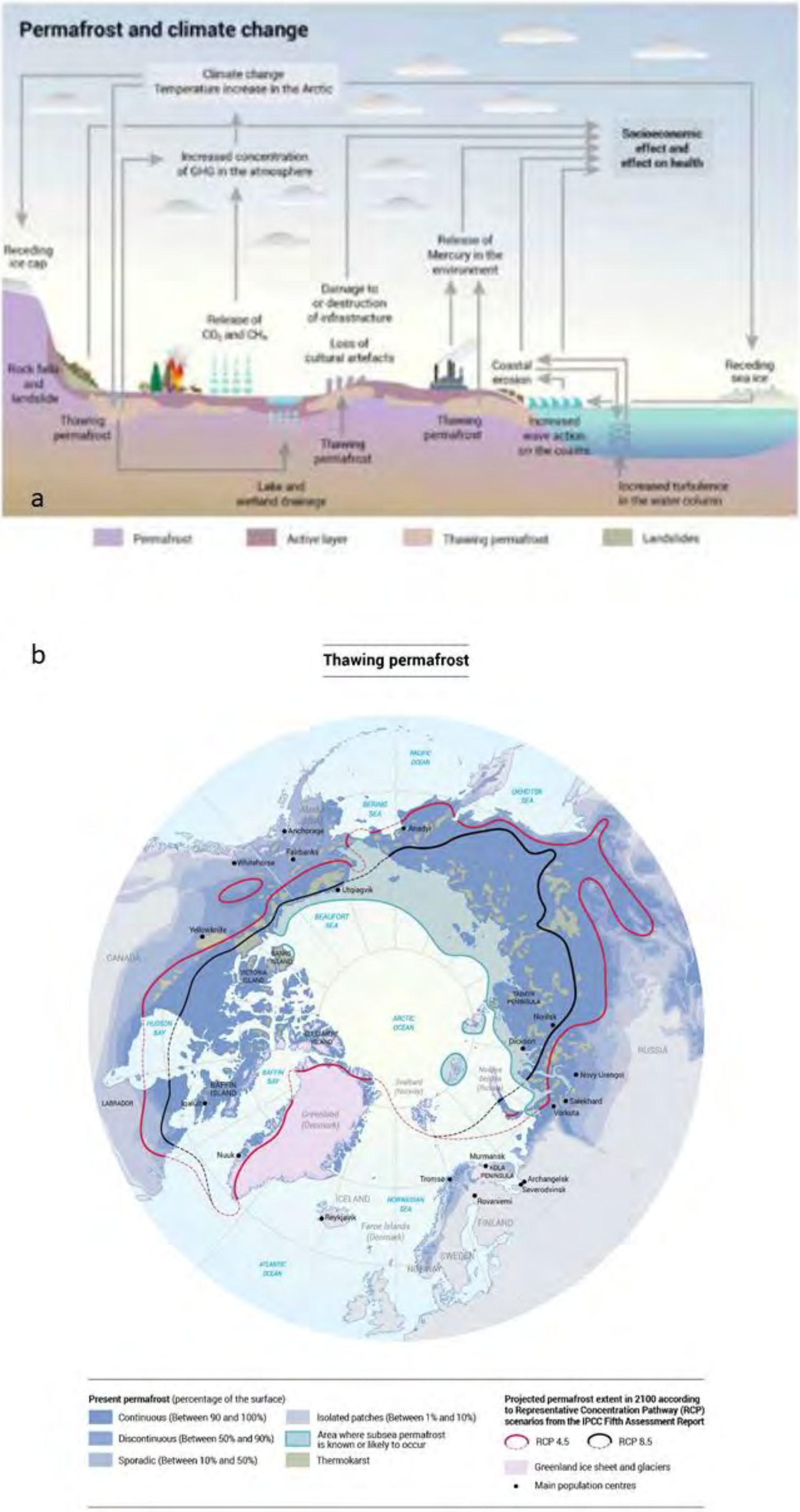


Fig. 9.16: (a) Scheme of change in Arctic habitats under the influence of thawing permafrost; (b) the evolution of Arctic permafrost melting based on the RCP4 climate model (Schoolmeester et al. 2019).

Permafrost in Svalbard and the danger of its melting

Since 2000, there are records of increasing permafrost temperature from Alaska, the high Canadian Arctic and from Svalbard. The warming of the permafrost in Svalbard is the greatest in the high Arctic. The thickness of the permafrost in Svalbard is around 100 m in the valleys and 400 to 500 m in the mountainous areas. Permafrost temperatures are the highest in coastal areas and areas with high snow cover. In the central part of Svalbard around Longyearbyen, Barentsburg and the Kapp Linne area, the seasonal temperature on the soil surface varies from -1.3 to -4.1°C, and in the depth of the permafrost boreholes, where there are no seasonal temperature fluctuations, the temperature varies from -2.6 to -5.2° C. In the southern part of Svalbard around Hornsund, the permafrost is the warmest and the temperature at a depth of 2 m is around -1.1°C. On the other hand, the coldest permafrost in the north-western part of Svalbard, in the Ny-Ålesund area, is -2.8°C. In the boreholes where the permafrost temperature is measured, I have noticed a gradual increase in temperatures at depths from 10 to 20 m since 2000 (Fig. 10a.16). The annual increase in permafrost temperature at a depth of 20 m in different parts of Svalbard ranges from 0.06 to 0.15 °C, and even at a depth of 80 m this increase is still detectable. The depth of the active layer is also gradually increasing. In the period between 1999 and 2018, it increased annually by 1.6 cm and now ranges from 49 to 300 cm. Based on the rate of permafrost warming, mathematical model (RCP4.5) predicts that, by the end of the century in some areas of Svalbard, the permafrost will degrade to certain depths and in some types of substrates. The gradual degradation of the permafrost will have a great impact on the entire geo- and ecosystem of Svalbard. This impact will be manifested mainly in the slopes and coastal areas by the formation of snow and snow-mud, and rock landslides, increased solifluction and other geomorphological manifestations associated with the instability of the active surface layer of the soil (Fig. 10b.16).

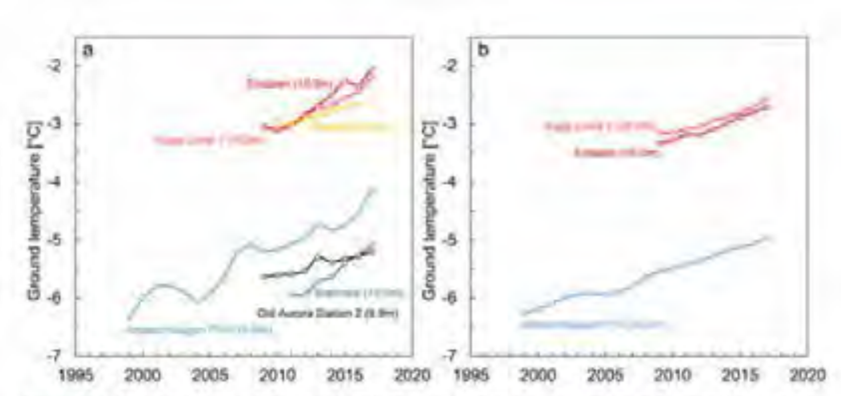


Fig. 10.16: (a) permafrost tempera-ture in Svalbard at 10 and 20 m; (b) Development of snow-ice avalanche and landslide intensity in Svalbard (Hanssen-Bauer et al. Eds. 2019).

Arctic ocean acidification

The water of the world's oceans is acidified (alkalinity decreases, pH values decrease) due to anthropogenic production of carbon dioxide. The more CO_2 emissions enter the atmosphere, the more seawater absorbs carbon dioxide, which lowers pH. Since the beginning of the industrial revolution, the surface layer in the oceans has been acidified by 30%. More acidic seawater is poorer in the calcium carbonate ($CaCO_3$) (Fig. 11.16) compounds that marine organisms need to build their skeletons and shells. The water of the Arctic Ocean is particularly susceptible to changes in acidity. Carbon dioxide is more easily soluble in cold water, and less salty brackish water (a huge amount of freshwater flows into the Arctic Ocean from large Siberian and North American rivers) is more susceptible to changes in acidity. For these reasons, the Arctic Ocean and the organisms that live there are exposed to great stress from the lack of calcium carbonate. This stress manifests itself in lower fertility of individual organisms and is expected to affect the entire ecosystem of the Arctic seas and ocean, especially at the level of food chains. The chemical composition and calcium carbonate content of seawater around Svalbard is highly variable, both in connection with the inflow of fresh water from melting glaciers and with seasonal changes in the production of phytoplankton and phytobenthos (increased photosynthesis - increased pumping of carbon dioxide). Especially the eastern areas of Svalbard can potentially be exposed to acidification and calcium carbonate deficiency.

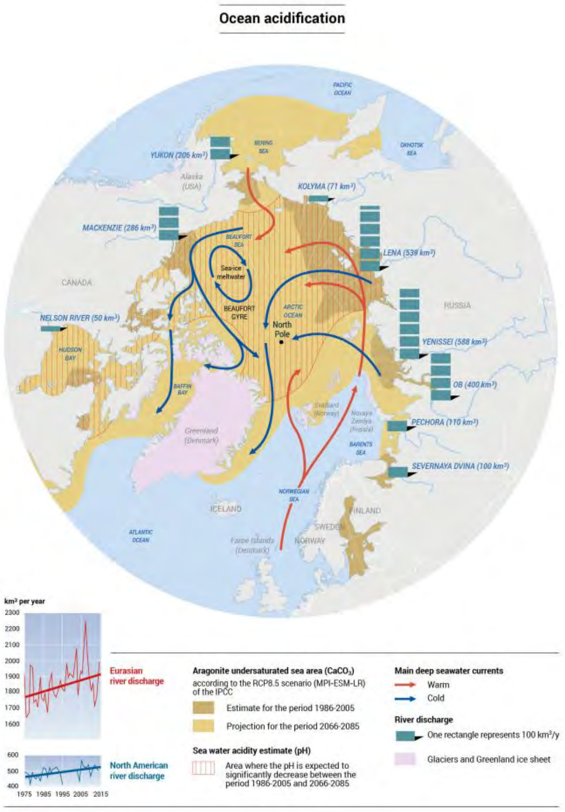


Fig. 11.16: Characteristics of Arctic Ocean acidification evolution according to different climate models depending on other ecological factors associated with ongoing climate change (Schoolmeester et al. 2019).

Pollution of the Arctic

Although pollution of all types acts mainly locally, thanks to sea and air currents, and also thanks to the outflow of large Siberian and North American rivers into the Arctic region, this part of our planet is a "dump" for waste that gets there from all over the world. Toxic substances originating from pollution are contained in air, water, snow, ice, soil and in living organisms. Some toxic substances from waste enter the food chain and cause health problems.

Toxic, industrially produced organic substances (such as pesticides and their decomposition products) are among the most dangerous. Although these substances are only rarely used in the Arctic region, they are transported here over long distances where they accumulate and are stored there for a long period. Their increased concentrations, together with mercury, are documented by toxic concentrations in the tissues of some organisms from various regions of the Arctic. Another important type of pollution to the Arctic region is micro- and nano-plastics.

Pollution of the seas, oceans and coasts with micro- and nano-plastics is socio-economically the biggest problem. There are currently around 150 million tons of plastic in the world's oceans, and they are carried by sea and air currents to all areas of the world, even the most geographically isolated (Fig. 12.16:). The vast majority of plastics that pollute the Arctic come from other areas; the local contribution is very small. Only Arctic industrial fishing contributes significantly to Arctic plastic pollution.

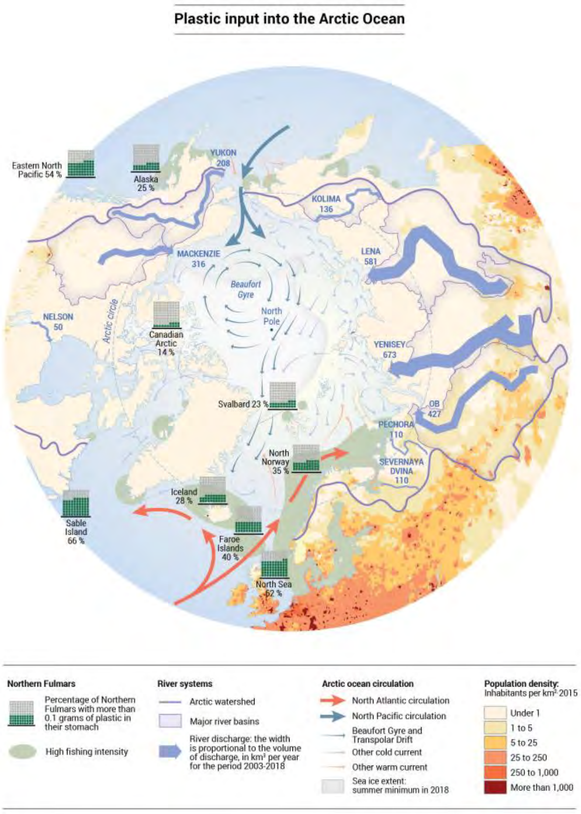


Fig. 12.16: Pathways of micro- and nanoplastics reaching the Arctic region and plastic content in the digestive tract of the fulmar *Fulmarus glacialis* (Schoolmeester et al. 2019).

Mercury, one of the dangerous heavy metals, enters the environment through a wide range of economic activities and is transported to the Arctic by air currents over long distances. In the Arctic, it subsequently accumulates in the soil and permafrost, where it is chemically and biochemically bound into complex compounds (Fig. 13.16). It is not yet known what effect warming will have on the release of toxic mercury components into the environment. It is only apparent that the concentrations of mercury deposited in the Arctic region are high.

Fig. 13.16: Mercury content in Arctic soils (Schoolmeester et al. 2019).

Pollution affects the health and functioning of all ecosystem components, from humans and other top consumers to the ecological relationships of the Arctic's terrestrial and marine systems. Toxic, industrially produced organics and some of the heavy metals (e.g., mercury) accumulate in food chains. Top consumers and predators (including humans) accumulate these toxic compounds in tissues, which can affect the health (hormonal and immune systems) of local populations. Local populations are mostly dependent on local sources of food, so foreign poisonous substances that cause health problems get into their bodies when they eat the food. Fig. 14.16 shows the content of selected poisonous substances in the blood and breast milk of Arctic mothers. Fig. 15.16 documents the current monitoring sites for chemical contaminants across the Arctic in all types of environments (atmospheric deposition, aquatic sediment, beaches, fish, ice and snow, invertebrates, mammals, seabirds, and water).

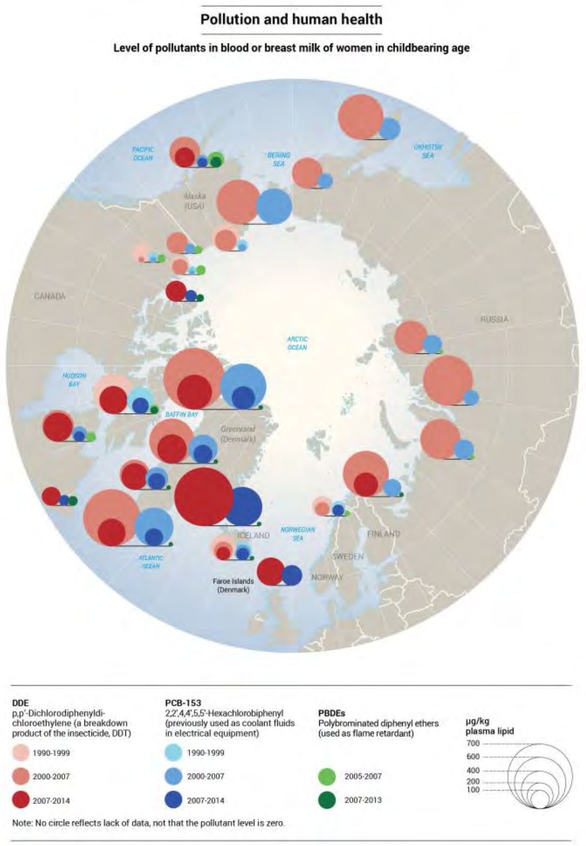


Fig. 14.16: Content of toxic substances in the blood and breast milk of women in the Arctic (Schoolmeester et al. 2019).

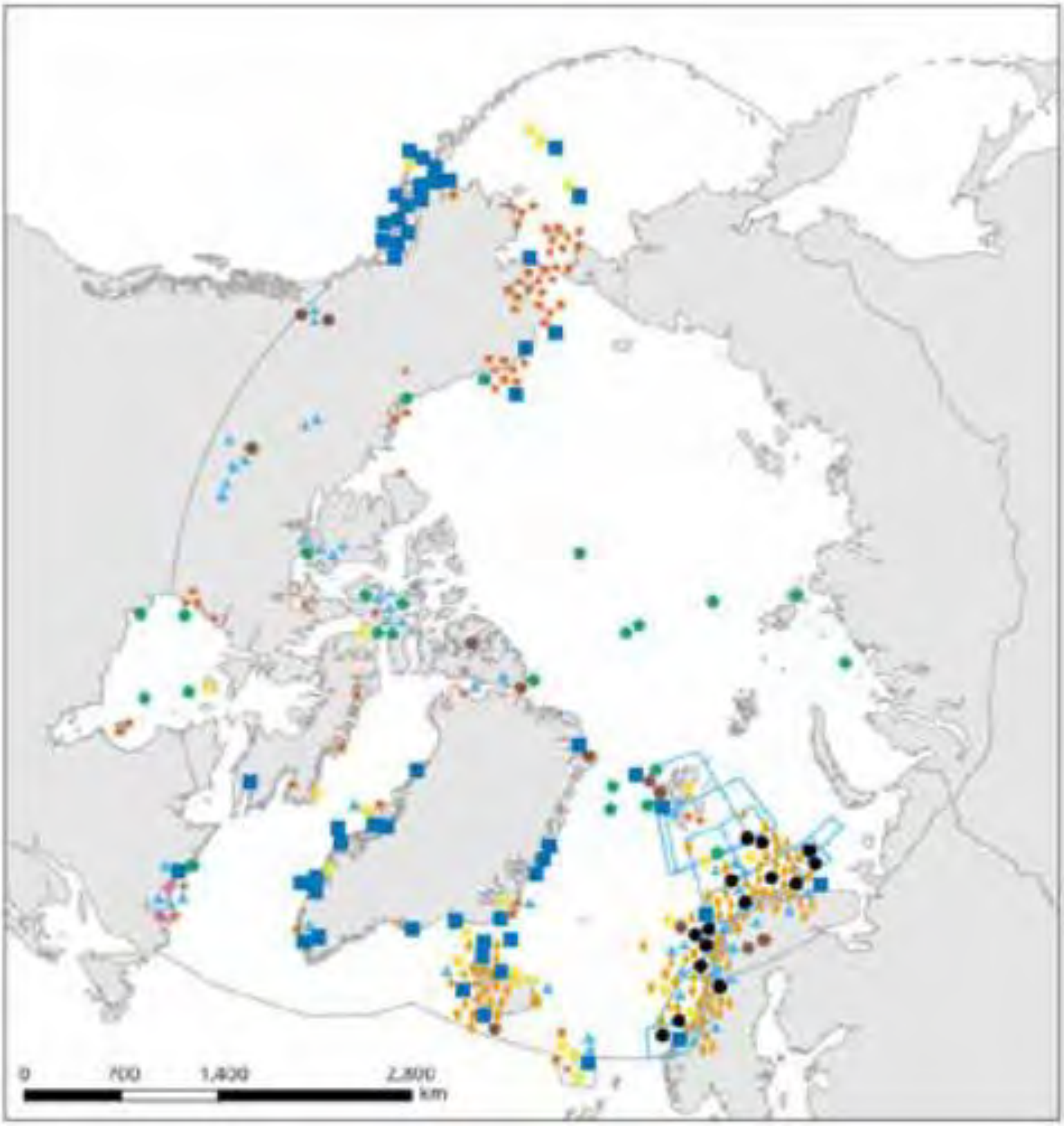


Fig. 15.16: Pollution is continuously monitored across the Arctic region (AMAP 2021).

Pollution of the arctic environment (both marine and terrestrial) by plastics and microplastics is one of the most pressing environmental problems today. The countries of the Arctic Council agreed on detailed monitoring and proposed a long-term monitoring methodology. We drew information on plastic and microplastic pollution from the AMAP Litter and Microplastics Monitoring Guidelines publication. Version 1.0. Arctic Monitoring and Assessment Program (AMAP 2021), Tromsø, Norway, 257pp. Fig. 16.16: documents which locations are currently being monitored for the occurrence of plastics and microplastics in all types of environments (atmospheric deposition, water sediment, beaches, fish, ice and snow, invertebrates, mammals, seabirds and water).

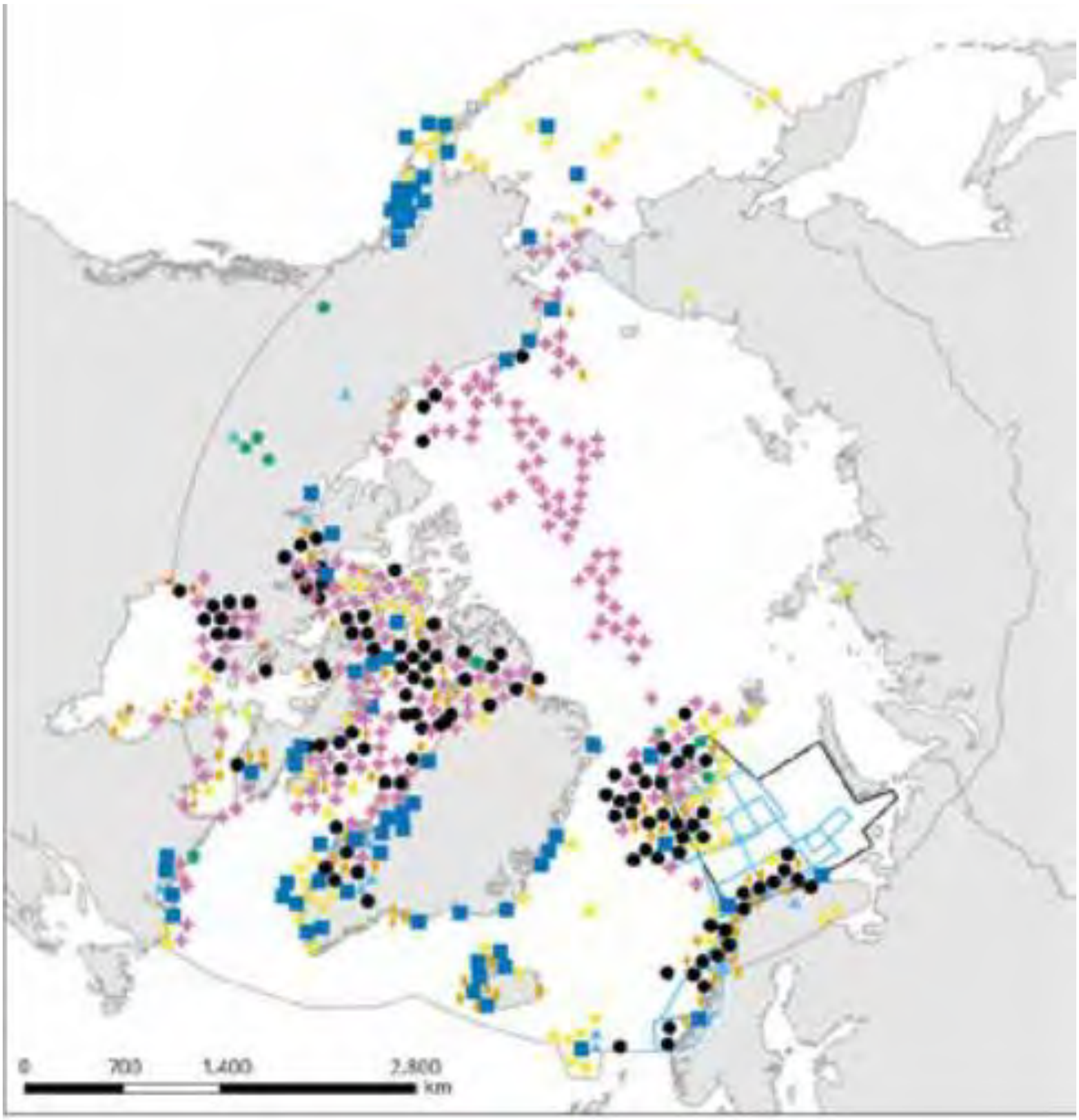


Fig. 16.16: Arctic plastic and microplastic pollution monitored in designated areas of the Arctic (AMAP 2021).

Pollution of Svalbard

Due to its geographic location and specific climatic conditions, the Svalbard archipelago has an important position in terms of pollution, being a kind of pollution reservoir in the Arctic. We drew the information presented in this chapter from the publication "Local contamination in Svalbard, Overview and suggestions for remediation action by Maria E. Granberg, Amalie Ask and Geir W. Gabrielsen, Norwegian Polar Institute 2017, report no. 044". Svalbard, as well as the entire Arctic region, is mainly polluted by substances that are transferred from the more southerly industrial areas of Europe and Eurasia. In Svalbard, long-term monitoring is carried out connected both to the transport of pollution over long distances, but also from local sources of pollution that are connected to mining activities (pollution by heavy metals and acids), from oil exploration, and landfills of household waste (polycyclic aromatic hydrocarbons, polychlorinated biphenyls, pesticides, heavy metals, etc.). Some localities that were contaminated in the past are being or have been remediated (an overview of environmental contamination around Longyearbyen is documented in Fig. 17.16). At the same time, a number of historically significant industrial sites are being monitored for pollution and remediation work is being prepared. Consistent pollution monitoring is still carried out with the Norwegian Environment Agency maintaining a pollution database (http://grunn.miljodirektoratet.no/).

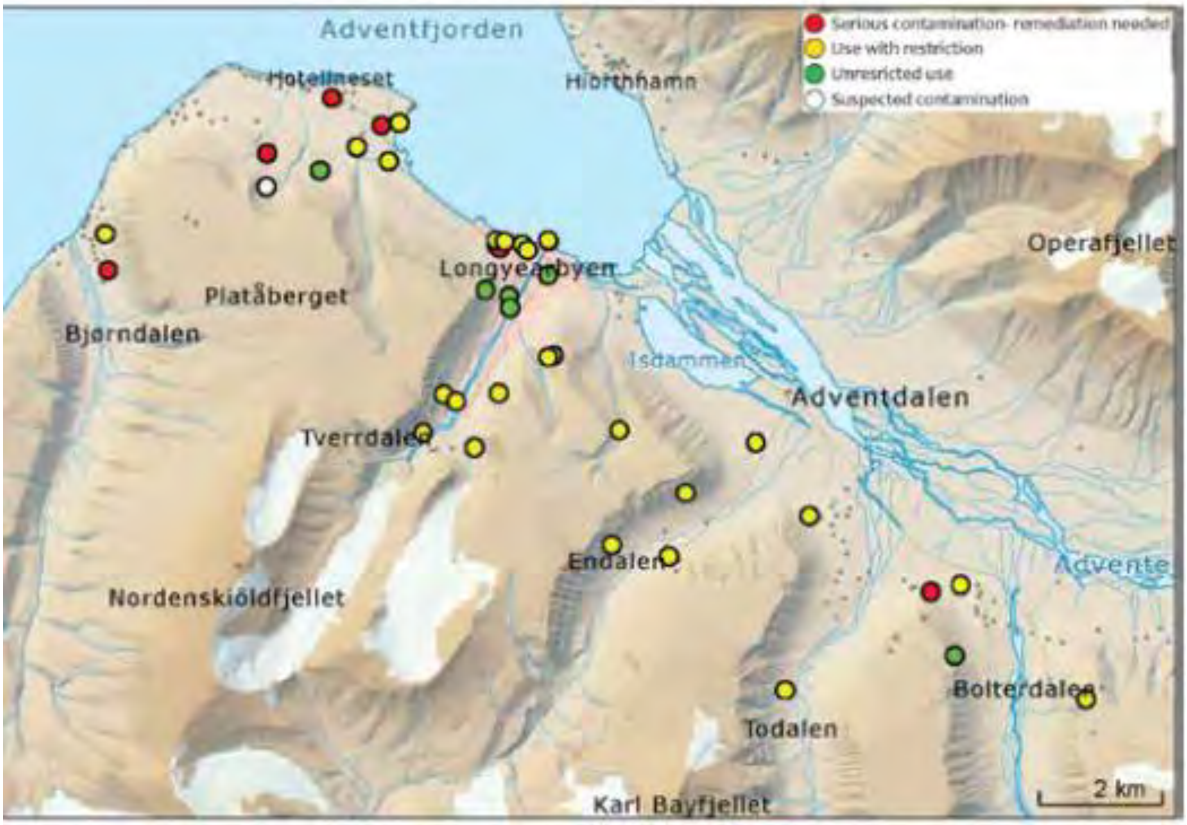


Fig. 17.16: Contaminated sites around Longyearbyen (Granberg, Ask et Gabrielsen 2017).

The marine and terrestrial environment of Svalbard is also very intensively exposed to plastic and microplastic pollution. The archipelago and its surrounding marine ecosystem is intensively monitored for the presence of this type of pollution (Fig. 18.16). The Svalbard Governor's Office organizes "Collecting Events" for volunteers, where the governor's ship goes to various coastal areas and volunteers collect the accumulated waste on and around the beaches. One of the locations that was cleaned in the past is the northern part of the archipelago, Nordaustlandet and the Brennevinsfjorden – Goosbukta bay (Fig. 18.16).

Fig. 18.16: Beaches on Svalbard are polluted with plastic (Archive CPE).

Migration and invasion of organisms

21 thousand species of plants, fungi, mammals, birds, fish, insects and invertebrates live in the Arctic. About one-third of all bird species live in the Arctic, and their food chain is tied to the marine ecosystem. For example, more than two-thirds of platypus (geese, ducks), species nest in the Arctic or sub-Arctic ecosystem. A large percentage of species of organisms living in the Arctic migrate between the Arctic region and the temperate zone, as well as between terrestrial and marine environments. We provide an overview of the development of migration and invasions of new species into the Arctic due to anthropogenic changes in this part of the world based on the report of the United Nations Environment Program from 2019 (Schoolmeester et al. 2019). The main migration directions between the Arctic region and the temperate geographical zone are documented in Fig. 19.16.

Fig. 19.16: Main migration routes of organisms between temperate region and the Arctic (Schoolmeester et al. 2019).

Migration directions, intensity of migration, timing of migration are influenced by a whole range of natural and anthropogenic changes. The migration of selected species also has a major impact on the economic development of specific areas (such as tourism, including sport hunting).

With the development of human civilization and the ability to travel and explore all parts of our planet, there is also the spread and invasion of new species. It is estimated that around 480,000 invasive species have been transferred to different parts of our planet as a result of human migration and travel (Fig. 20.16). native species and significantly impoverishing local biodiversity. The invasion of new species is, after the mechanical disturbance of local biotopes, the most important negative effect affecting biodiversity in specific areas. In the Arctic, there has not yet been as large a migration of new species as in the rest of the world. The exception is the spread of the American Mink in Iceland and Scandinavia, which is linked to the increase in fur farms, and the spread of the Pacific king crab (*Paralithodes camtschaticus*) into the Barents Sea. The expansion of this economically important crab has brought economic benefits to Norway and the Russian Federation. With the warming and de-icing of the Arctic Ocean, the construction of the North-West Sea Transport Sea Route (the transport link between Europe and Asia) will have a tremendous impact on the invasion of new species into the local seas of the North Asian region.

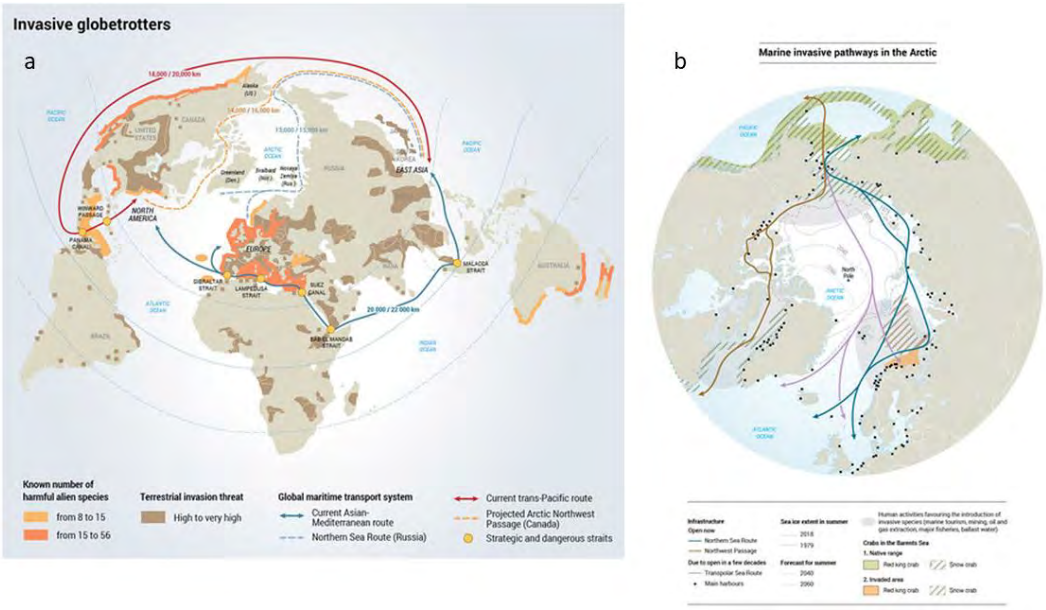


Fig. 20.16: Overview of global migrations of organisms to the Arctic: (a) on land; (b) in the sea (Schoolmeester et al. 2019).

Global pandemics spread infectious diseases (a good example is the recent global CARS 19 pandemic) to areas with reduced immunity, including most areas in the Arctic where indigenous people live. Viral, bacterial, parasitic or even fungal infections between animals and humans often occur here. Transmission is mediated by direct contact, through insects, with food and various wastes contaminated with parasites. Fig. 21.16 documents the areas where outbreaks of infectious diseases have currently been detected.

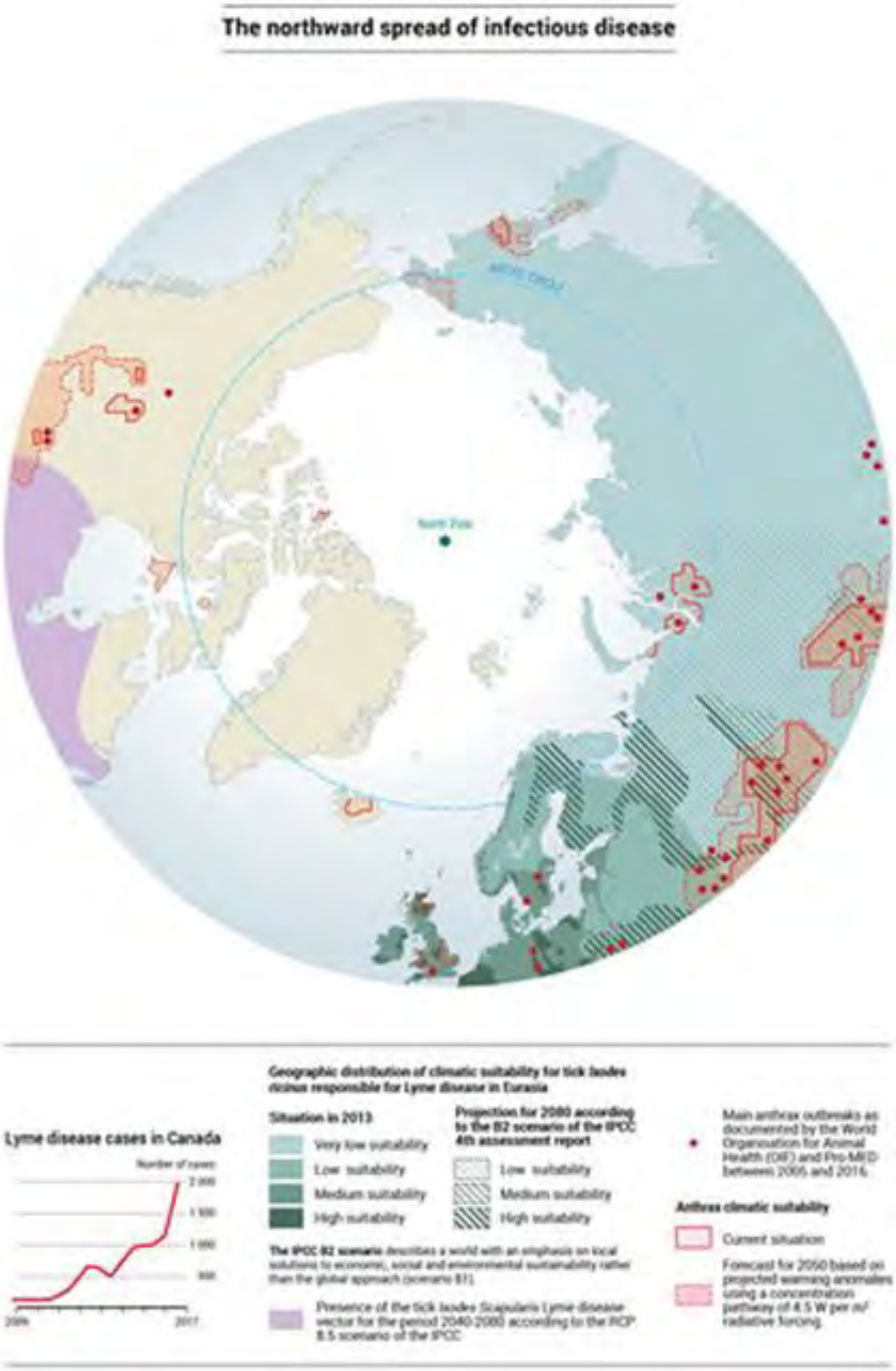


Fig. 21.16: Global spread of infectious diseases with marked localities with increased record (Schoolmeester et al. 2019).

Migration and invasion of organisms on Svalbard

The presence and frequent exchange of people in different areas of the Arctic (as mentioned earlier, the Svalbard archipelago is one of the most visited areas of the Arctic), together with the effect of warming, increases the likelihood of the occurrence of new invasive species for local biotopes. Human settlements and their immediate surroundings are places of species diversity, including the presence of newly arrived invasive species. In the Svalbard archipelago, a detailed study (Bartlett, J. et al. 2021) of the occurrence of invasive vascular plant species has recently been carried out. The study focused on the occurrence of invasive plants in the localities of housing estates, in places very often visited by people, and in seabird nesting sites, both areas with high mineral nutrient enrichment. The study brought evidence of ruderalization, or "dumping", especially in Barentsburg and its immediate surroundings. Ruderalization of Barentsburg is associated with the occurrence of cow parsley (*Anthriscus sylvestris*) and the rapid expansion of dandelion (*Taraxacum* sec. *ruderalia*). A total of 36 species of invasive vascular plants have been recorded in human settlements and their immediate surroundings, and in the nesting grounds of seabirds on Svalbard.

In terms of the composition of terrestrial invertebrates, Svalbard is one of the most thoroughly studied places in the entire Arctic (Coulson 2015). 15 invasive invertebrates were detected here, mainly in connection with the import of soil, which took place in the areas of Russian settlements (currently the import of land to Svalbard is strictly prohibited). The best-known invasive species are butterflies (Lepidoptera) and flies (Diptera). The introduced vole *Microtus levis* is discussed in chapters 14 and 15.

In connection with warming and an overall increase in anthropogenic influence (primarily an increase in industrial fishing and maritime transport), the Svalbard marine ecosystem is exposed to intensive atlantification, which is associated with an increase in the occurrence of non-native species (Hopkins 2002, Ware et al. 2014, van den Heuvel-Greve et et al. 2021).

17. Nature conservation and the environment in Svalbard

Josef Elster

Due to all the changes in the natural environment in the Arctic (shifting of the forest line, melting of permafrost and sea ice, increasing temperatures, invasion of new species, etc.), it is necessary that part of the land and oceans have some kind of protection status. The Arctic Nature Conservancy covers about 17% of the terrestrial and 10% of the marine ecosystems of the Arctic (Fig. 1.17). According to the 2019 United Nations Environment Program report (Schoolmeester et al. 2019), protection is primarily focused on limiting or excluding direct anthropogenic interventions and in some cases is linked to detailed and long-term comprehensive monitoring and subsequent management of the protected area. However, from an international perspective, the nature conservation status is very diverse and the degree of protection and subsequent management is very different. The protection level for the marine ecosystem in the Arctic is minimal and includes mainly coastal areas and areas of marine shelves. With the rapid loss of sea ice and the onset of industrial fishing, large areas of the Arctic Ocean are exposed to negative anthropogenic influences. Protection of the terrestrial and marine parts of the Arctic is currently one of the most important global international legal tasks.

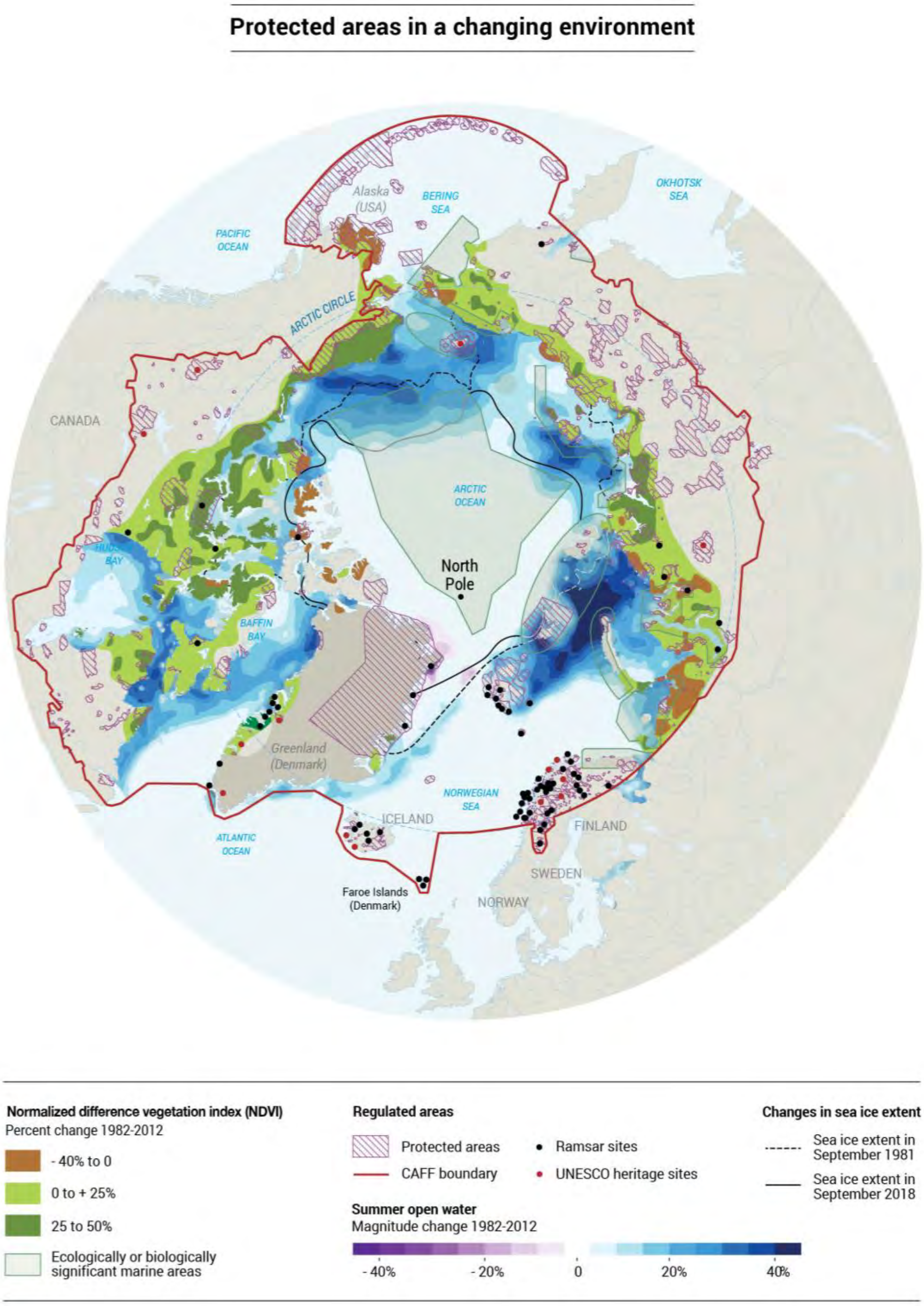


Fig. 1.17: Protected areas of the Arctic region (Schoolmeester et al. 2019).

Nature protection and the organization of domestic and international research in Svalbard takes place under the patronage of the Norwegian Government, which is represented by the Office of the Governor of Svalbard and its Department for Nature Conservation and other institutions established by the Norwegian Government (e.g. the Svalbard Science Forum - Svalbard Science Forum - SSF, which is managed Research Council of Norway). Regulation of research and nature protection is subject to the "Svalbard Environmental Protection Act - Svalbard Law on Nature Protection”, which came into effect on July 1, 2002. This law protects the landscape, flora, fauna and cultural heritage of Svalbard. Under this act, the Governor's Office issues permits for field research, including permits for all scientific installations located in the wild.

In the almost 350 years since the discovery of Svalbard, the archipelago has been subjected to ruthless exploitation of natural resources. In 1920, the Svalbard Treaty was ratified, and Norway gained sovereignty over the Svalbard archipelago. Five years later, the Svalbard Act was adopted. The treaty and act laid the foundations for the long-term and sustainable management of the archipelago's resources. After the law came into force, several species of animals were listed and with them came the first protected natural areas. The first two plant protection areas were already established in 1932.

At the end of the 1960s, with a strongly growing interest in oil, gas, coal and in the exploration of mineral resources in connection with growing tourism, the Kingdom of Norway forced to expand the nature protection of Svalbard (the establishment of three large national parks, two large nature reserves and fifteen bird reserves; the laws came into force in 1973).

Protected areas in Svalbard are divided into different categories based on what is to be protected and how strictly. In Norway, including Svalbard, there is a distinction between national parks, protected landscape areas, nature reserves, protected areas of special habitats and marine protected areas. Several coral reefs are also protected against bottom trawling. Currently, there are seven large-scale protected areas in Svalbard – the national parks, six nature reserves, one geological protected area and 15 bird reserves (Fig. 2.17).

Fig. 2.17: Large protected areas in Svalbard: 7 national parks (green), 6 nature reserves (red), 1 geological protected area (purple) and 15 bird reserves (red circles; NDNM 2012).

In 1998, the success of the protection of protected areas in Svalbard was evaluated. The assessment revealed that the most biologically productive and species-rich areas of the archipelago were also the least represented areas that received protection in 1973. Based on this, a new conservation plan was initiated in 1998 and completed through the Conservation Act, which was passed in the autumn of 2003. From 1 January 2004, the border area around Svalbard was extended from four to 12 nautical miles. The main principle of the Svalbard Environmental Protection Act 2001 is that there are protected areas in Svalbard which:

1. include the full diversity of natural environments and landscape types

2. contribute to the protection of areas of importance for natural or cultural history

3. protects marine and terrestrial ecosystems

4. contribute to the preservation of wild undisturbed nature and the pristine natural environment.

The current protected areas cover 65.2% of the area of Svalbard with a total area of 39,815 km^2. Of the marine areas within the territorial boundary surrounding Svalbard, 84.7% of the territory is now protected.

Seven national parks (NP, with an area of 1,100 – 13,200 km^2) have been declared on Svalbard, but the protection regime is not uniform. In the wider area of the administrative city of Longyearbyen, they can be visited, and nature-friendly activities are allowed in them. More remote NPs have stricter conditions. In general, it is forbidden in the NP to build buildings, explore deposits and extract minerals, store waste, move with motor vehicles, enter them with vessels that do not meet the given fuel quality standard, collect plants and fossils, hunt and disturb animals (includes- if NP sea, the conditions also apply to its bottom). Exceptions to the ban (e.g. for research) are granted by the governor of the archipelago.

The next category of nature protection is **six nature reserves** (9 – 55,500 km^2) with similar but stricter limits than those in NP. These restrictions can be strengthened, by decision of the governor, up to absolute protection of the reservation with a complete ban on entry.

In terms of biodiversity protection, **bird reserves** are important - a total of 15 territories (0.4 - 36 km2), five of which are also Ramsar sites. These are mostly small islands or rocky reefs with numerous nesting colonies of seabirds, which are subject to a special regime - no entry during the nesting period between May 15 and August 15 and a minimum distance of 300 meters that must be observed by vessels on the sea surface.

The last category of protection is the protection of **geologically significant localities** (geotope protection area). Currently, there is only one area on the west coast of Svalbard (17 km^2), protecting a unique geological and paleoentomological locality.

Last but not least, the Kingdom of Norway also protects the **cultural heritage** of Svalbard. In general, all structures, artefacts and other remnants of human activity on the archipelago, dating back to before 1946, are protected and may not be destroyed, collected (e.g. including worked pieces of wood) or tampered with. The most valuable sites have been declared protected cultural heritage sites; entry to ten of them is completely prohibited, camping within 100 m of the others is not allowed.

The archipelago as a whole is included in the preliminary list of natural and cultural heritage of UNESCO

Afterword

Expeditions for a deeper understanding of the High Arctic are no longer just a desire for adventure from the discovery of the hitherto unknown in this remote corner of our planet. The polar landscapes at both poles of planet Earth are among the least hospitable places where a human can enter, and the history of their discovery and exploration is associated with many moving stories. It is certainly no surprise that even the Czechs could not be missing in the past among the adventurers of polar landscapes: who does not know the name of Jan Eskymo Welzel (1868 to 1948), the legendary Eskimo chief and adventurer. However, we are primarily interested in courageous researchers who set out to gain expert knowledge of the High Arctic. From all of them, let us name the physicist František Běhounk (1898 to 1973), the geologist Josef Sekyra (1928 to 2008), the astronomer Antonín Mrkos (1918 to 1996) and, of course, also Josef Svoboda (1929 to 2022), a Canadian of Czech origin who made a significant contribution to knowledge of the behaviour of plants in the extreme conditions of the habitats of the Canadian part of the High Arctic.

At the Faculty of Science of the University of South Bohemia in České Budějovice and collaborating institutions across our republic, polar scientific research is being successfully developed not only in various areas of living and non-living natural sciences, but also in the field of social sciences, including political and security studies. Our researchers are doing a good job, because how else could they earn appropriate international recognition in the strong competition of world powers and also countries with a long tradition of research in the Polar Regions in the north and south, which have finally started to take us seriously. Thanks to this, the Czech Republic is gradually becoming a member of the wide family of countries with advanced polar research and a member country of respected international organizations for the High Arctic and Antarctica. Such respect is gained not only through scientific activities, the organization of conferences hosting internationally respected experts, but also through the sharing of our research infrastructures built and maintained by our own forces. Behind great success is always the enormous effort and commitment of individuals who live for such an idea. In the case of research in the High Arctic, it is Josef Elster, who continued the legacy of his teachers Jiří Komárek and the Czech-Canadian polar explorer Josef Svoboda and purposefully pursued the idea of building our own research base on Svalbard. He succeeded and the Czech Arctic Science Infrastructure Josef Svoboda Station on Svalbard saw the light of day in Longyearbyen in 2014. Josef Elster and later also Oleg Ditrich are mainly responsible for the systematic development of our intensive research in the High Arctic since the establishment of this research station and for the fact that dozens of scientists, students and their professors come to the base for seasonal research stays, not only from the parent University of South Bohemia, but also from other Czech and foreign universities and non-university research facilities, such as the institutes of the Academy of Sciences of the Czech Republic.

Today, no one doubts that the preservation of polar ecosystems is a necessary condition for the sustainability of life on our planet, for the sustainable development of human society. The main focus of polar research conducted in the demanding conditions of the Arctic is therefore focused on projects aimed at the very essence of global climate change, the role of modern technologies in times of global climate change, the behaviour and approaches of modern man in regards to the sustainability of life on our planet, and the possibilities of correcting the undesirable impact of all ill-considered human steps on the natural environment. Finally, this research helps us to reflect on the possibilities of science itself, namely whether scientific knowledge alone can answer all questions and enable the desired correction.

In the field of ecology, polar research is focused on microbial, plant and animal communities, including cyanobacteria, algae and vascular plants, soil microbiota and arthropods, but also bird fauna, migratory species and their role in the spread of infectious agents. Today, in the current epoch of the melting and retreat of glaciers and the discovery of terrestrial ecosystems, it is far from enough to describe the various forms of life in polar habitats without examining them in interaction with the factors of the extreme environment of the Arctic, an area of permafrost.

The melting of glaciers on our planet, including those in the polar regions of Antarctica and the High Arctic, is a convincing consequence of global climate change, which has been triggered by human civilization through the extensive treatment of natural resources, the exponential growth of economic performance, but also the increasing population in the already over-populated countries of the world and a generally irresponsible approach to management of the natural wealth of our planet. Anyone concerned about global climate change and its impact on the conditions for the sustainability of life on Earth should be interested in how climate change manifests itself in Polar Regions with a huge, but limited energy capacity to protect our planet from its fatal consequences. Preventing the growth or at least minimizing the consequences of global climate change is a huge task facing humanity today. This is certainly not possible without a modern multidisciplinary approach of experts from the field of living and non-living natural sciences, as well as the humanities, social and security sciences. Science and experimental research as a manifested form of human intelligence are the only hope for humanity and its sustainable development.

Libor Grubhoffer

April 16, 2023

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