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Norwegian contributions to Arctic environmental sciences from the 1880s to the third International Polar Year

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Abstract This paper reviews the major contributions made by Norwegian scientists to Arctic environmental sciences since the 1880s. The review begins with the first International Polar Year (IPY) in 1882–83. It then considers the 1890s to 1920s with the scientific expeditions focusing on ocean and sea ice conditions of Nansen, Amundsen and H. Sverdrup, and the mapping of the Queen Elizabeth Islands by Otto Sverdrup and colleagues. The period from 1911 to the mid-1920s also witnessed annual expeditions to Svalbard led by Adolf Hoel. The 1930s to 1945 period encompassed the Second International Polar Year when Arctic weather stations were established or maintained. The time interval post-World War II to 2000 witnessed major advances made possible by technical and organizational innovations. The establishment of the Norwegian Polar Institute in 1948 led to extensive research on the glaciers and snow cover in the Svalbard archipelago and to oceanographic and sea ice research in the Barents Sea and Arctic Ocean. Remote sensing methods began to be widely used from the 1980s. The new millennium saw the undertaking of the third IPY and a shift to multinational projects. New fields such as ocean–ice–atmosphere variability became active and there was much attention to high-latitude climate change in the context of global warming.

Keywords **Arctic, Svalbard, environmental sciences, climate change, International Polar Year**

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1 The beginning

Norway has a long and distinguished history of polar exploration and research as recounted by Drivenes and Jølle[1]. Barry[2] and Serreze and Barry[3] provide an historical view of the context of research in Arctic climate. This paper traces Norwegian contributions to Arctic research in the domain of physical sciences of the environment from the 1880s to the present. It shows the transition from largely individual ship or land expeditions to nationally and internationally-organized programs, to permanent bases and to interdisciplinary, multinational programs supported by technological advances in instrumentation, field equipment, transportation, navigation and communications.

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The first Scandinavian to complete the Northeast Passage around Eurasia was N. A. E. Nordenskiold[4], who in 1878–79 commanded the *Vega* expedition. Starting from Karlskrona in southeast Sweden on 22 June 1878, the *Vega* rounded Cape Chelyuskin in August, and after being frozen in at the end of September near the Bering Strait, completed the voyage successfully in the following summer. This demonstrated the feasibility, albeit with great difficulty of a Northeast Passage through the Arctic Ocean.

The Norwegians essentially began Arctic research during the First International Polar Year, 1882–83. A ring of 12 stations was set up around the Arctic that carried out meteorological, geomagnetic and auroral observations[4]. These included a weather station that was operated in northern Norway at Bossekop (69.97°N, 23.25°E) in Finnmark[6]. Meteorological, auroral, and oceanographic observations in the fiord at Alta were performed and the results published by the climatologist A. Steen[7]. Tammiksaar et al.[8] show that an unpublished chart of circumpolar temperatures for January 1883 was prepared from all available reports by S.B. Ehrhart in Munich in 1902. In 1888, F. Nansen, O. Sverdrup and four others made the first crossing of the Greenland Ice Sheet on skis from Umivik on the east coast to Godthaab on the west coast — a distance of 450 km[9]. Their main difficulties were landing on the icebound east coast and crossing crevasses on their descent to the west coast. They demonstrated that the inland ice was continuous. This success triggered a wave of enthusiasm for polar exploration in Norway that built on its prowess in maritime affairs and its experience in cold climates, snow and sea ice. Nansen was regarded as a national hero and the Greenland crossing boosted patriotic self-esteem[10]. Nansen's achievement led directly to the founding of the Norwegian Geographical Society according to Orheim[11].

2 Scientific research from the 1890s to the 1920s

This account draws heavily for its starting point on the chronology of Norwegian expeditions provided by Barr[12]. However, commercial expeditions for purposes of hunting are omitted from this discussion.

The earliest oceanographic work in the northern North Atlantic extending to Svalbard was undertaken in 1876–78 by H. Mohn and G.O. Sars who led the Norwegian North Atlantic Expedition. This also made geographical and zoological contributions[13].

Fridtjof Nansen and colleagues carried out the first major research program in the Arctic during the *Fram* expedition of 1893–96[14]. In 1885, sealskin clothing from George de Long's vessel the *USS Jeanette*, that had been abandoned after drifting from the Bering Strait in the pack ice off Siberia to 77°15′N, 154°59′E in June 1881, was found in 1885 on the southwest coast of Greenland. Nansen was among a few scientists who argued that this demonstrated the existence of an ocean circulation westward from Siberia and he planned to make use of it by freezing the specially built *Fram* into the ice and allowing it to drift. He hoped the motion would carry it close to the North Pole. De Long's ill-fated expedition had finally laid to rest the long-standing notion of an open polar ocean[15]. On 25 September, 1893 the vessel *Fram* was frozen into the pack ice near the New Siberian Islands and from there it slowly drifted northwestward reaching 86°N. Nansen and a colleague skied some distance to the north and then turned back, whilst the ship drifted southward before becoming free of the ice in the Greenland Sea on 14 August, 1896. A large collection of oceanographic and meteorological observations was assembled and these are now available in digital form[16]. The meteorological observations made on this first *Fram* expedition were reported by Mohn[17]. The coldest winter months averaged between 36°C and 37°C. It is interesting to note that the results were still of interest five decades later to Hisdal[18], who examined diurnal temperature variations in polar regions in winter.

From 1898–1902, Otto Sverdrup led the second *Fram* expedition to northwest Greenland and the high Canadian Arctic islands. For four years he overwintered on Ellesmere Island and the expedition discovered and explored Axel Heiberg, Amand Ringnes, and Ellef Ringnes islands. His surveyor Gunnar Isachsen carried out extensive mapping over an area of 240000 km^2, and significant botanical, zoological, and geological work was undertaken by the expedition[19]. Again Mohn reported on the meteorological findings[20].

Between 1900 and 1906 there were almost annual cruises around Bear Island making oceanographic and fishery investigations. In 1900 an oceanographic expedition led by J. Hort sailed to the north of Iceland, the sea ice area known as the Western Icefield, Jan Mayen and Bear Island (Bjørnøya). Expedition members included F. Nansen, oceanographer B. Helland-Hansen, a biologist and a zoologist. In 1901 Amundsen made oceanographic observations in the Arctic seas[21] that were referenced 80 years later by Rudels[22]. They concerned the Atlantic source of deep water in the Arctic Ocean and the possible additional role of the Barents Sea and continental shelves. In 1902–03 the Norwegian *Aurora Polaris* expedition was organized by K. Birkeland. Parallel observations were maintained at stations on Iceland, Svalbard, Novaya Zemlya, and in Finnmark, Norway. Two observatories on Novaya Zemlya operated from 30 August 1902 to 11 Mach 1903. In addition to meteorology, botanical and zoological studies were undertaken. Nansen undertook further oceanographic observations during a cruise of the *Veslemøy* off Spitsbergen in summer 1912[23]. On this occasion he was able to employ the Nansen bottle, that he had invented two years earlier, to collect water samples at various depths. This device was only replaced in 1966,

The union of Norway and Sweden ended in 1905 and Sörlin[10] points out that Norway's main foreign policy concern became the "northern areas" i.e. the Arctic waters and islands of the Svalbard Archipelago.

In the North American Arctic, Otto Sverdrup was followed by Roald Amundsen[24] on the sloop *Gjoa*, who during 1903–06 successfully traversed the Northwest Passage via Lancaster Sound, south on the west side of Somerset Island, and then south of Victoria Island, which was mapped, to Alaska. Amundsen made a sledge trip to Eagle City near the Yukon River to telegraph news of conquering the Northwest Passage.

In 1909 zoologist J. Koren travelled from Nome, Alaska, through Bering Strait to the Chukchi Peninsula studying bird life, becoming the first to locate the nesting sites of the spoonbill sandpiper. During 1911–13 Koren returned and overwintered up the Kolyma River. After their ship sank in the ice, the party returned in a whaleboat to the Diomede islands from where Koren walked over the sea ice to Alaska in March 1913.

Adolf Hoel published a summary report on the Norwegian expeditions to Svalbard from 1906 to 1926[13].

In 1906 and 1907, Gunnar Isachsen, with financial support from Prince Albert of Monaco, led a research and cartographic team on the first Norwegian expedition to northwest Spitsbergen. This built on information collected by Norwegian sealers and trappers over the previous sixty years. Topographic and geological maps were prepared; the former using triangulation covered ~3525 km^2 on a scale of 1:100,000. Hydrographic surveys were also made. The expedition was repeated by Isachsen in 1909 and 1910 with an additional 5348 km^2 mapped at a scale of 1:200,000 mainly north of Icy Fiord (78°N). From 1909 the mapping was done by photogrammetry. The results are extensively reported by Isachsen[24-25]. Thereafter, the expeditions primarily led by Adolf Hoel became annual and were focused on geological surveys and topographic mapping. From 1916 measurements of tidal range were collected. From 1918 the expeditions were funded by the Norwegian Government and the Nansen Fund. In February 1920 the sovereignty of Svalbard was assigned by treaty to Norway, which resulted in intensive survey work between 1922 and 1925. The sovereignty actually became effective in August 1925. In 1920 stereo-photogrammetry was introduced with mapping at scales of 1:20,000 to 1:50,000. Significant botanical work was carried out in the extreme southwest of Spitsbergen. In 1922 and 1924 oceanographic sections were taken west of Bear Island across the Gulf Stream, north of Bear Island to South Cape and south of Bear Island to the Norwegian coast. Temperatures and water samples were collected down to 3076 m at 81°29′N, 19°20′E, near the farthest north ever reached in ice-free waters. In summers 1922 and 1923 water temperatures west of Spitsbergen were 6−7°C. These conditions were part of a two-decade warm anomaly that is attributed to natural variability in the high latitude climates system. The 1923 and 1924 expedition of Hoel included topographic mapping of Bear Island. Botanical work on Bear Island and Spitsbergen in 1924 collected plants and measured air and active layer temperatures. 1925 saw a continuation of earlier activities and the completion of geological mapping on Bear Island. In 1928 these activities led to the establishment of the Norwegian Svalbard and Arctic Studies program.

The Norwegian government established meteorological stations at Green Harbour, Svalbard in 1911 and on Bear Island in 1923. In 1917, Vilhelm Bjerknes founded the Geophysical Institute at the University of Bergen. With his son Jacob and Swedish meteorologist Tor Bergeron he laid the foundations of the Department of Meteorology and the modern basis of the science[27]. While most of their work concerned mid-latitude weather forecasting, the north polar region was involved as it was the source of arctic air masses that flowed into mid-latitude cyclones. Moreover, J. Bjerknes and Solberg[28] also showed cyclone systems tracking towards the North Pole, a fact that most subsequent meteorologists overlooked for some 35 years.

During the 1920–30s, the Norwegian meteorologist, Sverre Petterssen, worked with the Bjerknes group on synoptic meteorology before moving to the USA and Britain during and after World War II.

Roald Amundsen organized and Harald Sverdrup[29] led the protracted *Maud* expedition in the East Siberian Sea. During 1918–20 Amundsen navigated the Northeast Passage to Bering Strait becoming the first to traverse both Arctic sea routes. The *Maud* became frozen in the ice at 72°18′N, 175°24′W and drifted to 76°30′N, 143°12′W between 1922 and 1925, although the vessel did not drift towards the Pole as Amundsen had hoped. Extensive meteorological and oceanographic data were collected by Sverdrup[30] and the expedition was noteworthy because the observations of Swedish meteorologist Finn Malmgren[31] laid the foundation for modern sea ice research. Malmgren[32] also reported on air temperature, humidity, and rime accumulation (termed hoar frost in his paper) in relation to wind velocity. He demonstrated from a few kite and balloon soundings the existence of a low-level temperature inversion, to at least 1000 m, and the effect of wind speed on its structure.

In summer 1921 there was a Norwegian expedition to Novaya Zemlya led by Olaf Holtedahl[33-35]. He provided an extensive three-volume report on the results. Their vessel sailed through Matochkin Strait between the two islands until they were stopped by ice drifting from the Kara Sea. They then sailed northward along the west coast of the north island to Mashigin Fiord. From here a sledging party crossed to the east coast. They reached Admiralty Peninsula (~75°N) before working southward to two fiords on the west coast of the south island around 73°N. The work undertaken was geological, botanical and zoological and Holtedahl noted that up to that time very little was known about the geological history of those two islands. Edlund reports on the meteorological observations including aerological soundings and sea ice conditions and provides a summary of the climate of Novaya Zemlya[36].

Also in 1921 Norway established a weather station on Jan Mayen, which continues to operate and in 1929 Jan Mayen became part of Norway. The transfer of sovereignty of Svalbard to Norway took place in August 1925. In 1928 Norwegian state-supported expeditions to Spitsbergen became the Institute for the Exploration of Svalbard and the Arctic Ocean (Norges Svalbard og Ishavsundersøkelser (NSIU)

In May 1926, the Amundsen-Ellesworth-Nobile Transpolar Flight successfully flew the Italian-built N1 Norge airship from Ny Ålesund over the Arctic to Teller, Alaska. This was the first crossing of the Arctic Ocean.

3 The 1930s to 1945

After some five years of planning, the Second International Polar Year (IPY) was undertaken in 1932–33, fifty years after the first IPY[37]. H.U. Sverdrup and T. Hesselberg were important figures in the planning[6]. A major goal was to investigate the polar atmosphere, estimate the air balance of the Arctic, and determine whether the Greenland-Icelandic-Norwegian (GIN) Sea region received cold air from the Arctic Basin or had its own air regime. Norway operated a permanent station at Tromsø and Jan Mayen, two magnetic stations in north Norway, Bjørnøya, on Svalbard, and four stations in East Greenland (Jonsbu, Finnsbu, Torgilsbu and Storfjord). Myggbukta had been established in 1922.

Meteorologist Sverre Petterssen took a position at Massachusetts Institute of Technology, Cambridge, in 1939, becoming professor and chairman of the meteorology department. He wrote a seminal text on Weather Analysis and Forecasting[38]. During World War II he served with the British Air Ministry; where he played a major role in the D-Day forecast. In 1948 he returned to the United States to join the Air Force weather service and then the University of Chicago.

During 1940–44, Norwegian-born Henry Larsen in the RCMP became the first person to sail through the Northwest Passage in both directions in the vessel St. Roch. He completed the east-west return journey in a single summer.

4 Post-World War II to 2000

The "Cold War" gave an impetus to Norwegian activities in the Arctic from 1946–1989. Post-World War II, Norway pursued Arctic research in and around Svalbard, beginning in 1948 when the Norwegian Polar Institute was established in Oslo as a direct successor to the NSIU. The renowned Swedish glaciologist, Hans W. Ahlmann[39], played a large role in its establishment and the oceanographer Professor H.U. Sverdrup was invited back from the United States to become its director. Important early players in polar research were glaciologist Olav Liestol and sea ice specialist Torgny Vinje[40-41].

In 1956, Professor Sverre Pettersen et al. published the first book in English on the meteorology of the Arctic[42]. However, their view that the circulation in the Arctic was predominantly anticyclonic was soon revised by new studies of the Arctic Meteorology Research Group at McGill University in Montreal[43]. The presence of cyclones in the Arctic was a fact that Bjerknes and Solberg[27] had long ago anticipated and that Soviet meteorologist B. L. Dzerdzeevski had demonstrated in an at-the-time little noticed Russian publication[44].

During the International Geophysical Year, 1957–58, Norway maintained Arctic stations on Jan Mayen, Bear Island, and Svalbard (Isfjord Radio, Ny Ålesund), as well as Weather Ship M in the Norwegian Sea[45]. The Bear Island station was set up by Norway to preempt any move there by the Soviet Union according to Sörlin[10]. Norway was particularly involved in research on Svalbard. However, most international attention was devoted to the Antarctic because for the first time technological advances allowed safe travel and overwintering.

Continued work in the 1960–70s accelerated in 1982 with the publication by the Polar Institute of the journal *Polar Research*. While initially focused on geology and biology, papers then began to appear on Arctic oceanography, meteorology, glaciology, and sea ice.

A German oceanographer at the Polar Institute, Rudels[46] analyzed the outflow of polar water through the Canadian Arctic Archipelago, and estimated for the upper layer 7×10^{8} $kg \cdot s^{-1}$ with a salinity of 32.9 PSU. A further study assessed the mass balance of the Arctic Ocean, focusing on the fluxes through the Fram Strait[22]. He used data from CTD sections obtained in 1980 and 1983.

A substantial part of the Atlantic Water in the West Spitsbergen Current is found to recirculate in the northern part of the strait. Loeng[47] reviewed the oceanography of the Barents Sea, which is a shallow continental shelf sea. He showed that its physical conditions are determined by three main water masses: Coastal Water, North Atlantic Water, and Arctic Water. These three water masses are linked to three different current systems: the Norwegian Coastal Current, the Atlantic Current, and the Arctic Current. Haugan analyzed the structure and heat content of the West Spitsbergen Current based on measurements obtained in summers 1997 and 1998[48]. Midtun studied the surface temperature of the Barents Sea in winter and summer and used data collected from 1977–87 in a section across the inflow between Bjørnøya and northern Norway[49]. The relation of the Atlantic inflow to the climate (air temperature, pressure and ice cover) of the Barents Sea for 1970–86 was reviewed by Ådlandsvik and Loeng[50]. The sea ice cover in the Barents Sea (68°–83°N, 10°–55°E) at the end of the melt season showed a 40 percent decrease between 1966 and 1988 according to Vinje and Kvambekk[51] although the maximum extension had not changed significantly. Vinje published many papers on sea ice in the Barents Sea providing historical reconstruction of ice conditions for the past four centuries[40].

Remote sensing using SAR data from ERS-1 was illustrated by Korsnes[52] in a study of Fram Strait ice drift for January-March 1992. Haarpaintner used European Remote Sensing Satellite(ERS)-2 SAR data to study the polynya in Storfjorden in the southeastern Svalbard archipelago[53]. SPOT images were used by Lefauconnier et al. to determine flow speed and calving rate of the Kongsbreen glacier in Svalbard[54]. A GIS system was applied to photogrammetric and radio echo data of the Erikbreen glacier in Spitsbergen to asses mass balance and surface changes between 1970 and 1990[55]. From the mid-1980s, Jon Hagen and Olav Liestol became active in glacier studies in the Norwegian Arctic with annual reports on glacier mass balance for two glaciers in Svalbard that started in the mid-1960s[56]. Lefauconnier et al. presented mass balance data for three glaciers in western Spitsbergen in relation to climate[57]. The records begin in 1966–67 and 1967–68 for two of them and 1986–87 for a third one.

Field surveys of snow accumulation were undertaken along three transects across Spitsbergen between 77.5°N and 78.8°N in May 1997 by Winther et al.[58].

Hisdal analyzed the spectral distribution of global and diffuse solar radiation (0.3–0.8 μm) at Ny Ålesund for various sky conditions and solar elevation angles[59]. The variability of the radiation budget at the same location from 1983–91 was analyzed by Ørbæk et al.[60]. The large variation in spring was shown to be related to the albedo changes while in winter it was related to cyclone passages and the alternation of warm, humid maritime airflow from the south and cold, dry Arctic air from the north. In summer and autumn, Ny Ålesund is influenced by the ocean to the west while in winter and spring it is more 'continental'. In summer, oceanic cloud and Arctic sea fog have a major influence on the fjord where the station is located. Surface spectral reflectance and solar radiation attenuation in snow and first-year fast ice at Kongsfjorden, Svalbard were observed in spring 1997 and 1998 by Gerland et al.[61]. They characterized the physical processes involved in snowmelt and ice thickness changes.

In the 1990s the Norwegian government expanded Arctic science funding. In 1993, the creation of University Studies on Svalbard (UNIS) at Longyearbyen led to educational expansion in geophysics and biology. The Norwegian Polar Institute was moved from Oslo to Tromsø in 1998 and the Oslo facility was closed. In 1986 the Nansen Environmental and Remote Sensing Center was established as a non-profit research foundation affiliated with the University of Bergen. It was initially directed by O. M. Johannessen and its initial focus was on Arctic and marine remote sensing and especially on mapping changes in Arctic sea ice[62]. By the end of the decade, a multi-institutional partnership was being developed—the Bjerknes Centre for Climate Research—which was soon thereafter granted Centre of Excellence status in 2000.

5 The new millennium

The advent of the new millennium is associated with the emergence of new themes and paradigms. In September 2000 the Polar Environmental Centre in Tromso hosted the H. U. Sverdrup Symposium on the role of ocean−sea ice−atmosphere interaction in polar and subpolar climate. It celebrated the return of the *Maud* expedition ship 75 years earlier. The symposium featured many papers on Arctic oceanography, which were notable for their international collaboration[63-65].

A second development followed the increased recognition of global warming in the 1990s, which focused attention on high northern latitudes with the identification of polar amplification of the warming[66]. This interest expanded vastly in the 2000s with concerns over rapid glacier retreat, Greenland ice sheet mass loss, permafrost thaw, and sea ice shrinkage in the Arctic Ocean. Førland and Hanssen-Bauer investigated the recent climatic conditions in the Norwegian Arctic−Svalbard and Jan Mayen[67]. They demonstrate that although air temperatures have increased in the last few decades, levels are still below those in the 1930s. Precipitation has increased by more than 2.5 percent/decade since measurements began in the early 20th century. The fraction of solid precipitation has decreased in the most recent decades, however, and this implies that part of the increased total precipitation is fictitious due to the reduction in the undercatch of snowfall. Johannessen et al. give an overview of century-scale Arctic climate change and changes in sea ice[68]. They find that two pronounced twentieth-century warming events, both amplified in the Arctic, were linked to sea-ice variability. However, the 1920–30s warming was due to internal climate variability, whereas that since 1980 is a result of anthropogenic forcing, superposed on natural climate modes.

Vinje developed a data base of winter (April) and summer (August) sea ice in the western and eastern Nordic Seas, based on Norwegian ice charts from 1864 to 1998[69]. Shapiro et al. developed a data base of April sea ice extent in the Barents Sea from 1850 to 2001 based on two series of Norwegian ice charts for 1850–1949 and 1966–2001 and Soviet air reconnaissance charts from 1950 to 1966[70]. They show a steady northeastward retreat of the ice edge with the largest change between 1850–99 and 1900–49.

An overview of snow research conducted on Svalbard from the 1990s is presented by Winther et al.[71]. They address distribution patterns, melt, snow pack characteristics, remote sensing and biology. They show that the altitudinal increase is 97 mm w.e. per 100 m. Progress in modeling snow distribution and its melt are discussed. Measurements of snow accumulation across the Austfonna ice cap in Svalbard were reported by Taurisano et al.[72].

Hagen et al.[73] report on glacier mass balance, runoff and freshwater flux on Svalbard, Svendsen et al.[74] characterize Svalbard fjords, and Killingtveit et al.[75] discuss the water balance on Svalbard. Rasmussen and Kohler reconstruct the mass balance of three Svalbard glaciers back to 1948[76].

Norwegian scientists became team players, especially in the 2007–2009 Third International Polar Year (IPY). Goldman lists the 26 projects that were funded in Norway[77]. Four of them focused on Arctic environmental sciences as defined in this review. These concerned Arctic glaciers, permafrost, the bipolar Atlantic thermohaline circulation, and polar measurements of climate, chemistry, aerosols and transport. The outcomes of the IPY Science Conference that was held in Oslo in June 2010 are reported in *Polar Research* [78]. According to Olav Orheim, Steering Committee Chair and former Director of the Norwegian Polar Institute, the conference had 2323 registered participants representing 49 countries. Significant papers included Divine et al.[79] on winter air temperature variability over the last 1000 years in Longyearbyen, Svalbard and Vardo in northern Norway from ice core reconstructions. They show a progressive winter cooling from 800 to 1800 AD and no distinct Little Ice Age in Svalbard. However, the 19th century in Svalbard was 4°C colder than the 20th century. Rotschky et al.[80] monitor the annual total of melt days and the date of summer melt onset across the Svalbard archipelago during 2000–2008 using microwave backscatter measurements. They find a trend towards earlier summer melt onset (2.5–5 $d\cdot a^{-1}$) and an increasing number of melt days per year (2.1–2.5 $d\cdot a^{-1}$ for different regions). Team work on Svalbard glaciers is continuing. Aas et al. model the mass balance of Svalbard glaciers from September 2003 to September 2013[81]. They find a mean specific net mass balance of −167 mm w.e. $\cdot a^{-1}$, corresponding to a mean annual mass loss of about 5.7 Gt.

Norway continues to play a major role in polar science far beyond what might be expected based on its population (which grew from 2.3 million in 1905 to 5 million in 2012) and national resources, and considerably more than its neighbor Sweden. It maintains northern bases and a major installation on Svalbard with a university program.

6 Concluding remarks

The last 130 years have witnessed a transformation in our knowledge and understanding of the Arctic environment. This has been made possible in the first instance by the extraordinary efforts of individual scientists in field expeditions. Norwegians played a key role in these activities. Gradually, technical advances in the use of ships and aircraft and developments in instrumentation have greatly facilitated access to remote locations and in the last 5–6 decades satellite remote sensing has removed some of the need to be on the ground or at sea. The organization of national programs and institutions, an increasingly international research staff, as well as the participation of Norway in the International Polar Years, have provided a sound basis for Norway to continue to play a major role in Arctic environmental sciences into the future.

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References

1 Drivenes E A, Jølle H D. Into the ice: the history of Norway and the polar regions. Oslo: Gyldendal, 2006

2 Barry R G. Climate: research programs//Nuttall M. Encyclopedia of the Arctic. Vol. 1. New York: Routledge, 2004: 379–383

3 Serreze M C, Barry R G. The evolution of knowledge about the Arctic and its climate//The Arctic climate system, 2nd edn. Cambridge: Cambridge University Press, 2014: 1–16

4 Nordenskiöld N A E. Vegas Reise omkring Asia og Europa (English translation, 2012). Cambridge, UK: Cambridge Library Collection, 1881

5 Corby G A. The first international Polar Year, 1882/83. WMO Bull, 1982, 31(3): 197–214

6 Bones S. Norway and past International Polar Years- a historical account. Polar Res, 2007, 26(2): 195–203

7 Steen A S. Beobachtungsergebnisse der norwegischen Polarstation Bossekop im Altenfjord, 2 vols., Christiania 1887. 1888

8 Tammiksaar E, Sukhova N G, Lüdecke C. The International Polar Year 1882–1883//Barr S, Lüdecke C. The history of the international Polar Years (IPYs), From Pole to Pole. Berlin: Springer-Verlag, 2010: 7–33

9 Hagen N U. Fridtjof Nansen's crossing of Greenland in 1888. Norsk Geogr Tidsskr, 1989, 43(3): 175–182

10 Sörlin S. Circumpolar science: Scandinavian approaches to the Arctic and the North Atlantic, ca. 1920 to 1960. Sci Context, 2014, 27(2): 275–305

11 Orheim O. A hundred years of Norwegian exploration of the polar regions. Norsk Geogr Tidsskr, 1989, 43(3): 123–127

12 Barr S. Expeditions and events//Drivnes E A, Jølle H D. Into the ice: the history of Norway and the polar regions. Oslo: Gyldendal, 2006: 481–507

13 Hoel A. The Norwegian Svalbard expeditions, 1906–1926. Oslo: Norske Videnkaps-Akademi, 1929

14 Norwegian North Polar expedition 1893–1896: oceanographic data. http://nsidc.org/data/docs/noaa/g02120_fram_hydro/

15 Sides H. In the kingdom of ice: the grand and terrible polar voyage of the USS Jeannette. New York: Doubleday, 2014

16 Arctic Climatology Project. Environmental working group Arctic meteorology and climate atlas. Boulder, CO: National Snow and Ice Data Center, 2000, http://dx.doi.org/10.7265/N5MS3QNJ

17 Mohn H. The Norwegian North Polar expedition, 1893–1896, scientific results, vol. VI//Nansen F. Meteorology. Christiania: J. Dybwad, 1905

18 Hisdal V. The diurnal temperature variation during the Polar Night. Quart J Roy Meteor Soc, 1960, 86(367): 104–106

19 Sverdrup O N. New land: four years in the Arctic regions: volume 2. London and New York: H. Longman, 1904

20 Mohn H. Report of the second Norwegian arctic expedition in the "Fram", 1898–1902, No. 4. Meteorology. Norway: Kristiania, 1907

21 Nansen F. Northern waters: Captain Roald Amundsen's oceanographic observations in the Arctic seas in 1901. With a discussion of the origin of the bottom-waters of the northern seas. Michigan: University of Michigan Library, 1906

22 Rudels B. On the mass balance of the Polar Ocean with special emphasis on the Frain Strait. Norsk Polar Inst Skrifter, 188: 1–53

23 Nansen F. Spitsbergen waters: Oceanographic observations during the cruise of the "Veslemöy" to Spitsbergen in 1912. Videnskapsselskapets Skrifter I. Math-naturv Klasse, no. 2, 1912

24 The Roald Amundsen's Memmorial Fund. The scientific results of the Norwegian Arctic expedition on the Gjøa, 1903–1906. Oslo: Geofis Publ, 1932

25 Isachsen G. Expedition Isachsen au Spitsberg, 1909–10. Vols 1 and 2. Oslo, 1916

26 Isachsen G. Expedition Isachsen au Spitsberg, 1909–10. Vol 3. Oslo, 1927

27 Friedman M R. Appropriating the weather: Vilhelm Bjerknes and the construction of a modern meteorology. Ithaca, NY: Cornell University Press, 1989

28 Bjerknes J, Solberg H. Life cycle of cyclones and the polar front theory of atmospheric circulation. Kristiania, Geophysisks Publikationer, 1922

29 Sverdrup H U. The Norwegian North Polar expedition with the "Maud" 1918–1925: scientific results I. Bergen: A. S. J. Griegs Boktrykkeri, 1930

30 Sverdrup H U. The Norwegian North Polar Expedition with the "Maud" 1918–1925, Scientific Results, vol. II, Meteorology. Bergen, Norway: Geofys Inst, 1933

31 Malmgren F. On the properties of sea-ice. Bergen: A. S. J. Griegs Boktrykkeri, 1927

32 Malmgren F. Studies of humidity and hoar-frost over the Arctic Ocean. Oslo: Geofis Publ, 1927

33 Holtedahl O. Report of the scientific results of the Norwegian expedition to Novaya Zemlya, 1921. Vols. 1. Oslo: Videnskapsselskapet i Kristiania, 1924

34 Holtedahl O. Report of the scientific results of the Norwegian expedition to Novaya Zemlya, 1921. Vol. 2. Oslo: Videnskapsselskapet i Kristiania, 1928

35 Holtedahl O. Report of the scientific results of the Norwegian expedition to Novaya Zemlya, 1921. Vol. 3. Oslo: Videnskapsselskapet

i Kristiania, 1930
36 Edlund O. Meteorologische und aerologische Beobachtungen der Norwegischen Nowaja Semlja-Ecpedition im Sommer 1921. Report of the Scientific Results of the Norwegian Expedition to Novaya Zemlya 1921. No. 39. Oslo: Norske Videnkaps-Akademi i Oslo, 1928
37 Lüdecke C, Lajus K. The second International Polar Year, 1932–1933//Barr S, Lüdecke C. The history of the International Polar Years (IPYs), from Pole to Pole. Berlin: Springer-Verlag, 2010: 135–173
38 Petterssen S. Weather analysis and forecasting: a textbook on synoptic meteorology. New York: McGraw-Hill, 1940
39 Sörlin S. Hans W: son Ahlmann, Arctic research and polar warming: from a national to an international scientific agenda, 1929–1952. Northern Studies Reprint 14, Umea, 1997
40 Vinje T. On the variation during the past 400 years of the Barents Sea ice edge position and Northern Hemisphere temperatures// Proceedings of the WCRP Symposium on Polar Processes and Global Climate. Geneva: WCRP, 1998: 271–273
41 Loeng H, Vinje T E. On the sea ice conditions in the Greenland and Barents seas//POAC 79, Proceedings of the 5th International Conference on Port and Ocean Engineering under Arctic Conditions. Trondheim, Norway, 1980: 163–176
42 Petterssen S, Jacobs W C, Haynes B C. Meteorology of the Arctic. Washington, DC: Chief of Naval Operations for Polar Projects, 1956
43 Hare F K, Orvig S. The Arctic circulation: a preliminary view. Arctic Meteorology Research Group Publication in Meteorology, No. 12. Montreal: McGill University, 1958
44 Dzerdzeevskii B L. The distribution of atmospheric pressure over the central Arctic. Meteorologia i Gidrologia, 1946, 1: 33–38 (in Russian)
45 Orvin A K. Norway's contributions to the International Geophysical Year. The American Scandinavian Review, 1960, 48: 33–41
46 Rudels B. The outflow of polar water through the Arctic Archipelago and the oceanographic conditions in Baffin Bay. Polar Res, 1986, 4(2): 161–180
47 Loeng H. Features of the physical oceanographic conditions of the Barents Sea. Polar Res, 1991, 10(1): 5–18
48 Haugan P M. Structure and heat content of the West Spitsbergen Current. Polar Res, 1999, 18(2): 183–188
49 Midtun L. Surface temperatures of the Barents Sea. Polar Res, 1990, 8(1): 11–16
50 Ådlandsvik B, Loeng H. A study of the climatic system in the Barents Sea. Polar Res, 1991, 10(1): 45–49
51 Vinje T, Kvambekk Å. Barents Sea drift ice characteristics. Polar Res, 1991, 10(1): 59–68
52 Korsnes R. An ice drift series from the Fram Strait January–March 1992 based on ERS-1 SAR data. Polar Res, 1994, 13(1): 55–58
53 Haarpaintner J. The Storfjorden polynya: ERS-2 SAR observations and overview. Polar Res, 1999, 18(2): 175–182
54 Lefauconnier B, Hagen J O, Rudant J P. Flow speed and calving rate of Kongsbreen glacier, Svalbard, using SPOT images. Polar Res, 1994, 13(1): 59–66
55 Etzemüller B, Vatne G, Degard R S, et al. Mass balance and changes of surface slope, crevasse and flow pattern of Erikbreen, northern Spitsbergen: an application of a Geographical Information System (GIS). Polar Res, 1993, 12(2): 131–146
56 Hagen J O, Liestøl O. Glacier mass balance investigations in the balance years 1984–85 and 1985–86. Polar Res, 1987, 5(2): 261–265
57 Lefauconnier B, Hagen J O, Ørbæk J B, et al. Glacier balance trends in the Kongsfjorden area, western Spitsbergen, Svalbard, in relation to the climate. Polar Res, 1999, 18(2): 307–313
58 Winther J G, Bruland O, Sand K, et al. Snow accumulation distribution on Spitsbergen, Svalbard, in 1997. Polar Res, 1998, 17(2): 155–164
59 Hisdal V. Spectral distribution of global and diffuse solar radiation in Ny-Ålesund, Spitsbergen. Polar Res, 1987, 5(1): 1–27
60 Ørbæk J B, Hisdal V, Svaasand L E. Radiaition climate variability in Svalbard: surface and satellite observations. Polar Res, 1999, 18(2): 127–134
61 Gerland S, Winther J G, Ørbæk J B, et al. Physical properties, spectral reflectance and thickness development of first year fast ice in Kongsfjorden, Svalbard. Polar Res, 1999, 18(2): 275–282
62 Johannessen O M, Miles M W, Bjørgo E. The Arctic's shrinking sea ice. Nature, 1995, 376(6536): 126–127
63 Østerhus S, Turrell W R, Hansen B, et al. Observed transport estimates between the North Atlantic and the Arctic Mediterranean in the Iceland-Scotland region. Polar Res, 2001, 20(2): 169–175
64 Alekseev G R, Johannessen O M, Korablev A A, et al. Interannual variability in water masses in the Greenland Sea and adjacent areas. Polar Res, 2001, 20(2): 201–208
65 Fahrbach E, Meineke J, Østerhus S, et al. Direct measurements of volume transports through Fram Strait. Polar Res, 2001, 20(2): 217–224
66 Serreze M C, Barry R G. Processes and impacts of Arctic amplification: A research synthesis. Global Planet Change, 2011, 77(1-2): 85–96
67 Førland E J, Hanssen-Bauer I. Past and future climate variations in the Norwegian Arctic: overview and novel analyses. Polar Res, 2003, 22(2): 113–124
68 Johannessen O M, Bengtsson L, Miles M W, et al. Arctic climate change: Observed and modelled temperature and sea-ice variability. Tellus, 2004, 56(4): 328–341
69 Vinje T. Anomalies and trends of sea-ice extent and atmospheric circulation in the Nordic Seas during the period 1864–1998. J. Climate, 2001, 14(3): 255–267
70 Shapiro I, Colony R, Vinje T. April sea ice extent in the Barents Sea, 1850–2001. Polar Res, 2003, 22(1): 5–10
71 Winther J G, Bruland O, Sand K, et al. Snow research in Svalbard – an overview. Polar Res, 2003, 22(2): 125–144
72 Taurisano A, Schulaer T V, Hagen J O, et al. The distribution of snow accumulation across the Austfonna ice cap, Svalbard: direct measurements and modelling. Polar Res, 2007, 26(1): 7–13
73 Hagen J O, Kohler J, Melvold K, et al. Glaciers in Svalbard: mass balance, runoff and freshwater flux. Polar Res, 2003, 22(2): 145–159
74 Svendsen H, Beszczynska-Møller A, Hagen J O, et al. The physical environment of Kongsfjorden–Krossfjorden, an Arctic fjord system in Svalbard. Polar Res, 2002, 21(1): 133–166
75 Killingtveit Å, Petterssen L E, Sand K. Water balance investigations in Svalbard. Polar Res, 2003, 22(2): 161–174
76 Rasmussen L A, Kohler J. Mass balance of three Svalbard glaciers reconstructed back to 1948. Polar Res, 2007, 26(2): 168–174
77 Goldman H V. Polar research evolves, and Norway and the IPY. Polar Res, 2007, 26(1): 1–6
78 Divine D, Isaksson E, Martma T, et al. Thousand years of winter surface air temperature variations in Svalbard and northern Norway reconstructed from ice-core data. Polar Res, 2011, 30: 7379
79 Goldman H V. Oslo IPY Science Conference, 2010. Polar Res, 2011, 30.
80 Rotschky G, Schuler T V, Haarpaintner J, et al. Spatio-temporal variability of snowmelt across Svalbard during the period 2000–08 derived from QuikSCAT/SeaWinds scatterometry. Polar Res, 2011, 30: 5963
81 Aas K S, Dunse T, Collier E, et al. The climatic mass balance of Svalbard glaciers: a 10-year simulation with a coupled atmosphere–glacier mass balance model. Cryosphere, 2016, 10(3): 1089–1104