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978-1-108-42316-8 — Polar Environments and Global Change
Roger G. Barry , Eileen A. Hall-McKim
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The Setting, History of Studies, and the Climatic Role of the Cryosphere

1

1.1 Introduction

Polar environments experience the coldest conditions on Earth, including extensive areas of persistent snow cover, land ice, permafrost, and sea ice. They are, however, undergoing the most rapid changes in environmental conditions of any place on Earth. The process of polar amplification of global warming has led to temperature increases of 2–4 °C over the last five decades, with increases that are two to three times the global average occurring in most of the Arctic and around the Antarctic Peninsula. The area covered by summer sea ice in the Arctic has decreased by more than half since the 1980s, and Arctic ice caps and glaciers are shrinking at an unprecedented rate (Zemp et al. 2015). Since 2000 there has been accelerating loss of ice from the ice sheets of Greenland and Antarctica. A review of the global changes in the cryosphere is provided by Williams and Ferrigno (2013), while the Arctic Mapping and Assessment Program (AMAP 2011, 2017) has published reports on Arctic snow, water, ice, and permafrost, and Barry (2017) has surveyed changes in the Arctic cryosphere in this century. These changes are of vital importance for global sea level, plants, land and marine animal species, and indigenous populations. Arctic states (members of the Arctic Council: Canada, Denmark, Finland, Iceland, Norway, the Russian Federation, Sweden, and the United States, and six organizations representing indigenous peoples) are seeking to exploit mineral resources in the Arctic and make use of the diminishing cover of Arctic sea ice to facilitate and increase Arctic shipping, as well as to ensure environmental protection and sustainable use of the Arctic environment. Twelve other nations (France, Germany, India, Italy, Japan, Korea, the Netherlands, People's Republic of China, Poland, Singapore, Spain, and the United Kingdom) are now Official Observers at the Arctic Council.

The Antarctic Treaty entered into force in 1961 and now has fifty-three member states (see www.ats.aq/seleccion.htm). The Scientific Committee for Antarctic Research (SCAR) is part of the International Council for Science (ICSU) and has Science Groups on geosciences and physical sciences, as well as Scientific

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Research Programs that include Antarctic climate change in the twenty-first century and past Antarctic ice sheet dynamics (www.scar.org).

A major survey of climate impact assessments for the Arctic was published by the Arctic Climate Impact Assessment (ACIA 2004). The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) provides an assessment of both polar regions (Larsen and Anisimov 2014). From 1964 to 2003 the American Geophysical Union published seventy-nine volumes in its Antarctic Research Series; these were put online in 2013.

Comprehensive encyclopedia volumes on each polar region have been published by Nuttall (2005) for the Arctic, and by Stonehouse (2002) and Riffenburgh (2007) for the Antarctic.

This book aims to present an up-to-date account of the various environments in the polar and subpolar regions, including the mountain ranges of Central Asia and the Tibetan Plateau – Himalaya–Karakorum, now commonly referred to as the "Third Pole." It also seeks to show how these environments have evolved over the last fifty million years, how they are responding to current global climate changes, and how they are projected to change over the rest of the twenty-first century.

1.2 Setting

The definition of "polar" depends very much on the viewpoint that is adopted. The Arctic and Antarctic circles at 66.3° N and S latitude define the regions where the sun does not set and does not rise for at least one day per year. Each of these polar regions encompasses approximately 4 percent of Earth's surface. Geographically, the Arctic and Antarctic can be defined by their climatic and biotic conditions. For example, Köppen (1923) determined that a July mean temperature below 10 °C approximately defined the limit of tree growth, with tundra (treeless land) found poleward of this limit. There are outliers such as Greenland, which extends to 60° N, and temperatures well above the zonal average value are found at 80° N around Svalbard. Antarctica is well defined by the southern continent, but ice caps cover many of the sub-Antarctic islands and sea ice extends seasonally to 40° S. In the northern hemisphere, sea ice is present to 40° N off East Asia in winter.

The two polar regions differ markedly in their geography. The Arctic is largely an ice-covered ocean ringed by the continents of Eurasia and North America/Greenland (Figure 1.1). The Arctic Ocean is connected to the North Pacific Ocean by the narrow Bering Strait and to the North Atlantic Ocean by the Greenland–Icelandic–Norwegian (GIN) seas. These latter passageways transport warm water

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from the North Atlantic Current into the Arctic between Svalbard and northern Norway, and sea ice and cold polar water out of the Arctic via Fram Strait and the Canadian Arctic archipelago. By contrast, the Antarctic is almost totally covered by a massive ice sheet that rises to more than 4 km elevation, and is encircled by the cold Southern Ocean, which has an extensive seasonal sea ice cover. The Arctic mainland and islands are occupied by polar desert, tundra, glaciers, and ice caps, whereas only approximately 2 percent of Antarctica is ice-free polar desert. There are some seventeen Antarctic islands larger than 1,000 km^2 lying south of the oceanic Antarctic Convergence at about 60° S. This convergence is where cold, northward-flowing Antarctic waters meet the relatively warmer waters of the sub-Antarctic. Most of the island surfaces are ice covered or bare rock with moss and lichens.

The Tibetan Plateau and surrounding mountain ranges of Central Asia are often referred to as the "Third Pole" because this region contains the largest area of ice and frozen ground outside the polar regions proper. It has comparable climatic conditions as a result of its continentality (large annual range of temperature) and its high altitude, implying low average temperatures.

The southern hemisphere high latitudes are characterized by a high degree of zonality (i.e., latitudinal arrangement of their characteristic features). Only the Antarctic Peninsula markedly disrupts this pattern. The Arctic, by comparison, is highly azonal, with cold currents and winter sea ice extending far into mid-latitudes off the eastern coasts of Asia and North America and open water extending far into Arctic latitudes in the vicinity of the Svalbard archipelago (80° N). There are similar environmental contrasts between the eastern and western parts of the northern continents in terms of climates, plant cover, land ice, and permafrost.

1.3 History of Scientific Study

1.3.1 Arctic

The term "Arctic" is derived from the Greek word *arktikos*, which means "near the Great Bear" (constellation). Systematic scientific study of the polar regions began only in the late nineteenth century with the First International Polar Year (IPY, 1882–1883). Barr (1985) provides accounts of twelve national expeditions during this era. Only five years earlier George De Long had led the last US Navy Arctic expedition in the *USS Jeanette* seeking a passage northwest of Bering Strait to the mythical Open Polar Ocean, which was thought to be maintained by warm waters branching northward from the Kuro Shio Current (Sides 2014). During 1878–1879, the *Jeanette*, frozen into the sea ice, drifted for some 1,250 km from

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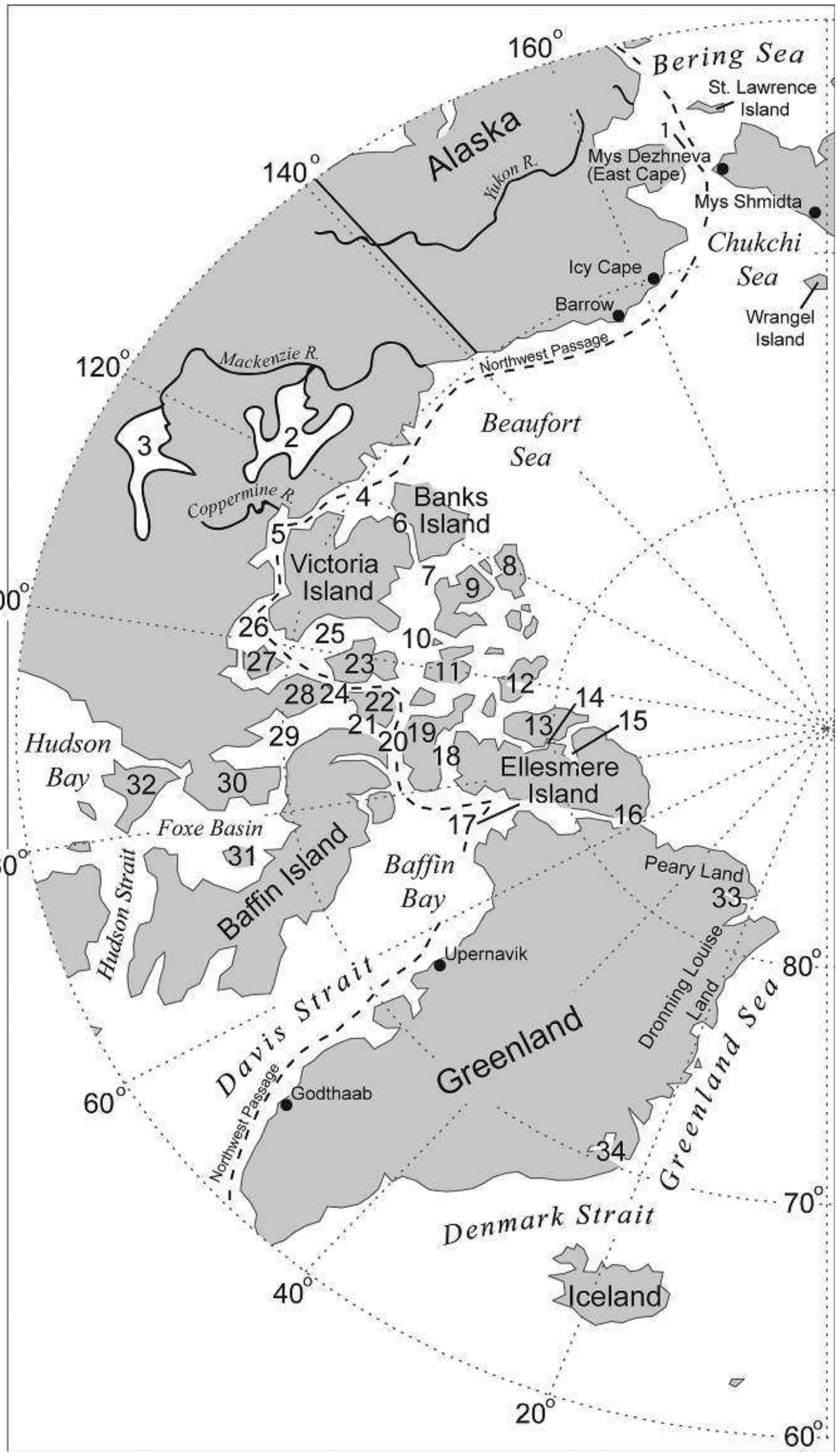

Figure 1.1 Map of the Arctic. 1. Bering Strait. 2. Great Bear Lake. 3. Great Slave Lake. 4. Amundsen 9. Melville Island. 10. Melville Strait. 11. Bathurst Island. 12. Ellef and Admund Ringnes Island. Sound. 18. Jones Sound. 19. Devon Island. 20. Lancaster Sound. 21. Prince Regent's Inlet. 26. Queen Maud Gulf. 27. King William Island. 28. Boothia Peninsula. 29. Gulf of Boothia. Fiord. 34. Scoresby Sound.

Source: Courtesy M. Lavrakas, National Snow and Ice Data Center, University of Colorado, Boulder.

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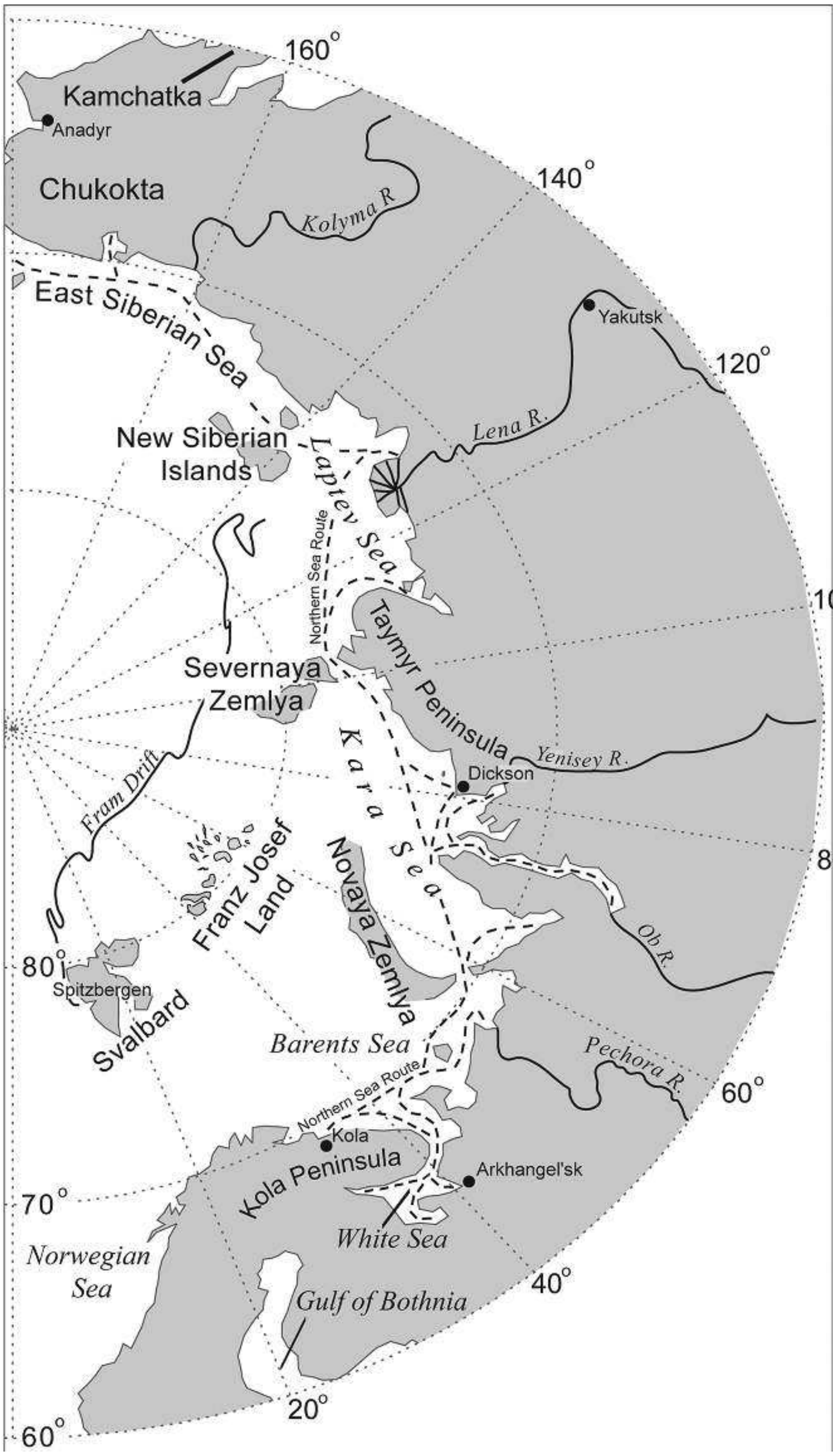

Gulf. 5. Coronation Gulf. 6. Prince of Wales Strait. 7. M'Clure Strait. 8. Prince Patrick Island.
13. Axel Heiberg Island. 14. Eureka Sound. 15. Greeley Fiord. 16. Lady Franklin Bay. 17. Smith
22.Somerset Island. 23. Prince of Wales Island. 24. Bellot Strait. 25. M'Clintock Channel.
30. Melville Peninsula. 31. Prince Charles Island. 32. Southampton Island. 33. Independence

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north of Wrangel Island to northeast of the New Siberian Islands, where it was crushed by the ice and sank. The crew made their way by sledges and boats to the Lena delta, where De Long and twenty-one members of the crew of thirty-three men died from starvation and hypothermia. Wreckage from the *Jeanette* drifted to the east coast of Greenland, and this sighting encouraged the Norwegian explorer Fridtjof Nansen to mount the famous *Fram* expedition in 1893–1896.

The Austrian Carl Weyprecht, who had co-organized the Austro-Hungarian Polar Expedition of 1872–1874, led the planning for the First International Polar Year. The scientific and political context of the First IPY (and the International Geophysical Year, 1957–1958) is detailed by Launius et al. (2010). Eleven nations took part in the First IPY, which involved a ring of twelve stations set up around the Arctic that carried out meteorological, geomagnetic, and auroral observations (Corby 1982; Wood and Overland 2006). However, the stations were too far apart to enable synoptic meteorological studies to be made. The Second IPY in 1932–1933 saw ninety-four Arctic meteorological stations established (Laursen 1982), although World War II prevented much of the data from being published and analyzed. The Second IPY benefited from radio transmissions and airborne reconnaissance and transportation.

A review of climatological research programs undertaken in the Arctic is provided by Barry (2005). The first significant data for the central Arctic were collected by Henrik Mohn during the 1893–1896 drift of the *Fram* (Mohn 1905). Nansen's expedition carried out significant meteorological and oceanographic research (Barry 2016). During 1910–1915, the Russian government organized the Arctic Ocean Hydrographic Expedition (GESLO) to explore the Arctic coast of Siberia (Starokadomskii 1976). This scientific expedition comprised two icebreakers and was commanded by B. A. Vilitsky. The expedition charted the entire Arctic coast of Siberia and in 1913 discovered Severnaya Zemlya, the last significant land discovery on the globe. The Norwegian A. Hoel organized annual expeditions to Svalbard from 1911 to the mid-1920s (Barry 2016). Roald Amundsen organized the *Maud* expedition, 1922–1925, to perform a drift similar to Nansen's in the Arctic. The scientific program, led by H. Sverdrup (1933), is noteworthy because the observations of Finn Malmgren laid the foundation for modern sea ice research. Another major pre-war milestone was the establishment by aircraft of the first of the Soviet Union's Arctic drifting stations, North Pole 1, on an ice floe in 1937. This floe eventually drifted to East Greenland, where the party was picked up by a Soviet icebreaker.

There were two major expeditions to Greenland in the 1930s. The British Arctic Air Route Expedition (Merles 1932) and Alfred Wegener's Greenland Expedition, which operated their stations – Watkins Ice Cap (67.1° N, 41.8° W, 2,440 m) and

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Eismitte (70.9° N, 40.7° W, 3,000 m) – during 1930–1931, yielded the first detailed information on the ice sheet climate (Loewe 1936; Putnins 1969).

The Soviet North Pole (NP) drifting station program resumed in 1950 and continued until July 1991, with stations NP-2 to NP-31 (Romanov et al. 2000). Most of these stations were established on multiyear ice floes. The program was resumed by the Russian Federation in 2003 with NP-32, and continues to operate, with NP-2015 being established in 2015.

The United States had two stations on "ice islands" that had broken away from the Ward Hunt Ice Shelf (Hattersley-Smith et al. 1952; Sater 1968). They were T-3 (originally called Fletcher's ice island), established in 1952, and the Arctic Research Laboratory Ice Station (ARLIS) II, established in 1961; other stations were set up on multiyear sea ice. Sporadic work on T-3 lasted until 1974. ARLIS II had a more extensive and successful program, lasting from its occupation in 1961 in the southern Beaufort Sea until its evacuation in Denmark Strait in 1965. Many of the synoptic weather observations were reported by radio to the Global Telecommunications System (GTS) and so incorporated into operational weather maps. The presence of even two reporting stations from the central Arctic proved invaluable in detecting large-scale weather systems within the Arctic Basin. Meteorological data from the NP and US drifting stations, and other Arctic climate data for the period 1951–1990 have been assembled on digital media (Arctic Climatology Project 2000; National Snow and Ice Data Center 2000).

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 (Barry 2016).

The US Air Force began weather reconnaissance flights from Alaska to the North Pole in the 1940s (Anonymous 1950), which in turn led to the compilation of Arctic cloud statistics by Huschke (1969). In 1998, the First International Satellite Cloud Climatology Project (ISCCP) Regional Experiment (FIRE) Arctic Clouds Experiment was carried out in the Arctic (Curry 2001). Data on Arctic clouds remain uncertain in several respects – the seasonal cycle, thickness, and phase.

Following World War II, it was decided to mount an International Geophysical Year (IGY), lasting from July 1957 to December 1958. While the emphasis was on Antarctic observations (discussed later in this chapter), some specific programs were carried out in the Arctic. McGill University operated the first station in the interior of the Canadian Arctic archipelago at Lake Hazen, Ellesmere Island (Jackson 1959); the permanent weather stations in the Canadian Arctic archipelago, established during 1947–1950, were all at coastal sites. Barry and

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Jackson (1969) published summer data for Tanquary Fiord, Ellesmere Island, for 1963–1967, while Atkinson et al. (2000) assembled climate data for the High Arctic from archives of the Canadian Polar Continental Shelf Project.

Ice Station Alpha in the Arctic Ocean was the first US drifting station with a large, multidisciplinary research program. Russian scientific expeditions were mounted to study the glacial meteorology of the ice caps of Franz Josef Land (Krenke 1961).

During 1972–1976, a US–Canadian–Japanese program – the Arctic Ice Dynamics Joint Experiment (AIDJEX) – was carried out in the Beaufort Sea. Apart from advances in modeling sea ice dynamics, an important outcome of this program was the improved understanding of the energy balance over sea ice. Data from the main experiment in summer 1975 are archived at the National Snow and Ice Data Center (http://nsidc.org/noaa/aidjex). A Marginal Ice Zone Experiment (MIZEX) was carried out in the Bering Sea (MIZEX-West) and the Greenland Sea (MIZEX-East) by the US Office of Naval Research in the 1980s (MIZEX '87 Group 1989). The Labrador Ice Margin Experiment was conducted in the Labrador Sea in 1987 (McNutt et al. 1988). These efforts were followed by the Coordinated Eastern Arctic Research Experiment, 1988–1989, in the northern Norwegian and Greenland seas. The data are archived at http://nsidc.org/data/docs/daac/nsidc0020_cearex.gd.html.

Drifting buoy technology for the Arctic was developed during AIDJEX, which led to new information on surface pressure, air temperature, and ice drift in the central Arctic Ocean. Beginning in 1979, the Arctic Buoy Program was initiated by the University of Washington. In 1991, it became the International Arctic Buoy Program (IABP), which now involves eight nations. Initially, approximately twenty buoys were deployed, mainly from airdrops, but in the 1990s the number rose to more than thirty operating at any one time. Data from these buoys are relayed via the Argos satellite system to the GTS. The quality of Arctic surface pressure analyses greatly improved as a result.

Greenland has been the site of numerous ice core drilling projects since the first at Camp Century in northwest Greenland led by W. Dansgaard in 1969. Data on Greenland Summit ice cores obtained in the 1970s were reported by Hammer et al. (1976). The deep cores of the European Greenland Ice Core Project (GRIP), 1989–1995, and the Greenland Ice Sheet Project (GISP2), 1988–1993, were both extracted from the central dome and spanned approximately 100 kiloyears (ka). The North Greenland Eemian Ice Drilling Project (NEEM) was conducted in 2009–2013 in northwest Greenland with the aim of collecting Eemian-age (115–125 ka) ice. A Greenland Climate network of eighteen automatic weather stations was established around the ice sheet in 1994 as part of the National Aeronautics and Space Administration's (NASA's) Program for Arctic Regional

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Climate Assessment (PARCA) that aimed to improve knowledge of the ice sheet's mass balance (Thomas et al. 2001).

The International Biological Program (IBP) included a Tundra Biome component in the 1970s. Each site carried out detailed climatological measurements, including energy budget studies. There were comparative field measurement programs in 1972 at Barrow, Alaska; Truelove Lowland, Devon Island; and Abisko, Sweden (Barry et al. 1981). In the 1990s, the US National Science Foundation funded the Land–Atmosphere–Ice Interactions (LAII) project in the Arctic (Kane and Reeburgh 1998; LAII Science Steering Committee 1997).

The *USS Nautilus* made the first underwater traverse of the Arctic Ocean in August 1957; this feat was repeated by the *USS Queenfish* in August 1970. The sonar data of ice draft were analyzed by McLaren (1989), skipper of the *Queenfish*, for his doctoral dissertation (see Chapter 7). United States and British submarines performed numerous studies of Arctic sea ice draft (Wadhams 1997; Yu et al. 2004).

Surface vessels began sailing to the North Pole in 1977, when the Soviet nuclear icebreaker *NS Arktika* completed the first passage. Subsequently, many nations deployed icebreakers in both polar oceans, including Russian icebreakers, *Polarstern* (Germany), *Oden* (Sweden), *Aurora Australis* (Australia) and *Amundsen and Des Grosseiller* (Canada). The United States currently has only one heavy-duty icebreaker, the fifty-year old *Polar Star,* and a research icebreaker, the *Healy*.

Through the Arctic Climatology Project (2000) of the Russia–US Environmental Working Group, comprehensive atlases of Arctic oceanography, sea ice, and meteorology/climate during the second half of the twentieth century were prepared. Other projects with Arctic components include those of the World Climate Research Program (WCRP): the Global Energy and Water Experiment (GEWEX) projects for the Mackenzie GEWEX Study (MAGS) during 1992–1994 and the GEWEX Asian Monsoon Experiment (GAME) (see www.gewex.com). MAGS involved large-scale hydrological, atmospheric, and land–atmosphere studies within the Mackenzie Basin to improve understanding of cold-region, high-latitude hydrological and meteorological processes and their roles in global climate. GAME began in 1998 with hydroclimatological measurements along the Lena River in Yakutia, related to the Asian winter monsoon.

The Study of Environmental Arctic Change (SEARCH) was launched by the Arctic Research Consortium of the United States (ARCUS) in 2001 following workshops in 1997 and 1999 (SEARCH Science Steering Committee 2001). Currently it involves three Action Teams on sea ice loss, permafrost degradation, and land ice loss and sea level impacts.

A list of polar institutes may be found in Appendix A.

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1.3.2 Antarctic

During the nineteenth century, numerous discoveries were made by expeditions in the Southern Ocean: Antarctic islands, the Antarctic Peninsula, and coastal ice shelves. However, the first overwintering expeditions were the Belgian one led by A. de Gerlache, whose vessel the *Belgica* was beset in the Bellingshausen Sea in 1897–1899, and the British Southern Cross Expedition of C. Borchgrevink, 1898–1900, which overwintered at Cape Adare on the continent and whose explorers reached 78.8° S. In 1904, Scottish explorer W. S. Bruce established a permanent weather station at 60° S at Orcadas in the South Orkney Islands that was later transferred to Argentina.

The early twentieth century saw numerous expeditions vying to reach the South Pole, a goal that was achieved by R. Amundsen in December 1911 and by R. F. Scott in January 1912. Scientific work in the Southern Ocean by the *Guass* during 1901–1903 was extensively reported by von Drygalski and Raraty (1991). In 1912, Australian D. Mawson established a base at Cape Denison, where an annual *mean* wind speed of 20 m s^{-1} was recorded during 1912–1913, making it the windiest place on Earth. Mawson was the first person to reach the South Magnetic Pole. Scientific expeditions to Antarctica essentially began with Richard Byrd's expedition of 1928–1930, when Little America was established on the Ross Ice Shelf and Byrd flew to the South Pole and back. The British–Australian–New Zealand Research Expedition (BANZARE) of 1929–1931 mapped parts of the coastline. However, despite the various efforts aimed at ground and satellite mapping, a complete coastline of Antarctica was not available until 2004, when Liu and Jezek (2004) produced one from SAR imagery.

In the 1940s, the number of Antarctic expeditions increased greatly with many nations taking part. The listing found at https://en.wikipedia.org/wiki/List_of_Antarctic_expeditions#20th_century includes these expeditions.

In 1946, Rear Admiral Richard Byrd organized Operation Highjump, a US Navy expedition that established Little America IV during August 1946 through February 1947. Also, soon after World War II (1949–1952), a Norwegian–British–Swedish expedition was conducted in Dronning Maud Land. It was the first in Antarctica involving an international team of scientists (Robin 1953). A base camp was established at a location named Maudheim (71.1° S, 10.9° W) on a floating ice shelf some 3 km from an inlet. The program addressed geology, glaciology, and meteorology, as well as photo-reconnaissance.

In 1954, the Australian Antarctic Division established Mawson station, located at 67.6° S, 62.5° E; it is the oldest continuously manned base in Antarctica. Most bases on the continent were established immediately prior to, or during, the International Geophysical Year (IGY), 1957–1958, which focused on Antarctica.

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