1. Introduction

The development of polar meteorology has faced unique challenges, including the remoteness and the harsh environments of the Arctic and Antarctic. Whereas the 1800s and early 1900s provided data from expeditions and only a few subarctic stations, the past 100 years have seen an acceleration of observations and understanding of polar meteorology. In addition to the establishment of new observing stations, technology has benefited polar meteorology through advances in instrumentation, especially autonomously operated instruments. Moreover, spatial coverage from satellites and computer models revolutionized polar meteorology, which has emerged over the past half century as a widely recognized subdiscipline of atmospheric and climate science. In this review, we
summarize the evolution of polar meteorology in both hemispheres, beginning with measurements made during early expeditions and concluding with the recent decades in which polar meteorology has been central to global challenges such as the Antarctic ozone hole, weather prediction, and climate change.

2. Review of the pre-1919 period (before the establishment of the American Meteorological Society)

The development of polar meteorology in the nineteenth century is inextricably linked to the engines of commerce, territorial expansion, and geographic exploration. From an American perspective, these begin with the U.S. South Seas Exploring Expedition (also known as the Wilkes Expedition, or simply the U.S. Ex. Ex.) during 1838–42 (Wilkes 1845a,b), followed by the lesser-known U.S. North Pacific Exploring and Surveying Expedition (Ringgold–Rodgers Expedition) of 1853–56 (Ringgold and Rodgers 1950; U.S. National Archives 1964), both U.S. Navy expeditions. The U.S. Navy, often with private support, contributed to the search for the missing British expedition of Sir John Franklin in the Arctic islands north of Canada, and to a number of other early explorations along the west coast of Greenland. These efforts added to early knowledge of Arctic meteorology, mainly by providing observations (e.g., Kane 1854; Kane and Schot 1859; Tyson and Howgate 1879; Bessels 1876) for comparison with modern observational data and also descriptions of the atmospheric (as well as ice and ocean) phenomena they encountered. Steep inversions and associated mirages, ice fog, sea ice ridges and leads, and floating ice islands are examples. The first documented measurements of surface-based inversions were actually made by measuring temperatures from the “crow’s nest” at 32 m above sea level on Nansen’s Fram expedition (Palo et al. 2017). The Army Signal Service, the Coast Survey, and the Smithsonian Institution frequently supported observers, supplied meteorological instruments, and provided expert data reduction and publishing assistance to these endeavors (e.g., Abbe 1893).

The Wilkes Expedition reached Antarctica, but there were no follow-up scientific expeditions to this region organized in the United States until the first of the Byrd expeditions in 1928 (Riffenburgh 2006). In the Arctic, however, the development of the whaling industry in the Chukchi and Beaufort Seas beginning in 1848, the purchase of Alaska from Russia in 1867, and the rise of collaborative scientific exploration of the polar regions as demonstrated by the landmark first International Polar Year (IPY; 1881–84), provided steady impetus for exploration and research in the far north.

The ill-fated 1879 expedition of the USS Jeannette, which set out to reach the North Pole by following a hypothetical “thermometric gateway” through Bering Strait to an open polar sea (Bent 1872; Hayes 1867), was perhaps the last to be motivated in large part by speculative geographical notions about the Arctic, including the possibility of an ice-free polar ocean. Today the Jeannette expedition, or more directly the part of its wreck that turned up years later in Greenland, is known as an inspiration for Fridtjof Nansen’s attempt to drift with the sea ice across the North Pole in the Fram (Nansen 1898).

While expeditions like those carried out with the Jeannette and the Fram certainly pressed the frontier of discovery—often at a high cost—and produced extremely valuable results, the underlying story of scientific progress is perhaps best revealed in the sustained, even routine, work to measure, describe, and map the lands and oceans, their resources, and the weather and climate. Innovation was a key factor from the beginning, as new tools for observing the deep sea and the upper atmosphere were constantly being developed, along with more capable ships (and later aircraft) for operation in harsh polar conditions. The value to science of the vast archive of data that was diligently collected by hundreds of people over these years is still being realized.

a. Early investigations of weather and ice

The earliest sustained and systematic investigations of the weather, climate, and oceanography of the Arctic by the United States came with the Alaska Purchase (https://www.loc.gov/rr/program/bib/ourdocs/Alaska.html). The U.S. Coast Survey and the Revenue Cutter Service (predecessor of the U.S. Coast Guard) began with an initial reconnaissance in 1867 with a view toward collecting information necessary for the production of navigational charts and for the Coast Pilot of Alaska (U.S. Coast Survey 1869). Starting in 1880 the Revenue Cutter Service/Coast Guard made annual summer cruises to the northern Bering and Chukchi Seas, and in the process collected a nearly unbroken series of marine-meteorological and sea ice observations that extends to the present day (Fig. 21-1). The U.S. Navy’s Bureau of Navigation also issued Findlay’s (1869) Directory for the Behring’s Sea and Coast of Alaska, a compendium of previously published information about the region, including a review of weather and sea ice conditions in the Arctic recorded by earlier explorers over the previous 100 years, back to Cook and Clerke’s voyages in 1778 and 1779 (Beaglehole 1967).

At the same time, the U.S. Army garrisoned Sitka (New Archangelsk) and a few other former Russian outposts, forming the beginning of the station network in Alaska that would later be developed by the Army Signal Service (as the first official weather agency, then known as
the Division of Telegrams and Reports for the Benefit of Commerce and Agriculture). A break in operations occurred in 1886, and all Signal Service work in Alaska was abandoned the following year (Henry 1898). In 1890 the meteorological duties of the Signal Service were transferred to the U.S. Weather Bureau, newly organized as a civilian agency within the U.S. Department of Agriculture. The Weather Bureau began to rebuild the Alaska station network in the late 1890s, with coverage of the coasts of Alaska beginning to fill in by 1920, marked by the reestablishment of a station at Point Barrow (Weather Bureau 1925), initially occupied by the Signal Service for the first IPY in 1881. The development of the station network between 1867 and 1921 is shown in Fig. 21-2. Observations from these stations have become an important part of the record used to understand long-term climate trends—in sights that depend on data “since record-keeping began.”

The first thorough synthesis studies of the meteorology and oceanography of the Pacific Arctic to be produced in the nineteenth century were made by William Dall of the U.S. Coast Survey. These were *Coast Pilot of Alaska, Appendix I: Meteorology* (Dall 1879) and *Report on the Currents and Temperatures of Bering Sea and the Adjacent Waters*, published as Appendix 16 of the Annual Report of the Superintendent of the U.S. Coast and Geodetic Survey (Dall 1882). Both are exhaustive examinations of the data available from earlier times, especially from Russian and British sources dating back to the 1820s, and included new observations collected by the Coast Survey, the Medical Department of the Army, and the Signal Service. Information was also compiled from whaling ship captains and other sources, both published and from original logbooks. Dall assembled and published in *Coast Pilot of Alaska, Appendix I: Meteorology*, a bibliography and list of charts containing more than 4000 titles.

For *Coast Pilot of Alaska: Meteorology* (1879), Dall produced the first set of synoptic-scale charts of mean annual and monthly barometric pressure for the Pacific Arctic region, which provided a reasonable characterization of the Aleutian low. Dall (1882) notes:

The most striking feature presented by the curves of mean annual pressure is a region of depressed barometer, extending from Unimak Pass to Kadiak [Kodiak] Island, over which area, so far as the material permits of generalization, a mean pressure is exerted of only 29.65 inches. This area of depression, which I shall term the Kadiak area, was first
FIG. 21-2. The meteorological station network developed by the U.S. Army Signal Service and the Weather Bureau in Alaska, 1867–1921. The IPY stations at Fort Conger, on Ellesmere Island, and at Fort Chimo (Kuujjuar, Nunavit) are also included. The IPY period is marked by gray lines. The collapse of the Signal Service network in 1887 is apparent.
indicated by Mr. Ferrel (1875), but from incompleteness of data in his possession, it was located somewhat too far north.

Ferrel, at the time with the Coast Survey and subsequently with the Signal Service, outlined the general circulation of the atmosphere based on physical principles (Abbe 1892), including the Coriolis force, well in advance of work by Teisserenc de Bort (1883), Exner (1913), Walker (1923), and others. Figure 21-3 shows the Northern Hemisphere sea level pressure and prevailing winds for January from his analysis. Dall's (1879) regional map for the same month (Fig. 21-4, top panel) shows a more accurate placement of the Aleutian low based on station data that were unavailable to Ferrel, and it provides an example

FIG. 21-3. Ferrel's map in *Meteorological Researches for the Use of the Coast Pilot* (Ferrel 1875) "showing by isobaric lines the mean pressure of the atmosphere for January in millimeters, reduced to the gravity of the parallel of 45°, and by arrows the prevailing directions of the wind, for the Northern Hemisphere." Although the center of action in the Pacific (Aleutian low) is placed too far north, as his colleague Dall noted, the resemblance to modern maps is unmistakable (see, e.g., Hurrell et al. 2003, their Figs. 1 and 2).
FIG. 21-4. (top) Dall’s (1879) regional map of barometric pressure in January showing a split Aleutian low (referred to by Dall as the Kadiak area in general, with the Kamchatka area appearing in the case of split development). Dall recognized that the lack of data from the western Aleutians left this question ambiguous, but today it is seen to be the correct interpretation (e.g., Rodionov et al. 2005). (bottom) Dall’s (1879) map of summer sea surface isotherms and main ocean currents. The average extent of sea ice in summer is also shown and is generally consistent with what is known about ice distribution in the early satellite era and before (e.g., Danske Meteorologiske Institut 1900–1939, 1946–1956; U.S. Hydrographic Office 1946).

of the characteristic west–east split of the Aleutian low. Simultaneous international observations supported this interpretation (e.g., Bulletin of International Meteorological Observations, 1875–87, from the U.S. Army Signal Office). It is now understood that, in winter, the positions of the one versus two centers of the Aleutian low are more important with respect to influence on the Bering Sea environment than its central pressure (e.g., Rodionov et al. 2005).

Dall also documented general outlines of other important features of the regional climate in the areas of meteorology, oceanography, and biology. These include mean annual and monthly air temperature patterns and prevailing winds; ocean currents and sea surface temperatures; the summer distribution of sea ice, winds, and temperatures over boreal and tundra regions (Fig. 21-4, bottom panel); and associated plants and animals. The
oceanography of the Bering Sea is dealt with in more detail in Dall’s subsequent work.

In his Report on the Currents and Temperatures of Bering Sea and the Adjacent Waters, Dall (1882) turned his attention to questions that are still relevant today. What ocean currents pass between the Pacific Ocean into the Bering Sea and thence into the Arctic by way of Bering Strait, or from the Arctic to the south? What are the temperatures of these currents and what effect do they have on the climate, including the distribution of sea ice? As he did in his work on meteorology for the Coast Pilot, Dall scoured the literature (and primary sources) from around the world for data and collected new oceanographic observations as well in his role as assistant-in-charge of the Coast Survey vessels Yukon and Humbolt.

Of particular note is the hydrographic transect of the Bering Strait completed in 1880, likely the first ever obtained (Fig. 21-5). In part, the motivation for the transect was to test the hypothesis that a branch of the warm Kuro Siwo (Kuroshio) passed through Bering Strait, creating a “thermometric gateway” (Bent 1872) that the USS Jeannette would have followed into the Arctic. At the same time, the USRC (Revenue Cutter) Corwin was searching the area around Wrangel Island for signs of the missing ship, last seen the previous September in the ice near Herald Island (Hooper 1881). Unbeknownst to both Dall and Captain Hooper of the Corwin, Commander De Long and the officers of the Jeannette had already exploded two of the prevailing myths that inspired their expedition: there was no such thing as a thermometric gateway, and Wrangel Land was an island and not a large landmass extending across the Arctic (De Long 1884).

Dall’s hydrographic transect, combined with the general survey of the region, yielded a number of particular insights. He found that the current through the Bering Strait is mainly to the north, although reversible by the wind, and that the northward flow is around 1 ft s⁻¹—corresponding to a total flow of 42,289,425 ft³ s⁻¹ (1.2 Sv; 1 Sv = 10⁶ m³ s⁻¹), which corresponds well to modern measurements (e.g., Woodgate et al. 2005). The temperature structure resolved by the Yukon transect in September shows the warm Alaska Coastal Current (ACC) on the
eastern side of the strait and the cold Siberian Coastal Current (Weingartner et al. 1999) on the western side. The presence of sea ice at East Cape and southward seems unusual when compared with recent data, but this was once a common occurrence (e.g., Danske Meteorologiske Institut 1900–1939, 1946–1956). Otherwise the temperature range found by Dall is fairly typical. As to the source of ocean heat present in the region, Dall observed that it was primarily due to local solar radiation rather than to heat transported into the area from the Pacific Ocean as suggested by Bent (1872), a result consistent with the recent findings by Timmermans et al. (2018).

b. The first International Polar Year

The first IPY is notable as the first attempt to extend a wide meteorological network into the Arctic, and to collect simultaneous observations with similar well-calibrated instruments and methods. The first IPY was inspired by the Austro-Hungarian naval officer and scientist Karl Weyprecht (Wood and Overland 2006). The idea for a coordinated international expedition arose from his experience as co-commander of the Austro-Hungarian Polar Expedition of 1872–74. After returning home, he reflected on the value of the thousands of meteorological measurements made during the expedition and noted:

But whatever interest all these observations may possess, they do not possess that scientific value, even supported by a long column of figures, which under other circumstances might have been the case. They only furnish us with a picture of the extreme effects of the forces of Nature in the Arctic regions, but they leave us completely in the dark with respect to their causes (Weyprecht 1875).

To answer that question, he understood that large-scale synchronous data collection was required just as it is now. Weyprecht’s address to a meeting of German naturalists and physicians in 1875 included an enduring assessment: “The entire meteorology of our day rests upon comparison. All the successes of which it can boast—the laws of storms, the theories of winds—are the result of synchronous observations” (Wood and Overland 2006).

The Second International Meteorological Congress, held in Rome in 1879, supported Weyprecht’s conception of a coordinated international polar research effort and established a commission to put it into effect. It was to be, as Abbe (1893) described it, “a simultaneous invasion of the polar regions from all sides.” International participation was invited, and in due course 11 nations established 14 polar research stations: 12 in the Arctic and two in the subantarctic. A number of auxiliary stations were also established, including several in Alaska. Participation by the United States was the responsibility of the Army Signal Service, which established two stations: one at Lady Franklin Bay, Ellesmere Island, and another at Point Barrow, Alaska. Lieutenant Adolphus W. Greely (an early member of the American Meteorological Society) took command of the former expedition, and Lieutenant Patrick Henry Ray commanded the latter.

The results of the first IPY were mixed. Lieutenant Greely’s expedition to Lady Franklin Bay was marred by the loss of all but seven members to deprivation and other causes. Abbe (1893) stated that

the large volumes and results of the two Signal Service international polar stations, as well as the work of the Polaris and Florence expeditions, have contributed not a little to advance our knowledge of the immense country lying to the north of the United States; in fact, the great importance of this work becomes more and more evident as other governments publish their own contributions to this year of cooperative research, and thus enable us to take a comprehensive survey of the atmospheric conditions at that time.

The full publication of the synchronous observations unfortunately took 25 years—it was not completed until 1910, and the data were never analyzed all together as Weyprecht had envisioned.

The meteorological observations of the first IPY were recently transcribed, digitized, and assimilated by modern retrospective analysis (reanalysis) systems (e.g., Compo et al. 2011) and in this sense have finally fulfilled their intended purpose (Wood and Overland 2006). The greater legacy of the first IPY may be that its successful demonstration of international collaboration in polar science carried on to three subsequent iterations: the second IPY of 1932–33, the International Geophysical Year (or third IPY) of 1957–58 (IGY), and the recent IPY of 2007–09.

c. Arctic work of the Weather Bureau

The Alaska Section of the Weather Bureau was officially started in 1898 with the establishment of the Climate and Crop Service and set up of a first-class weather station at Sitka, under the direction of H. L. Ball (Ball 1898). From the end of the Signal Service years until the 1920s, much of the meteorological data for the region was collected by volunteer observers. Aside from the Sitka station, 10 new subsidiary stations were also expected to be operated by volunteers. Henry (1898) also noted, “It is hoped that those to whom instruments have been issued from time to time in previous years will also revive their interests and report to [Ball].” Of 18 volunteer stations listed by Henry that were issued instruments by the Weather Bureau, the most successful were located at Coal Harbor (1889–1911) and Killisnoo (1881–1910). Other efforts were not as successful. Instruments sent to observers in the Northwest Territories (Canada) were seized, and in another case the observer, a missionary, was murdered and the records
were lost. Further development by the Weather Bureau in Alaska in the early twentieth century was spurred by economic development around the gold rush and the establishment of radio and cable communications (Jessup 2007), as well as the increased need for aviation weather services beginning in the 1920s (see Encyclopedia Arctica, 1947–51, https://collections.dartmouth.edu/arctica-beta/).

The Weather Bureau’s further contributions to polar meteorology followed a similar pattern as in previous years, although on very small scale. Between 1893 and 1902 Evelyn Briggs Baldwin, a Weather Bureau observer, took part in three privately supported Arctic adventures: Peary’s North Greenland Expedition in 1893–94, the Second Wellman Expedition to Franz Josef Land in 1898–99, and the Baldwin–Ziegler Arctic Expedition 1900–02. This would be the only polar activity directly related to the Weather Bureau until the 1920s (Encyclopedia Arctica, 1947–51, https://collections.dartmouth.edu/arctica-beta/).

**d. Early Antarctic observations**

While efforts by the United States were focused on the Arctic, important work in the Antarctic was being carried out, especially by other nations. Major meteorological studies in Antarctica commenced with two historical expeditions. The first was in conjunction with Robert F. Scott’s attempt (1910–13) to be the first to reach the South (geographic) Pole. Scott’s Party perished in 1912 on the Ross Ice Shelf after having arrived at the Pole 1 month after Roald Amundsen. The role played by weather in this tragedy remains controversial to this day (Solomon 2001; Fogt et al. 2017). Detailed meteorological observations were collected during 1911–12 at the base location of Cape Evans on Ross Island by George C. Simpson, who later became Director General of the United Kingdom’s Meteorological Office. The reporting and analysis of the observations were delayed by World War I, but appeared in a series of volumes published in India (Simpson 1919, 1921, 1923). Important was that the analysis suggested the origin of “pressure waves” in West Antarctica (Loewe 1967), which became a prime motivation for the establishment of Byrd Station (80°S, 120°W) during the IGY (1957).

Although the observations have not been continuous, the early observations from the Byrd Station location have enabled recent studies to demonstrate large annual temperature increases since the IGY: 2.2°C ± 1.3°C from 1958 to 2010 (Bromwich et al. 2013, 2014).

The second expedition of major meteorological importance was led by Douglas Mawson (the Australasian Antarctic Expedition 1911–14), whose experiences were outlined in a well-known book entitled The Home of the Blizzard (Mawson 1915). In an ironic twist of events, the party came ashore at Cape Denison (67°S, 142.7°E) because there was open water right to the coast, providing easy access for their ship. The meteorological records from 1912–13 revealed the most intense sustained wind regime on Earth (Madigan 1929). The anemometer was recalibrated because of doubts about the extreme conditions experienced, and it now appears that the revision was overly conservative. The uncorrected records reveal an annual average wind speed of 22 m s⁻¹, with over 60% of all hourly wind speed reports falling in the range of 15–30 m s⁻¹ (Parish and Walker 2006). The easy summer access to the coast was caused by the intense katabatic winds blowing the sea ice offshore to create coastal polynyas (Morales Maqueda et al. 2004), and therefore choosing this location turned out to be an unfortunate choice in retrospect. A similar sequence of extreme katabatic wind events was experienced in 1912 by a satellite party of the Scott Antarctic Expedition at Terra Nova Bay (75°S, 165°E) (Bromwich and Kurtz 1982; Bromwich et al. 1993).

**e. A modern renaissance in historical climatology**

The advent of sparse-input reanalysis and reanalysis-forced modeling and reconstruction techniques in recent years has brought new interest in data that were collected in the past but never integrated into modern large-scale datasets [e.g., the International Comprehensive Ocean–Atmosphere Data Set (ICOADS); the International Surface Pressure Databank (ISPD)]. A surprisingly large amount of marine-meteorological and sea ice data collected in the polar regions by the U.S. Navy, Revenue Cutter Service/Coast Guard, and other federal vessels since the 1880s has never been extracted from primary sources and compiled. This deficit, however, is steadily being reduced through collaborative data recovery projects organized under the Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative (Allan et al. 2011) and with support from citizen-scientists participating in Old Weather (http://www.oldweather.org) and similar projects (Freeman et al. 2016).

Of particular note in this regard are the sea ice observations collected in the nineteenth and early twentieth century. Some of these data were used in a few early studies (e.g., Page 1900; Simpson 1890), and from 1900 to 1939 as occasional contributions to the Danish Meteorological Institute’s annual publication State of the Ice in Arctic Seas (Danske Meteorologiske Institut 1900–1939, 1946–1956). This publication remains a primary source of sea ice data for the period in modern datasets, for example, the Hadley Centre’s Sea Ice and Sea Surface Temperature Dataset, version 2 (Titchner and Rayner 2014; Walsh and Chapman 2001), and reanalyses that assimilate ice information [e.g., the European Centre for Medium-Range Weather Forecasts (ECMWF) twentieth century reanalysis (ERA-20C); Poli et al. 2016)]. Reanalyses
require a good characterization of the ice edge to establish appropriate boundary conditions. Moreover, more complete recovery of available ice observations provides an invaluable baseline reference to understand the dramatic loss of sea ice taking place in the Arctic today. Ice observations from whaling ships for the period 1850–1913 have been extracted (Bockstoce and Botkin 1983; Mahoney et al. 2011) and compiled into a sea ice dataset, the Historical Sea Ice Atlas (Walsh et al. 2016). However, the data-rich federal logbooks have only recently been addressed comprehensively by Old Weather citizen-scientists and applied in current research (Schweiger et al. 2018, manuscript submitted to J. Geophys. Res. Oceans). Thus, thousands of sea ice observations from more than a century ago have been gleaned from the logbooks of the Bear, Corwin, Thetis, Northland, and other federal vessels and are being put to new uses that were unimaginable to the officers who originally recorded them (Fig. 21-6).

3. From 1919 to the 1940s

Systematic aircraft-based observations of the Arctic began in 1929, when the Soviet Polar Aircraft Fleet was created (Polyakov et al. 2003). The 1920s also saw reports of a loss of sea ice in the subpolar North Atlantic Ocean, together with early conjectures that reduced sea ice coverage should contribute to changes in cyclone activity (Wiese 1924). In a report that would not have been out of place in the early 2000s, the American consul in Bergen, Norway, provided the following report to the U.S. State Department in October of 1922:

The Arctic seems to be warming up. Reports from fishermen, seal hunters and explorers who sail the seas around Spitsbergen and the eastern Arctic, all point to a radical change in climate conditions, and hitherto unheard-of high temperatures in that part of the earth’s surface . . . The oceanographic observations have, however, been even more interesting. Ice conditions were exceptional. In fact, so little ice has never before been noted. The expedition all but established a record, sailing as far north as 81°29’ in ice-free water. This is the farthest north ever reached with modern oceanographic apparatus (Ifft 1922).

a. Second International Polar Year (1932–33)

Increased interest in the Arctic during this period led to the second IPY held in 1932–33. A major goal was to
investigate how observations in the polar regions could improve the accuracy of weather forecasts and, as a result, the safety of air and sea transport. The second IPY was also motivated in part by the recognition that the electromagnetic processes in the polar regions were affecting telegraph, telephone, and electric power lines. In addition, the availability of new instruments such as the radiosonde as well as aircraft and motorized vehicles for sea and land transport provided new opportunities for measurements, including below the surface. Altogether a total of 94 meteorological stations operated in the Arctic for at least part of the second IPY (Laursen 1959). This period provided the first systematic upper-air measurements in the Arctic by radiosonde and pilot balloons. Plans for a network of Antarctic stations never came to fruition because of the global financial crisis of the 1930s. In the summer of 1932, the Russian icebreaker Sibiryakov completed a transit of the Northern Sea Route from Arkhangelsk to the Far East (Barr 1978). Although World War II prevented the planned archival of all the data at the Danish Meteorological Institute, much of the data eventually found its way into a world data center that was created under an organization that eventually became known as the World Meteorological Organization (Barr and Lüdecke 2010).

b. Russian North Pole stations

A major milestone of the period between the two world wars was the Soviet Union’s establishment of the first North Pole Drifting Station (NP-1). Established on pack ice near the North Pole in May of 1937, the ice station drifted more than 2800 km before its abandonment 9 months later. This was the first of many such stations (from NP-1 through NP-31) deployed by the Russians prior to the breakup of the Soviet Union. A resumption of deployments in 2003 has included stations from NP-32 through NP-40. These stations, occupied for periods typically ranging from several seasons to several years, provided the first multyear records of atmospheric, oceanic, and sea ice variables from the central Arctic Ocean. In addition to standard surface and upper-air (sounding) meteorological observations at regular intervals each day, the NP stations provided surface radiation (solar, longwave, and spectral albedo) measurements, total ozone and UV measurements, tethered balloon measurements in the lowest 2 km, and atmospheric composition measurements. These data are invaluable in the construction of twentieth-century climatologies for atmospheric variables as well as snow and ice thickness. The NP data have also been widely used in the validation of historical simulations of the central Arctic Ocean by global and regional climate models (as well as atmospheric reanalyses). Much of our early knowledge of the surface energy budget of the central Arctic Ocean was built on surface flux measurements made at NP stations (e.g., Fletcher 1965), as was information on cloud conditions (e.g., Vowinckel and Orvig 1971) and cloud radiative forcing. Even after the first stage of NP observations ended in the early 1990s, the NP measurements formed the basis for studies of surface–atmosphere interactions in the Arctic Ocean. For example, NP data showed that cloud-radiative forcing is negative for two to three months in the summer, with a strong dependence of the surface radiative fluxes on cloud fraction (Walsh and Chapman 1998).

Although the second IPY targeted Arctic observations and measurements to improve forecasts, the 1930s also saw the first attempts to document and understand understanding the warming of the Arctic during the 1920s and 1930s. The Ifft (1922) report was among the first to point to this notable climate event. As shown in Fig. 21-7, the early twentieth-century Arctic warming was followed by several decades of cooling, then by the strong warming of recent decades. These variations are apparent in the global as well as the Arctic time series of Fig. 21-7, which illustrates the tendency for variations of global temperature to be amplified in the Arctic (section 5i). While various recent studies have placed the early twentieth-century warming into a framework of climate drivers, several notable observational reports and diagnostic studies addressed the warming while it was ongoing or shortly thereafter. Scherhag (1936) noted that warming of the North Atlantic Subarctic region was accompanied by a retreat of sea ice that was consistent with anomalous wind forcing in the region. A role of the
ocean, including a shoaling of the halocline (eerily similar to discussions of Arctic Ocean change in the past few decades), was proposed by Brooks (1938), Carruthers (1941), and Manley (1944). The Second World War led to a hiatus in the debate about the Arctic’s early twentieth-century warming. However, interest resurfaced in the early twenty-first century (e.g., Bengtsson et al. 2004; Wood and Overland 2010; Yamanouchi 2011). While there is evidence that internal variability played a key role in the early twentieth-century warming (Fyfe et al. 2013), there is still debate about the precise roles of the atmospheric circulation and the ocean. The most recent IPCC assessment (AR5) explicitly states, “There is still considerable discussion of the ultimate causes of the warm temperature anomalies that occurred in the Arctic in the 1920s and 1930s” (Bindoff et al. 2013, p. 907).

4. From the 1940s to the 1970s (the Cold War period)

a. The Second World War

The Second World War led to rapid expansion of meteorological services. In 1939, the focus in Canada was to meet the growing needs of Trans-Canada Airlines. The onset of war brought added needs, especially to support the Royal Canadian Air Force (RCAF), the British Commonwealth Air Training Plan, and the U.S. Army Air Force for ferrying activities over the Atlantic Ocean and to Alaska. In northern Canada, the United States assisted in establishing observing stations and forecast offices (Thomson 1948; Thomas 1971). Starting in 1940, after the German occupation of Denmark, a number of stations were set up along the coast of Greenland; these included weather stations in places like Thule and Scoresbysund. This action resulted from an agreement with the Danish Ambassador of Denmark for the United States to defend Danish colonies in Greenland. In 1941, when Germany attacked the Soviet Union, the Barents Sea gained great strategic importance, leading to a series of efforts by Germany, the United Kingdom, and Norway to gain control of Svalbard, critically situated to provide data for forecasting weather in central Europe and for attacking Atlantic convoys headed for Murmansk, Russia. In this “war for weather,” the Germans established several secret stations in Svalbard as well as in northeastern Greenland and Franz Josef Land (https://www.spitsbergen-svalbard.com/).

b. Early work on Greenland

From September 1949 to August 1951, the meteorologists of the French Polar Expeditions under the direction of Paul-Emile Victor carried out soundings of wind and temperature on Greenland at Station Centrale (70.9°N, 40.6°W, 2965 m above sea level) (e.g., Bedel 1954). The station, near the location of Alfred Wegener’s “Eismitte” (1930–31), was close to, but downslope of, the crest of the ice sheet. Analysis of profiles collected under strong temperature inversion conditions allowed Schwerdtfeger (1972) to infer that the sloped-inversion pressure gradient force arising from the presence of cold air over sloping terrain, which was developed to explain the behavior of the wind field in the high interior of Antarctica, also applied to interior Greenland, indicating that the governing dynamics were the same.

c. Early work on Antarctica

Following the historical Antarctic expeditions in the early 1900s, meteorological studies entered a period with slow progress. Richard E. Byrd led three expeditions to Little America on the eastern edge of the Ross Ice Shelf, starting with the base location to stage the first aircraft flight over the South Pole in 1929. All of these featured extensive meteorological programs that included upper-air observations. Perhaps the most important advance came in 1946 before the U.S. Navy was demobilized after World War II. The 1946–47 U.S. Navy Antarctic Expedition, designated as Operation Highjump (Byrd 1947), was conceived to map almost the entire periphery of the Antarctic continent for the first time. Led by Rear Admiral Byrd, it involved many navy ships and aircraft. This information and the associated photographs helped to set the stage for establishing the network of Antarctic coastal stations for the 18-month (1957–58) IGY, which marked the start of sustained instrumental observations from Antarctica and thus the beginning of many climatic records from this remote continent.

d. Glacial anticyclones

While the need for climate and weather information over the North Atlantic and Alaska remained critical throughout the war, the climate and weather of the central Arctic remained understudied, and data were sparse. A persistent view was of an Arctic Ocean dominated by a largely permanent anticyclonic cell. First put forth by von Helmholtz (1888), the idea was elaborated on by Hobbs (1910, 1926), in his “glacial anticyclone” theory and subsequently gained traction. Jones (1987) notes that charts from the U.S. Historical Weather Map Series, prepared during the Second World War, contained considerable positive pressure biases over the Arctic Ocean up to 1930 and lesser errors up to 1939. It seems that these maps were compiled by relatively untrained analysts extrapolating pressures into the data-poor central Arctic with the preconceived notion of a high pressure cell.
Hobbs maintained his “Greenland glacial anticyclone” theory (Hobbs 1945), involving a persistent high pressure cell over the Greenland ice sheet with strong influences on weather in midlatitudes. Although other investigations found little support for the idea (Loewe 1936; Dorsey 1945; Matthes 1946; Matthes and Belmont 1950), the thinking of anticyclones as dominant features of the central Arctic Ocean persisted (e.g., Pettersen 1950; Rae 1951). Pettersen’s (1950) maps depict most of the Arctic Ocean, in both summer and winter, as a “quiet zone of minimum cyclonic activity.” Such views may have been influenced by Otto Sverdrup’s observations during the Maud expedition (1918–25) of the frequent passage of cyclones along the fringes of the Arctic Ocean.

**e. The growing data network**

With the deployment of a series of the Soviet NP drifting stations on the Arctic sea ice, U.S. drifting stations, the Ptarmigan series of aircraft overflights, the establishment of weather stations in the Canadian Arctic, and studies prompted by the IGY in 1957, the observing network started to improve. A key need was better coverage over the Arctic Ocean. The Soviet NP-2 station, led by Mikhail Mikhailovich Somov (Hero of the Soviet Union and recipient of three Orders of Lenin), was deployed in April of 1950, and NP-3 assumed duties in 1954. Starting in 1954, from one to three NP stations began operating simultaneously each year, collecting meteorological data of all types including atmospheric soundings from radiosondes. The United States maintained a number of drifting stations, notably T-3 (also called Fletcher’s Ice Island, named after Colonel Joseph O. Fletcher who discovered it). Starting in 1952, T-3 was used as a scientific drift station and included huts, a power plant, and a runway for wheeled aircraft. T-3 was a tabular iceberg that presumably broke off from the small ice shelves along the northern coast of Ellesmere Island. The NP Stations were located variously on ice islands (tabular icebergs) and thick floes of sea ice. Ptarmigan was a series of aircraft reconnaissance missions conducted by the U.S. Air Force over the period from 1950 to 1961. The missions included collecting soundings in the lower troposphere over the Arctic Ocean from dropsondes that descended by parachute (Kahl et al. 1992).

In terms of land-based stations, Eureka, on Ellesmere Island, then part of the Northwest Territories, Canada, was established in April of 1947. Weather station Alert, on the northern end of Ellesmere Island, was established in 1950, and a military station was set up in 1958. The station is named after the HMS Alert, which wintered near the site of the station in 1875–76. The community at Resolute Bay, on Cornwallis Island, was created in 1953 as part of the “high Arctic relocation efforts.” This was an effort by Canada to assert sovereignty in the high Arctic because of the region’s perceived strategic importance. As part of this effort, the Canadian Government forcibly relocated Inuit from northern Quebec to Resolute (and to Grise Fiord). By 1947, Canada and the United States had already built a weather station at Resolute, as well as an airstrip. This was followed in 1949 by the establishments of a Royal Canadian Air Force base.

Another major driver of the improved observational network in Canada was the establishment during the 1950s of the Distant Early Warning (DEW) Line (Fig. 21-8). The DEW Line was a system of radar stations installed in a line across Arctic Canada (some at existing villages, such as at Cambridge Bay in 1955), intended to provide early warning of a Soviet bomber attack. Additional stations were built along the northern coastline and Aleutian Islands of Alaska as well as in Greenland, Iceland, and the Faroe Islands.

**f. Evolving thought**

Following World War II, two major Canadian research groups emerged at McGill University: a radar meteorology group led by J. Stewart Marshall and R. H. Douglas in the Department of Physics and an Arctic meteorology group within the Department of Geography led by F. K. Hare. The two groups merged in 1959 to form the Department of Meteorology. McGill became a dominant force in studies of Arctic meteorology and climate during this period. By 1958 (before the merger) the McGill Arctic meteorology research group had already published a number of key reports on Arctic meteorology that took advantage of the growing observational network (e.g., Wilson 1958; Hare and Orvig 1958).

However, it is noteworthy that in the Soviet Union a mature view of the circulation over the central Arctic Ocean had emerged as early as 1945. In a remarkable accomplishment, especially given the very trying wartime conditions, Dzerdzevskii (1945) correctly concluded that cyclone activity was common in the central Arctic Ocean, especially during summer. His study took advantage of data from the Russian drifting icebreaker Sedov, the drifting ice island NP-1, and other high Arctic stations (Jones 1987).

Western scientists may have been unaware of this work; indeed, even in 1958, the idea of a quiescent Arctic Ocean persisted in some circles. For example, the quiet central zone [of the Arctic Ocean] in summer coincides fairly closely with the permanent pack ice of the Arctic Sea. Although a few frontal cyclones appear to cross it, the prevailing state is one of monotonously slack and ill-defined circulation, appropriate enough to what is
certainly the world’s largest quasi-homogeneous surface. Only along the flanks does cyclonic cloud and rainfall become at all common (Hare and Orvig 1958, p. 69).

It is clear, however, that by the late 1950s there was an epiphany. A series of studies emerged in rapid-fire succession that form a framework for our modern view of the Arctic atmospheric circulation. As noted by the pioneering meteorologist Jerome Namias,

the present generation of meteorologists is especially fortunate in being able to realize earlier hopes of obtaining a reasonably accurate synoptic picture of the three-dimensional structure of the atmosphere over the entire polar area. These data have brought to light many phenomena of circulation and weather hardly suspected in former years and thereby have been vital in the development of scientific long-range prediction (Namias 1958, p. 46).

Although long-term prediction (a topic of great interest to Namias) has remained an elusive goal, the new data certainly enabled a much better definition of the structure of the circumpolar vortex and features of the surface circulation. It quickly became clear that while anticyclones are common and often persistent features of the Arctic circulation, especially in winter and over land areas, cyclones are also frequent and, depending on the season, may be found anywhere in the Arctic (Keegan 1958; Reed and Kunkel 1960). As a sufficient number of soundings began to reach the 25-hPa level, it became possible to investigate stratospheric dynamics, and the McGill University group played a leading role (e.g., Hare 1960a,b, 1961) as did the Institute of Meteorology at the Free University of Berlin under Richard Scherhag (Scherhag 1960).

Interest grew about the nature of Arctic air masses and Arctic fronts. Any synoptic analysis will reveal high-latitude weather fronts and associated jet streams, but can an Arctic frontal zone, separate from the polar frontal zone, be identified? Some early studies that were based on prevailing conceptual views (e.g., Palmén 1951; Palmén and Newton 1969) did not include a separate high-latitude Arctic frontal zone. Nevertheless, early Canadian analysis schemes (Anderson et al. 1955; Penner 1955) adopted a three-front model, with the northernmost (in any season) representing individual Arctic fronts. The Meteorological Branch of Canada prepared routine synoptic charts showing the location of...
three fronts on the 850-, 700-, and 500-hPa levels. Using these data, Barry (1967) examined the location of the Arctic frontal zone over North America for January, April, July, and October. Shapiro et al. (1987) more recently presented clear evidence in winter of Arctic jet streams with tropopause folds between the lower Arctic troposphere to the north and the higher Arctic troposphere to the south. These fields are associated with what are now known as tropopause polar vortices (Cavallo and Hakim 2009, 2010, 2012).

A prominent climatological feature of the Arctic summer is the thermal contrast between the Arctic Ocean and the surrounding land areas. There has long been interest in the concept of a summer Arctic frontal zone, separate from frontal activity in midlatitudes. Dzerdzevskii (1945) was the first to present evidence for its existence. Reed and Kunkel (1960) subsequently looked at the issue in more detail. They noted the existence, in summer only, of a band of high frontal frequencies extending along the northern shores of Siberia and Alaska and southeastward across Canada, and stated that it is “abundantly clear that the polar front remains separate from, and well to the south of, the Arctic frontal zone.” Bryson (1966) demonstrated that the modal position of the summer Arctic frontal zone over North America coincided closely with Reed and Kunkel’s (1960) analysis as well as the position of the tree line. This led to a recurring notion of a vegetation link. Bryson (1966) proposed that the summer frontal position might be important in determining the distribution of forest versus tundra, but other investigators (Hare 1968; Hare and Ritchie 1972) instead argued that the tundra–forest boundary actually helps to control the position of the frontal zone in summer because of contrasts in albedo, evaporation, and aerodynamic roughness. However, it has now been clearly established that a primary control on the summer Arctic frontal zone is differential heating between the land and ocean (Serreze et al. 2001; Crawford and Serreze 2015), an idea first advanced as early as 1945 by Dzerdzevskii (1945).

Arctic frontal activity, in particular the summer Arctic frontal zone, remains an active research area. Using an analog approach, Day and Hodges (2018) argue that, because of increasing land–ocean temperature contrasts, the summer Arctic frontal zone will sharpen, and that Arctic cyclones are likely to become more frequent and intense as the Arctic continues to warm. However, work by Crawford and Serreze (2016) show the summer Arctic frontal zone is not in itself a region of cyclogenesis, but rather acts to intensify cyclones that pass through it. Based on coupled climate model simulations, Crawford and Serreze (2017) argue that the frontal zone will remain a significant cyclone intensifier in the future, but that changes in frontal strength will be largely restricted to June, when earlier snowmelt sharpens land–ocean temperature contrasts.

### g. NWP and climate models

By the 1940s, through the work of Bjerknes, Rossby, and others, the physical mechanisms controlling weather processes were fairly well understood, enabling some skill in forecasting, which was critical to the wartime effort. The widely studied “D-day” weather forecasts are a prime example of the importance of meteorology to the wartime effort. However, successful numerical prediction had to await the advent of digital computers. The first successful effort in the United States was in 1950, when a team led by Jule Charney and John von Neumann used the Electronic Numerical Integrator and Computer (ENIAC) to solve the barotropic vorticity equation (https://en.wikipedia.org/wiki/History_of_numerical_weather_prediction). In the United Kingdom, the first numerical model forecast was made in 1952. Operational numerical forecasting in the United States started in 1955, and the United Kingdom followed suit in 1965 (https://www.metoffice.gov.uk/research/modelling-systems/history-of-numerical-weather-prediction). That same year, Norman Phillips completed a 2-layer, hemispheric, quasi-geostrophic computer model that is generally regarded as the first atmospheric general circulation model (AGCM; Phillips 1956).

The year 1955 also marked the birth of the first continued effort under the U.S. Weather Bureau to focus on the development of AGCMs (Smagorinsky 1983). Smagorinsky’s laboratory, initially located in Suitland, Maryland, moved to Washington, D.C., and in 1968 gelled at Princeton University as the Geophysical Fluid Dynamics Laboratory (GFDL). Syukuro Manabe, who joined Smagorinsky’s group in 1959, was a pioneer in model development (Manabe et al. 1965). In a seminal paper published in 1975, it was shown that the temperature response to a doubling of atmospheric carbon dioxide would be magnified in high latitudes as a result of the recession of the snow and sea ice boundaries and the thermal stability of the lower troposphere that limits vertical mixing (Manabe and Wetherald 1975).

By the mid-1960s, climate model development was being led by several groups in addition to GFDL: the University of California, Los Angeles, Department of Meteorology; the Lawrence Livermore Laboratory; and the National Center for Atmospheric Research. By the 1970s, this had expanded to include the RAND corporation, the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Sciences, and the Australian Numerical Meteorological Research Centre. The Arctic was not a primary consideration in
the development of the atmospheric component of models, although credible simulations of sea ice and snow cover were recognized as important to realistic simulations of the albedo–temperature feedbacks.

h. The International Geophysical Year (third International Polar Year)

The IGY, also referred to as the third IPY, took place from July 1957 through December 1958. The IGY was an international effort to coordinate the collection of geophysical data from around the world, including both polar regions. It marked the beginning of a new era of scientific discovery at a time when many innovative technologies were appearing. While Greenland and the upper atmosphere were emphases of Arctic activities, the IGY was a watershed event for the Antarctic. A continentwide distribution of weather stations was established (Fig. 21-9). The IGY marks the start of sustained instrumental observations from Antarctica, and thus the beginning of many climatic records from this remote continent, such as are available from the Met READER database (https://legacy.bas.ac.uk/met/READER/data.html). An international analysis center was established at the Little America V station to produce the first surface and upper-air weather maps for Antarctica and the Southern Ocean (Moreland 1958) that were broadcast once a day. Several of the participants (e.g., H. van Loon and P. D. Astapenko) subsequently made major advances in Antarctic meteorology. The launch of the first satellites during the IGY presaged the start of the comprehensive satellite network that today is a foundation for modern numerical weather prediction in high southern latitudes. A symposium on Antarctic meteorology, held in Melbourne in February 1959, highlighted the coming explosion of meteorological
knowledge stimulated by the IGY. One contribution was the seminal effort of Ball (1960), who formulated a simple set of equations describing the first order behavior of the Antarctic surface winds. Once Antarctic terrain elevations were determined with sufficient accuracy, this system of equations was exploited by Parish and Bromwich (1987) to derive a realistic depiction of the Antarctic katabatic winds and their concentration into a small number of confluence zones such as the one that sustains the “Home of the Blizzard” at Cape Denison.

Prior to the IGY, seven countries claimed parts of Antarctica, with some of the claims overlapping, while eight other countries made no assertions of sovereignty; the latter included the United States, which did not recognize the seven claims but reserved the right to make its own in the future (https://www.state.gov/t/avc/trty/193967.htm). To preserve the continent for cooperative scientific study and peaceful purposes that characterized the IGY, the Antarctic Treaty was signed at the National Academy of Sciences in Washington, D.C., on 1 December 1959 by the 12 nations whose scientists had been active in and around Antarctica during the IGY. The Antarctic Treaty set aside the issue of territorial claims but did not invalidate them. The treaty came into force in 1961. It has now been acceded to by 53 nations and governs international activities south of 60°S. The Scientific Committee on Antarctic Research (SCAR) that was established at the same time provides scientific advice to the Antarctic Treaty System and has, for example, been a leading proponent of the Year of Polar Prediction (Jung et al. 2016) that is under way at the time of writing (section 5k).

Several efforts resulting primarily from the IGY led to notable advances in meteorological knowledge of the Southern Ocean and Antarctica. Harry van Loon, Jan J. Taljaard, and colleagues were leaders in laying out the basic characteristics of the atmospheric circulation, culminating in the Meteorology of the Southern Hemisphere (Newton 1972) monograph. One topic emphasized by van Loon was the elucidation, explanation, and consequences of the semiannual oscillation in atmospheric pressure and wind so prevalent over the circumpolar ocean surrounding Antarctica (e.g., van Loon 1967). Rusin (1964) focused on the radiation and surface energy budget of Antarctica, primarily using observations from Russian stations. Schwerdtfeger (1970) presented a synthesis of Antarctic climate that included detailed surface climatic descriptions for 25 stations, many based on a decade of observations starting from the IGY.

5. 1970s to the present (the modern/satellite era)

In the period since 1970, progress in polar meteorology has greatly accelerated, largely as a result of advances in computer modeling, satellite remote sensing and autonomous instrumentation. Below we highlight these advances, together with several globally significant weather and climate challenges in which these advances have been essential for scientific understanding and, in at least one case (the Antarctic ozone hole), mitigation actions.

a. The Global Weather Experiment: The First GARP Global Experiment

In the early 1970s, the Global Weather Experiment, initially known as the First Global Atmospheric Research Program (GARP) Global Experiment (FGGE), led to major progress in numerical weather prediction. To paraphrase Hollingsworth (1989), the primary goals of FGGE were to describe the global behavior of the atmosphere for one full year, to greatly enhance numerical weather prediction on the global scale, and to design an optimal observing system for this purpose: “In practice, the goal of the observational programme was to describe the dynamics and thermodynamics of the atmosphere with a horizontal resolution of about 500 km for the whole year, and with as good a vertical resolution as possible. The main focus of the experiment was on the tropics, and on the Southern Hemisphere.”

The resources required for the experiment were substantial. For the first time, there was a global constellation of meteorological satellites consisting of “five geostationary spacecraft and two polar orbiters. In addition, extensive deployments of ships, aircraft with dropsonde capability, high-level and low-level supersonic balloons, and drifting buoys in remote ocean areas (especially in the Southern Ocean), along with greatly enhanced rawinsonde and synoptic station coverage, both in space and time, were implemented” (from Hollingsworth 1989 with edits). ECMWF was founded in 1975 to exploit the anticipated advances in global numerical weather prediction up to 10 days ahead following from the Global Weather Experiment.

b. Discovery and understanding of the Antarctic ozone hole

The stratospheric Antarctic ozone hole was discovered in the mid-1980s by scientists from the British Antarctic Survey (Farman et al. 1985) by using total ozone amounts that were derived from ground-based Dobson spectrophotometer measurements at Halley and Argentine Islands stations that started in the IGY. This severe ozone depletion was subsequently confirmed to be an Antarctic-wide phenomenon in the austral spring by instruments on the Nimbus-7 satellite that had been operating since 1978 (Stolarski et al. 1986); until the publication of the Farman et al. paper, overly conservative processing of the Nimbus-7 ozone retrievals had hidden the ozone hole’s presence.
Subsequently, satellite measurements have provided comprehensive mapping of the Antarctic ozone hole and its rate of change. Figure 21-10 shows that ozone depletion was modest in 1979 but extreme in the 2000s. Direct measurements of the stratospheric chemistry started in 1986 with the National Ozone Experiment (NOZE) at McMurdo Station. This led to the explanation that heterogeneous chemical reactions involving anthropogenic chlorofluorocarbons (CFCs) and polar stratospheric clouds release atomic chlorine gas that catalyzes the destruction of ozone (e.g., Solomon et al. 1986; Douglass et al. 2014). In 1987, the international Protocol on Substances that Deplete the Ozone Layer was signed in Montreal to phase out CFC emissions. Direct confirmation that the reductions in CFC emissions have led to the recovery of the Antarctic ozone hole was reported by Strahan and Douglass (2018).

The Antarctic ozone hole has a major impact on the tropospheric circulation by strengthening the circumpolar westerly winds over the Southern Ocean (Thompson and Solomon 2002) and moving them poleward. The varying strength of these circumpolar westerlies, known as the southern annular mode (SAM), represents the extratropical Southern Hemisphere’s dominant mode of large-scale atmospheric variability and has many climatic impacts (e.g., Thompson et al. 2011; Wang and Cai 2013).

c. The International Arctic Buoy Programme

A major milestone for monitoring the weather and sea ice in the Arctic Ocean was the establishment of a network of automatic data buoys to provide synoptic-scale fields of sea level pressure, surface air temperature, and ice motion (Thorndike and Colony 1981). From a recommendation of the National Academies of Sciences, the Arctic Ocean Buoy Program began its deployments of buoys on the sea ice surface in early 1979 in support of the Global Weather Experiment (section 5a). Coordinated by the University of Washington Applied Physics Laboratory’s Polar Science Center, the program in 1991 became known as the International Arctic Buoy Programme (IABP; http://iabp.apl.uw.edu), with funding provided by U.S. agencies and various other nations. As the buoy program approaches four decades of operation, its uses have included the real-time support of operations, ingestion into reanalyses, and diagnostic studies encompassing the time scales of weather, the seasonal cycle, interannual variability, and climate change.

The first buoys were sheltered instruments, deployed on the ice surface to measure atmospheric pressure, air temperature, and position. Interrogated by satellite at frequent (approximately hourly) intervals, the atmospheric measurements have always been available in near–real time for ingestion into models used for weather forecasts or reanalyses. Changes in a buoy’s location over time enable the calculation of ice velocity. With 20–30 buoys operating over the Arctic Ocean during much of the IABP’s first few decades (Fig. 21-11), more-accurate fields of sea level pressure and ice velocity were constructed. Such fields dating back to 1979 at daily intervals.
are available from the Polar Science Center (e.g., Thorndike and Colony 1981).

In the past two decades, measurement capabilities of the buoys have been expanded to include subsurface variables such as ice and ocean temperature and salinity. Some buoys include ice mass balance (IMB) measurements and an ice-tethered profiler (ITP) system. The IMB buoys consist of a series of thermistors spaced 10 cm apart from just above the sea ice down 3–5 m into the ocean and acoustic pingers to measure snow depth on sea ice and ice thickness from below, in addition to the fundamental surface air pressure and temperature to support the IABP. The ITP buoys consist of a small surface capsule that sits atop an ice floe and supports a plastic-jacketed wire rope tether extending through the ice and down into the ocean, ending with a weight (intended to keep the wire vertical). A cylindrical underwater apparatus mounts on the tether and cycles vertically along it, carrying oceanographic sensors through the water column. Water-property data are telemetered from the ITP to shore in near–real time. The IABP now maintains more than 100 buoys of varying sophistication over the Arctic Ocean. Most are placed on sea ice, but some are placed in open water. Buoys have an average life span of 18 months. In the future, IABP hopes to increase the average life span to 3–4 years.

The data collected are used for real-time operations and research. Real-time operations include collecting data for meteorological predictions. IABP buoys have helped to predict the trajectory of storms off the coast of Alaska that otherwise would have been difficult to determine. Data collected by IABP buoys are also important for forecasting sea ice conditions, which are crucial for coastal Alaskans, for those engaged in subsistence fishing, and those who work in the coastal commercial industry. Shipping traffic in the Arctic region has increased in recent years with the retreat of sea ice. A combination of sea level pressure, air temperature, and sea ice motion help forecasters to predict better the movement of Arctic Ocean sea ice.

IABP buoys are also used to validate satellite products and complement the capabilities of satellite remote sensing. The National Weather Service and the National Snow and Ice Data Center use buoy data for weather...
predictions and ice charting. IABP data are also used for atmospheric reanalysis studies. To date, more than 800 scientific papers have been written using data from the IABP. Much of the data collected supports efforts for the World Climate Research Programme and the World Weather Watch.

Contributors to the U.S. section of IABP include the U.S. Coast Guard, the U.S. Department of Energy, NASA, the U.S. Navy, the National Science Foundation (NSF), and researchers from academic institutions such as the Woods Hole Institution, the U.S. Army’s Cold Regions Research and Engineering Laboratory, and the Polar Science Center. Researchers from private and public organizations from the United States as well as France, Norway, China, Canada, Japan, South Korea, India, and Russia contribute to the IABP.

d. Antarctic automatic weather stations

Until 1980, direct surface and upper-air meteorological observations were provided by nearly the same network of staffed locations as established for the IGY (Fig. 21-9). Charles R. Stearns from the University of Wisconsin–Madison led the implementation of the satellite-transmitting automatic weather station (AWS) network (Lazzara et al. 2012). Funded largely by the NSF, the AWS network in Antarctica now consists of about 60 active sites maintained primarily by the University of Wisconsin. The AWS units typically measure pressure, temperature, winds, and atmospheric moisture at 2–3 m above the surface at intervals of a few minutes, but the variables observed continue to expand. The sensors now include acoustic depth gauges to measure changes in the snow surface height. Because the AWS are deployed in remote and challenging locations with at most annual maintenance visits, data outages do occur; therefore, data analysis requires care. The AWS network has expanded to more than 100 locations across Antarctica (Fig. 21-12) through sites provided by many nations, including Australia, France, the United Kingdom, China, Japan, and Italy as well as the United States. Observations from AWS sites are critical input for Antarctic numerical weather prediction, global reanalyses, and innumerable weather and climate studies.

e. Arctic clouds

Arctic clouds and their radiative interactions have emerged as a critical component of the climate research agenda. Clouds have a strong warming influence on the surface during much of the year in the Arctic, and a cooling effect for a short period in the summer. The period of negative cloud radiative forcing ranges from a few weeks in the central Arctic Ocean to several months over the subarctic land areas (Curry et al. 1993; Schweiger and Key 1994; Curry et al. 1996). Much of the early work on the radiative impacts of clouds over the Arctic Ocean was based on the radiation measurements and cloud observations from the Russian drifting ice stations (Marshunova and Mishin 1994; Walsh and Chapman 1998). Cloud radiative properties are strongly dependent not only on their elevation, as in lower latitudes, but also on the phase (liquid vs ice) of the cloud particles (Shupe et al. 2015).

Research on Arctic clouds accelerated during the 1990s and 2000s with several major field programs (see the appendix). The Surface Heat Budget of the Arctic (SHEBA), a yearlong field experiment centered on a ship intentionally frozen into the Arctic pack ice during 1997–98, showed that supercooled liquid water droplets are surprisingly frequent over the Arctic Ocean. Recent estimates have indicated that liquid water is present in 10%–80% of Arctic clouds, depending on the season and location (Shupe et al. 2011; Cesana et al. 2012). SHEBA was followed in the early 2000s by the Department of Energy’s Atmospheric Radiation Measurement/North Slope of Alaska (ARM/NSA) program, which included the deployment of a variety of instrumentation for measuring radiation and clouds on the northern Alaskan coast at Barrow and, more recently, Oliktok Point. The ARM program targeted improvements on model formulations of cloud/radiative processes as one of its key objectives. Over the years since 2000, the ARM program has included a wide variety of manned and remote-controlled airborne measurements (McFarquhar et al. 2011; Schmid et al. 2016), including the Mixed-Phase Arctic Cloud Experiment (M-PACE; Verlinde et al. 2007), during which Arctic cloud particles were sampled extensively. Another notable field study was the Arctic Summer Cloud Ocean Study (ASCOS), which took place in 2008 and utilized the Swedish icebreaker Oden (Tjernstrom et al. 2014). ASCOS targeted the physical and chemical processes responsible for the formation of the low-level clouds that are pervasive over the Arctic Ocean during summer. ASCOS measurements have been used to improve model simulations of late-summer Arctic clouds (e.g., Hines and Bromwich 2017). Another Arctic field campaign, the Indirect and Semi-Direct Aerosol Campaign (ISDAC) focused on the impact of aerosols on Arctic clouds (McFarquhar et al. 2011). From these various field programs, it has become apparent that atmospheric radiation is impacted much more by clouds containing liquid water than by ice-crystal clouds (Shupe and Intrieri 2004). While clouds containing liquid are in near-radiative equilibrium with the surface, thin clouds composed primarily of ice allow considerable surface-emitted longwave radiation to escape to space (Stramler et al. 2011).
Advances in remote sensing have also led to progress in documenting Arctic cloud characteristics and their radiative effects. While surface–cloud contrast limitations inherent in visible and infrared sensors hindered early uses of satellite products in the Arctic, lidar and radar profilers on the CloudSat and Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellites have been used to obtain Arctic cloud climatologies that differ in some ways from earlier depictions. For example, Liu et al. (2012) showed that cloud frequencies derived from radar and lidar profilers on CloudSat and CALIPSO have seasonal maxima and minima in autumn and winter, respectively. Climatologies based on surface observations generally showed maximum frequencies in summer (e.g., Vowinckel and Orvig 1971). The lidar and radar profile results also showed that about 25% of Arctic clouds are multilayered. CloudSat and CALIPSO products have also been used to assess weather prediction models simulations of clouds (Candlish et al. 2013) and radiative fluxes (Zygmuntowska et al. 2012).

Despite the importance of Arctic clouds and their composition, models still have difficulty in producing the correct Arctic cloud types (de Boer et al. 2012) and, for that reason, poorly represent Arctic surface energy fluxes (Tjernstrom et al. 2008; Pithan et al. 2014). For simulations of climate, these deficiencies have serious implications for surface temperatures and cryospheric change (Persson 2012). As noted in section 6, the Arctic surface energy budget and its relation to clouds remain major challenges of polar meteorology and polar climate science. This realization has driven the upcoming Multidisciplinary Drifting Observatory for Studies of Arctic Climate (MOSAiC) program, an international Arctic drift expedition planned for the marginal ice zone in 2019–20 (Shupe et al. 2016; https://www.mosaic-expedition.org/).
Satellite-derived soundings of the atmosphere

Radiation emitted by Earth’s atmospheric gases and by clouds is recorded by polar-orbiting satellites in the infrared and microwave wavelengths. These emissions can be used to infer the temperature and moisture content of the broad atmospheric layers from which they originate using emission weighting functions. Profiles of atmospheric temperature and water vapor amounts from across the globe are provided by spaceborne observations for numerical weather prediction. These profiles are especially valuable in the polar regions, where the network of rawinsonde stations has large gaps over the polar oceans and even over land.

The era of satellite sounding of the atmosphere primarily started with the launch of the TIROS-N spacecraft in 1978 (https://science.nasa.gov/missions/tiros) for the Global Weather Experiment. It included the first TIROS Operational Vertical Sounder (TOVS) that consisted of the High Resolution Infrared Radiation Sounder (HIRS), the Microwave Sounding Unit (MSU), and, on some satellites, the Stratospheric Sounding Unit (SSU). Satellite sounding has advanced tremendously since the 19 channel HIRS era. A recent example is the Infrared Atmospheric Sounder Interferometer–New Generation (IASI-NG) sounder that has 16 920 channels spanning the infrared from 3.62 to 15.50 μm. Designed for temperature and humidity sounding, ozone profiling, and total-column or profiles of greenhouse gases, it is planned for flight on the European MetOp series of polar orbiters starting in the 2021 time frame (https://www.wmo-sat.info/oscar/instruments/view/206).

The fourth International Polar Year (2007–09)

According to Krupnik et al. (2011), the International Polar Year (IPY) of 2007–2008 was sponsored by ICSU and WMO became the largest coordinated research program in the Earth’s polar regions, following in the footsteps of the IGY. An estimated 50,000 researchers, local observers, educators, students, and support personnel from more than 60 nations were involved in the 228 international IPY projects (170 in science, one in data management, and 57 in education and outreach) and related national efforts. The IPY generated intensive research and observations in the Arctic and Antarctic over a two-year period, 1 March 2007–1 March 2009, with many activities continuing beyond that date. All IPY projects included partners from several nations and/or from indigenous communities and polar residents’ organizations.

Although meteorology was the major focus of the first IPY (1882–83), the 2007–09 IPY was far broader in its scientific projects and involved a large range of disciplines spanning geophysics, ecology, human health, social sciences, and the humanities. This increased breadth indicates that modern atmospheric science has become multidisciplinary. In many cases, there was a significant atmospheric component to IPY projects carried out in topic areas such as ice, ocean, land, people, and others (Krupnik et al. 2011, p. 137). Purely atmospheric topics included the International Arctic Systems for Observing the Atmosphere (IASOA) observing network; radiation measurements from Spitzbergen; aerosol measurements in the Arctic and Antarctic; investigations of Antarctic polar stratospheric clouds and associated ozone depletion; initiation of the regional synthesis of the physical components of Arctic climate known as the Arctic System Reanalysis (section 5h); investigations of Arctic weather phenomena and their forecastability as a prelude to the Polar Prediction Project (section 5k); the Cordiasii Project over Antarctica that featured development of more effective assimilation of radiances from hyperspectral infrared and microwave sounders over snow and ice and also featured dropsondes launched remotely from stratospheric superpressure balloons, in part to improve numerical weather prediction and also as a run-up to the Polar Prediction Project; and investigations of air pollutants impacting the Arctic.

Reanalyses and the polar regions

Global reanalyses provide valuable tools for investigating climate variability and change in the data-sparse polar regions, for example, exploring the spatial and temporal variability of Antarctic snow accumulation (Medley et al. 2013). These reanalysis datasets are produced by merging a short-term numerical weather prediction with a wide variety of ground-based, aircraft, and satellite-based observations of the atmosphere while taking into account uncertainties in both the prediction and the observations. However, there are some important issues in using reanalyses to investigate polar climate change. Although the data assimilation system and the forecast model do not change, artificial shifts/trends can arise because of the changing observing system. This sensitivity is heightened in high southern latitudes because of limited direct meteorological observations prior to the Global Weather Experiment in 1979 (e.g., Bromwich and Fogt 2004). For example, the introduction of satellite atmospheric sounding data in late 1978 produced a jump in the Antarctic precipitation minus evapotranspiration \((P - E)\) simulated by the ERA-40 global reanalysis (e.g., van de Berg et al. 2005). Even during the modern satellite era (after 1978), the assimilation of radiances from the Advanced Microwave Sounding Unit (AMSU) in the late 1990s introduced a pronounced jump into the precipitation forecast by the MERRA global reanalysis (e.g., Bromwich et al. 2011a). Global reanalyses are
less problematic in high northern latitudes as a result of extensive surface and upper-air observations collected from the land areas surrounding the Arctic Ocean. As for the Antarctic, the greatest challenges arise for those variables that are not observed but depend on the model physics for their generation—namely, clouds, precipitation, radiative fluxes, and surface energy fluxes (Lindsay et al. 2014).

A regional reanalysis for the “greater” Arctic (poleward of ~40°N) has been produced for 2000–12 to provide a more refined tool to investigate rapid climate change happening in Arctic latitudes. Two versions of the Arctic System Reanalysis (ASR) are available at 30-km (version 1) and 15-km (version 2) grid spacing with a high vertical resolution (e.g., Bromwich et al. 2018), and the latter is being updated to the present. The strengths of this high-resolution regional reanalysis reside in its more accurate reproduction of surface variable behavior (10-m wind, 2-m air temperature, etc.), and in realistically capturing topographically forced winds. The ASR also provides an improved depiction of cyclones relative to coarser global reanalyses, including polar lows (Smirnova and Golubkin 2017), although approximately one-third of the polar lows are not analyzed by the ASR. For such purposes, the effective resolution of the ASR is about 7 times the 15-km resolution (Skamarock 2004).

### 1. Arctic amplification and the recent Arctic warming

Arctic amplification, which refers to the observation that the Arctic warms and cools faster than the rest of the Northern Hemisphere and the global mean, has become a major topic of climate research. Figure 21-7 illustrates this behavior by showing the annual values of the Arctic and global temperatures since 1900. In recent decades the Arctic has warmed at twice the rate of the global and Northern Hemispheric mean temperatures. Arctic amplification, a long-expected Arctic response to climate warming and evident in simulations from even the earliest generation of global climate models (e.g., Manabe and Wetherald 1975), started to clearly emerge toward the end of the twentieth century (Serreze et al. 2009; Screen and Simmonds 2010). One of the major drivers of observed Arctic amplification is sea ice loss; open water areas develop earlier in spring, allowing for more absorption and storage of solar energy in the ocean mixed layer through the summer. As the sun sets in autumn and winter, this stored heat is released upward to the atmosphere. This heat loss mechanism helps to explain why the Arctic amplification signal tends to be stronger in autumn than in summer.

However, it is increasingly recognized that Arctic amplification has other causes in addition to sea ice loss. Alexeev et al. (2005), for example, showed that polar amplification arises in climate models of “aquaplanets” (i.e., systems with no sea ice or snow cover). The complexity of the processes and feedbacks challenges observational assessments (and indeed has motivated special field programs such as SHEBA, described in the appendix, and MOSAiC). For this reason, comparative evaluations of key feedbacks involved in Arctic amplification have relied largely on global climate models (e.g., Taylor et al. 2013; Pithan and Mauritsen 2014). In the latter study, the largest contributions to Arctic amplification were found to arise from 1) the surface albedo (snow and ice) feedback and 2) the different vertical structure of the warming in high and low latitudes (lapse-rate effect). The next largest contribution to Arctic amplification in the climate models is the Planck effect, which arises because the Arctic is colder at the top of the atmosphere than the subtropics and radiates less energy to space. While the water vapor feedback is positive in the Arctic, it actually opposes Arctic amplification in climate models (Pithan and Mauritsen 2014, their Fig. 2). If relative humidity stays nearly constant in climate models, then the Clausius–Clapeyron equation dictates a larger increase of water vapor in the tropics than in the polar regions, thereby countering polar amplification. The net role of clouds in the models was found small, but can be large in a particular season of a particular year. The largest and only substantial negative feedback in the models is ocean heat transport, which decreases as the Arctic warms, thereby reducing the Arctic warming. The different contributions vary among the global climate models, and the range of uncertainty is especially large in the ocean transport feedback. The feedbacks associated with clouds and atmospheric transport also have wide ranges.

Atmospheric transport has also been a key contributor to recent extreme warming events. For example, during January 2016, the Arctic-wide averaged temperature anomaly was 2.0°C above the previous record of 3.0°C (Fig. 21-13a; Overland and Wang 2016; Kim et al. 2017). This event caught the public’s attention with reports of temperatures warming to near the freezing point at the North Pole. The event was caused by advection of heat and moisture into the Arctic on Atlantic and Pacific pathways as shown by contour directions of the 700-hPa geopotential height field for January/February 2016 (Fig. 21-13b). Northward advection of temperature and moisture also results in an increase of downward longwave radiation, further warming the surface and reducing sea ice buildup (Cullather et al. 2016; Binder et al. 2017; Rinke et al. 2017). A similar event occurred in the winter 2017/18 (Overland and Wang 2018). Consistent with the recent Arctic warming and the temperature–albedo feedback, the Arctic has experienced record low sea ice during multiple winters (2015–18), as shown in Fig. 21-14 for 2017. Arctic sea ice has shifted from mostly multiyear thick (>3 m) to
mostly thin (<1 m) sea ice that formed in the previous winter (Meier et al. 2014). Both Arctic temperatures and sea ice conditions are now well beyond previous experience from the twentieth century.

j. Regional modeling of the polar regions

1) THE ANTARCTIC MESOSCALE PREDICTION SYSTEM

The need for optimized numerical weather prediction for Antarctica became apparent in 1999 when Dr. Jerri Nielsen was stranded at Amundsen–Scott South Pole Station with a serious medical condition. The key question was, When would the temperature warm up enough for planes to land safely to evacuate her in the austral spring? No convincing forecast capability existed to provide this information. As a result, the Antarctic Mesoscale Prediction System (AMPS) started in 2000 as a collaboration between the National Center for Atmospheric Research (NCAR) and the Byrd Polar Research Center of The Ohio State University to provide an optimized forecasting capability for the U.S. Antarctic Program (Powers et al. 2012). It featured much higher spatial resolution than existing global models, physical parameterizations optimized for the Antarctic environment, and regional data assimilation. The current configuration of nested grids is shown in Fig. 21-15 with the finest resolution of 0.9 km around Ross Island where the extensive U.S. aircraft operations are focused near McMurdo Station, and an 8-km grid covering all of Antarctica. Every AMPS forecast is archived at NCAR. Exploration of the early parts of the forecast that are most accurate (after 12 h of spinup from a cold start) has led to substantial advances in understanding of Antarctic atmospheric processes, including the surface winds (e.g., Nigro and Cassano 2014), storm-generation mechanisms in the most active cyclogenesis region in the Southern Hemisphere (Bromwich et al. 2011b), Antarctic precipitation (Schlosser et al. 2016), and the climate of West Antarctica (Nicolas and Bromwich 2011).

2) REGIONAL CLIMATE MODELING

During the last two decades, there have been substantial efforts devoted to regional atmospheric modeling of both polar regions. The polar version of the Fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (Polar MM5; e.g., Cassano et al. 2001) and its successor the polar version of the Weather Research and Forecasting (WRF) Model (Polar WRF; e.g., Bromwich et al. 2009) were developed to better characterize the high-latitude environments such as sea ice areas, extensive ice sheets, and tundra regions. These models have been applied to a wide variety of weather and climate problems, such as simulating the climate of the Laurentide Ice Sheet during the last glacial period (Bromwich et al. 2004), Antarctic numerical weather prediction via AMPS [section 5j(1)], the surface winds near Greenland (e.g., DuVivier and Cassano 2013), and conditions causing summer melting of ice shelves in the Amundsen Sea embayment of West Antarctica (Deb et al. 2018). Other major efforts have involved the Regional Atmospheric Climate Model (RACMO; e.g., Noël...
et al. 2015) and the Modèle Atmosphérique Régional (MAR; e.g., Fettweis et al. 2017) and have focused in particular on the mass balance of the Greenland and Antarctic ice sheets and their contribution to sea level rise (e.g., Vernon et al. 2013). The Regional Arctic System Model (RASM; Cassano et al. 2017), is starting to be used to explore atmosphere–ocean–land coupled problems in high northern latitudes (e.g., DuVivier et al. 2016). RASM includes a regional ocean model that can be run at resolutions of several kilometers. Another regional ocean-ice model, the Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS), has been used to simulate the evolution of the Arctic sea ice cover, including an Arctic sea ice volume reanalysis (Schweiger et al. 2011) that is updated in near–real time. The global NCAR Community Earth System Model has been applied with a wide range of bipolar climate change problems, such as the impact of Arctic sea ice losses on the (northern) midlatitude atmospheric circulation (Vavrus et al. 2017) and the global climatic impacts of Arctic sea loss (Tomas et al. 2016).


The Polar Prediction Project (PPP; http://www.polarprediction.net/) is a 10-yr initiative (2013–22) of the World Weather Research Programme of the World Meteorological Organization (Jung et al. 2016). The mission of PPP is to “promote cooperative international research enabling development of improved weather and environmental prediction services for the polar regions (Arctic and Antarctic), on time scales from hours to seasonal.” Its core activity is the Year of Polar Prediction (YOPP) that will take place from mid-2017 to mid-2019. YOPP focuses on improving the polar observing system, facilitating field programs, implementing better representation of key polar processes in coupled and uncoupled

Fig. 21-14. Evolution of Arctic sea ice area in recent years (colored lines) relative to the historical range (gray shading: 1979–2006 average ± 1 std dev). Recent years (2015–18) have had the lowest winter ice areas of the post-1979 period of record. [Source: Nansen Environmental and Remote Sensing Center (http://web.nersc.no/WebData/arctic-roos.org/observation/ssmi1_ice_area.png); after a figure from the Arctic Regional Ocean Observing System (ArcticROOS; https://arctic-roos.org/).]
models, enhancing assimilation of polar observations into models, analyzing the predictability of sea ice on various time scales, evaluating the linkages between the polar regions and midlatitudes, developing forecast verification approaches optimized for the polar regions, and exploring the linkage between the providers and users of polar weather and ice information. YOPP features four special observing periods of enhanced observations and modeling, namely February–March 2018 in the Arctic, July–September 2018 in the Arctic, mid-November 2018–mid-February 2019 in the Antarctic, and February–March 2020 in the Arctic to overlap with MOSAiC drift across the Arctic Ocean (see section 6). YOPP participants include the academic community and operational forecast centers (including ECMWF and NCEP), greatly enhancing the likelihood that YOPP forecast improvements will be implemented to advance regional and global numerical weather prediction for both polar regions.

6. Priorities/opportunities for the next decade

It is apparent from the preceding review that there have been tremendous advances in polar meteorology over the past 100 years. The study of polar weather and climate has benefitted from advances in technology as well as a rapidly increasing cadre of scientists. The recent warming of the Arctic and the diminished coverage of sea ice and snow have brought prominence to the Arctic as a sentinel of global change, and the Antarctic’s ozone hole and its anticipated recovery continue to make the Antarctic a focus of monitoring and research.
Among the priorities that have emerged in polar meteorology and climate research are the linkages between polar and midlatitude weather and climate. Relationships between Arctic warming and extreme weather and climate events in midlatitudes have been suggested (Francis and Vavrus 2012; Cohen et al. 2014), but the robustness of the linkages has been questioned and the mechanisms are unclear (Barnes and Screen 2015; Screen et al. 2018). YOPP (section 5k) is an effort to advance understanding and operational forecasting capabilities in this regard. Systematic assessments of the impacts of polar data on forecasts in both hemispheres can contribute to a firmer understanding of the impacts of the polar regions on midlatitude weather and climate.

Extreme events in the polar regions represent another emerging research topic. While changes in extreme weather events in midlatitudes have been documented, especially increases of heavy precipitation events and high-temperature occurrences, comprehensive assessments of changing extremes in the polar regions are lacking. Of particular interest in this regard are extreme high-temperature events (Fig. 21-7), which are favorable for high-impact rain-on-snow events. Other high-impact events, such as Arctic cyclones and their dynamical precursors, tropopause polar vortices (e.g., Hakim and Canavan 2005; Cavallo and Hakim 2010), are poorly documented and inconsistently simulated by weather and climate models. Moreover, short-term sea ice variability has been linked to Arctic cyclones (Simmonds and Keay 2009; Simmonds and Rudeva 2012; Zhang et al. 2013; Parkinson and Comiso 2013; Kriegsmann and Brügger 2014), although the jury is still out on whether Arctic cyclone activity will increase in the future. On the one hand, increases in cyclone frequency and/or intensity will be favored by larger land–sea temperature contrasts in high latitudes during summer (Day and Hodges 2018); on the other hand, polar amplification will reduce the overall north–south baroclinicity of the midlatitudes, which are the source regions for many cyclones reaching the Arctic during the nonsummer months.

The surface energy budget of the Arctic—in particular, the role of polar clouds and radiation—continues to challenge weather and climate prediction models. Biases in the surface radiative fluxes in global models are larger than changes in those fluxes associated with changes in sea ice cover. Clouds and their radiative properties undoubtedly contribute to these biases. Model tuning is complicated by the ongoing transition from a multiyear sea ice cover to a seasonal sea ice cover over the central Arctic Ocean. The upcoming MOSAIC program (Shupe et al. 2016) offers promise as a coordinated effort to improve understanding and model simulation capabilities with regard to the drivers of the surface energy budget.

Finally, work remains to be done in assessing and anticipating the role of internal variability in polar climate and weather. As discussed in section 3h, internal variability has been at least partially responsible for multidecadal temperature variations in the Arctic and most likely the Antarctic as well. The magnitude of internal variations exceeds the changes arising from external forcing over decadal time scales (Hodson et al. 2013); anticipation of changes over the yearly to decadal time scales relevant to planners and decision-makers will have to contend with this issue. This challenge extends to the anticipation of changes not only in atmospheric variables such as temperature but in associated system components such as sea ice, snow cover, and terrestrial surface variables.

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APPENDIX

Significant Field Programs

a. AIDJEX (1970–78)

The Arctic Ice Dynamics Joint Experiment (AIDJEX) was the first major western sea ice experiment constructed specifically to answer emerging questions about how sea ice moves and changes in response to the influence of the ocean and atmosphere. In this respect, it was a scientific sequel to the voyages of the Jeannete and the Fram, as well as the drifting NP ice camps of the Soviet Union. AIDJEX was also the first major scientific effort conducted in the Arctic by U.S. agencies [NSF, the National Oceanic and Atmospheric Administration (NOAA), and the Office of Naval Research] since the IGY in 1957–58 (Untersteiner et al. 2009). Pilot studies in 1971 and 1972 were followed by the main AIDJEX field program from March 1975 to May 1976. The main experiment consisted of a central camp surrounded by three satellite camps arranged in a 150-km triangle. Surrounding these staffed camps was a polygon of eight buoys at a distance of about 300 km from the main camp.

AIDJEX was timely in that a new generation of observing technology was coming on line, including satellite navigation, battery-powered buoys capable of real-time transmission of position and other data via satellite, accurate temperature–salinity probes for the ocean in place of Nansen bottles, quartz-oscillator barometers, and laser equipment to measure ice deformation over scales of several kilometers to several tens of kilometers (Untersteiner et al. 2009). That climate
models were in need of more-realistic ice dynamics formulations added to the timeliness of AIDJEX.

One unexpected result from AIDJEX was the discovery that mesoscale eddies are widespread in the upper layers of the Arctic Ocean. These eddies, which were shown to be baroclinic in nature, have diameters of 10–20 km and are found in the uppermost 50–300 m of the water column. Current speeds in their high-speed cores are as large as 50–60 cm s$^{-1}$, about 5 times that of the surrounding water. A total of 146 eddies were crossed by the AIDJEX station array during the 14-month main observation period.

The successful use of automatic data buoys to determine air stress and ice deformation paved the way for expanded uses of buoys in the Arctic Ocean. AIDJEX led directly to establishment of the Arctic Buoy Program in 1978, followed by the extension to the IABP in 1991 (see section 5c). Another legacy of AIDJEX, stemming from the use of sequential Landsat imagery from the main observing period of AIDJEX, is the use of satellite data for ice kinematic information, including deformation rates and changes in leads and ridges. Synthetic aperture radar data from satellites are now routinely processed into kinematic sea ice data for testing modeled ice motion and for assimilation into model hindcasts. AIDJEX model development has a dual legacy in the state-of-the-art sea ice models, including those used in Earth system models: the ice thickness distribution and a plastic failure criterion. Both these features of sea ice models were foci of the AIDJEX measurement program.

b. SHEBA (1997–98)

The Surface Heat Budget of the Arctic, funded by NSF and the Office of Naval Research, was a field project designed to quantify energy transfer processes that occur between the Arctic Ocean and the overlying atmosphere. Planning for SHEBA started with a series of workshops held in the early 1990s. SHEBA was based on the premise that addressing climate feedbacks and improving the ability to model the Arctic system required improved understanding of the surface energy budget and atmosphere–ocean–ice interactions. SHEBA was in part driven by emerging observations that the Arctic was in the midst of rapid change (Uttal et al. 2002). Phase I of SHEBA involved analysis of historical data, preliminary modeling studies and development of instrumentation to be used in the field program. Phase II of SHEBA—the field element—got under way on 2 October 1997 when the Canadian Coast Guard icebreaker Des Groseilliers came to a halt in the Beaufort Sea and was allowed to be frozen in. Thus began a yearlong drift that lasted until 11 October 1998. At any given time, there were 20–50 researchers at Ice Station SHEBA. SHEBA collected a complete annual cycle of observations, over spatial scales from meters to tens of kilometers, of albedo; snow properties; melt ponds; ice growth and melt; radiation fluxes; turbulent heat fluxes; cloud height, thickness, and other properties; and ocean salinity, temperature, and currents. Persson et al. (2002) describe the atmospheric measurements made during the SHEBA field program. SHEBA data are still being widely used today. Scientific legacies of SHEBA include the realization that supercooled clouds are surprisingly frequent over the Arctic Ocean (section 5e), the recognition of the importance of Arctic cloud microphysical parameterizations in climate model simulations, and the discovery that an elevated temperature inversion is often associated with Arctic clouds (Pithan et al. 2014). The latter complements the earlier discovery that surface-based temperature inversions are widespread in the Arctic (section 2).

c. CHAMP (early 2000s)

The Community-wide Hydrologic Analysis and Monitoring Program (CHAMP) was a program to study Arctic hydrology and its role in global change. CHAMP had its origins in a September 2000 workshop supported by NSF to assess the existing state-of-the-art in Arctic systems hydrology and to identify research priorities that could lead to improved predictive understanding of feedbacks arising from changes to the Arctic water cycle. CHAMP was organized around three interacting components: 1) compilation of data to better enable monitoring and historical analysis of elements of the hydrologic system, 2) field observations and focused process studies, and 3) the development of models operating over multiple temporal and spatial scales. CHAMP [ultimately funded as the Freshwater Integration (FWI)] proved to be highly successful. The hydrologic cycle was shown to be intimately connected to all major processes defining the character of the Arctic system as a whole. CHAMP therefore provided a platform for collaboration between scientists from diverse disciplines (Vörösmarty et al. 2002). Among the many accomplishments of CHAMP was a much better understanding of the stocks and fluxes that constitute of Arctic hydrologic cycle, the freshwater budget of the Arctic Ocean, processes leading to variability and change in river discharge, and nutrient transports.

d. BOREAS (1990s–2000s)

The Boreal Ecosystem–Atmosphere Study (BOREAS) was a large-scale international interdisciplinary experiment in the boreal forests of central Canada. While most large field programs from the 1970s through the 1990s addressed interactions of the atmosphere with sea ice and the ocean, BOREAS focused on the exchanges of
radiative energy, sensible heat, water, carbon dioxide, and other trace gases between the boreal forest and the lower atmosphere. Key questions targeted by BOREAS included the following: What processes control the exchanges of gases and energy between the boreal forest and the atmosphere? How will climate change affect the forest? How will changes in the forest affect weather and climate? The most intensive field experiments took place in the mid-1990s, although additional measurements, analysis, and applications to model improvement continued into the 2000s. BOREAS integrated ground, tower, airborne, and satellite measurements of the interactions between the forest ecosystem and the lower atmosphere.

Among the key findings was the fact that atmospheric exchanges were affected at least as much by processes in the soil as by processes in the trees of the boreal forest. Annual carbon exchanges were found to be sensitive to summer temperatures and especially to the timing of snowmelt and soil freeze/thaw, which affect soil decomposition by microbial activity. While carbon uptake by photosynthesis is also dependent on the timing of snowmelt and spring/summer temperatures, net primary production was found to be generally more stable than heterotrophic respiration (Hall 2001). Flux measurements showed that the net ecosystem exchange of carbon in boreal wetlands is a small residual between the much larger uptake and respiration rates. However, sensitivities are such that a warming trend accompanied by permafrost thaw could change the boreal forest from a long-term carbon sink to a climatically important carbon source (Hall 2001). BOREAS contributed to improved parameterizations of fluxes of water (evapotranspiration) and trace gases in climate models. BOREAS measurements of forest albedo also led to improvements of weather forecasts by the ECMWF model (Viterbo and Betts 1999).

e. GEWEX/NEESPI (2000s)

The ongoing Global Energy and Water Exchanges Project (GEWEX) program is a coordinated suite of activities to improve understanding of the water cycle and its interactions with the atmosphere and the land and ocean surfaces. Within its global framework, GEWEX includes the Northern Eurasia Earth Science Partnership Initiative (NEESPI), which addresses climate and environmental change in northern Eurasia within the water and energy cycle framework. NEESPI targets not only the regional manifestations of change but also the impacts of these changes on the global Earth system. Over a period of a decade beginning in the early 2000s, NEESPI’s contributions include a wide range of atmospheric, terrestrial, cryospheric, and socioeconomic topics, the aggregate of which point to a more rapid rate of change in northern Eurasia than in other parts of the world. Changes include an earlier spring onset and longer warmer summers, which have increased the strength and duration of extreme events (drought, heavy precipitation, and extreme temperatures) (Groisman and Gutman 2013). The increasing temperatures and warm season duration are associated with decreases in river ice duration (Shiklomanov and Lammers 2014), changes in icing events (Bulygina 2015), permafrost thaw (Streletskiy et al. 2015), and shrinkage of Russian glaciers (Khromova et al. 2014). Future projections with climate and vegetation models point to accelerated change in climate and land surface state (degrading permafrost) as well as the potential for northward biome shifts of taiga vegetation into tundra regions (Shuman et al. 2015). The impacts of such changes on ecosystems and human activity have made the NEESPI region a target for integrated assessment modeling (Monier et al. 2017).

f. SEARCH (2010s)

The ongoing Study of Environmental Arctic Change (SEARCH) is a coordinated effort to observe, understand, and guide responses to changes in the Arctic system. Motivated by the recognition that interrelated environmental changes in the Arctic are affecting ecosystems and living resources and are having an impact on local and global communities and economic activities, the SEARCH program is supported by eight federal agencies in the United States. The NSF has overseen much of the planning and organization. The framing of SEARCH is provided by a set of overarching science questions, which are intended to bridge research and societal response: How predictable are different aspects of the Arctic system? How can improved understanding of predictability facilitate planning, mitigation, and adaptation? What are the Arctic system’s tipping points—the abrupt changes that are most consequential for ecosystems and humans? How will the critical intersections between human and natural systems in the Arctic change over the next several decades? What are the critical linkages between the Arctic system and the global system?

Among the specific targets of the early phases of SEARCH is improved understanding of changes in sea ice, permafrost, and land ice with their implications for global sea level. The goals of SEARCH also include analysis of the societal and policy implications of Arctic environmental change. An example of a SEARCH activity with societal applications is the Sea Ice Outlook, which has included seasonal forecasts of summer sea ice minima by several dozen research and operational groups (Stroeve et al. 2014, 2015). The Sea Ice Outlook has stimulated work to improve forecasts of sea ice over...
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