In Situ Observations of Sea Ice

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Abstract

Our understanding of sea ice and its role within Earth's climate system is underpinned by observation. Observations come in many forms, from qualitative records to quantitative data. Observations have one thing in common: they are made *in situ*. Direct measurements comprise most *in situ* observations; however, remote sensing technologies are also regularly used *in situ* to measure sea ice physical properties. In this chapter, we provide an overview of *in situ* observations (including remote sensing) of sea ice from expeditions, drifting ice stations, autonomous platforms, and ongoing observation programs. We give a chronological account of sea-ice observations, highlighting the technological breakthroughs in sea-ice measurement techniques that have expanded observational capabilities. The chapter concludes with an outlook of future sea ice observations and ways to bring observational and modeling efforts together to accelerate knowledge of the polar regions and Earth's climate.

1. The Earliest Sea Ice Observations

1.1 The Arctic

The earliest form of sea-ice observations originated from Arctic Indigenous peoples thousands of years ago. Sea ice served as a vital platform for subsistence hunting of marine mammals and enabled easier travel between Indigenous communities. Over the generations, a honed expertise of sea ice developed through the use of sea ice, especially in recognizing sea ice features and phenomena indicating impending ice instability. Breakout events, a process in which landfast ice breaks away from the coast, were particularly dangerous. To this day, sea ice serves as a cultural livelihood for many Arctic communities where Indigenous Knowledge of sea ice is actively practiced. In recent decades, collaborations have developed between Indigenous Knowledge holders and citizen science to document local observations of sea-ice conditions, wildlife, weather, and coastal waters across Alaska Arctic communities [e.g., the Alaska Arctic Observatory and Knowledge Hub: https://arctic-aok.org/]. The sharing of sea ice observations by Indigenous Knowledge holders has been particularly valuable for decision-making of on-ice activities by locals and researchers alike.

The first western perspective on sea ice may have occurred in 350 - 320 B.C. from Pythias of Massilia, a Greek geographer [Weeks, 1998]. His account of sea ice is presented by other writers (Strabo 63 B.C. – 25 A.D. and Pliny the Elder 23 - 79 A.D.), describing sea ice as a *Mare Concretum*, or frozen sea [Weeks, 1998]. The records that followed used similar terminology to describe sea ice. The *Mare Concretum* was observed by Irish monks on Icelandic voyages in 795 A.D., while Olaus Magnus Gothus (1539 A.D.) and several other navigators described a regular wintertime presence of *Mare Concretum* in the Baltic Sea [Weeks, 1998]. While many societies gained exposure to sea ice during the 7th to the 15th centuries, knowledge of the true extent of the frozen seas remained largely unknown.

During the age of exploration (15th-16th centuries), broader understanding of the Arctic and Antarctic sea ice materialized from voyages seeking shorter trade routes between Asia and Europe. Navigators seeking the Northeast and Northwest passages were particularly effective in mapping the peripheries of landmasses and sea ice in the Arctic (**Figure 1, left**). In the eastern Arctic, Willem Barentsz made notable discoveries (e.g., Svalbard) during his search for the Northeast Passage in 1594-1596. However, his three voyages were considered a mix of successes and failures. Thick, consolidated ice forced him to turn back during the first two voyages and, on the third voyage, his ship became trapped in the ice and was eventually abandoned. It was not until 1733 that a successful mapping of the Northeast Passage was achieved during the Great Northern Expedition. The expedition's leader, Vitus Bering, ultimately deemed the Northeast Passage infeasible due to the year-round persistence of sea ice in its narrower sections. Nevertheless, the Great Northern Expedition was considered successful as it mapped much of the Siberian coast as well as parts of the North American coast.

In the western Arctic, the search for the Northwest Passage was equally fraught with ice hazards. Numerous expeditions (i.e., led by William Scoresby, John Ross, and others) were turned back by consolidated ice packs, or, worse, became damaged or trapped in the freezing ice pack. Although these expeditions made notable geographic discoveries (**Figure 1**), the voyages were largely considered unsuccessful at the time due to their failure to locate and safely navigate the Northwest Passage. It was not until 1819 that substantial progress was made charting the Northwest Passage by William Edward Parry and his crew. However, a portion in the western Canadian Arctic Archipelago remained uncharted for decades. In 1845, the ill-fated expedition of Sir John Franklin came to a disastrous end when the *HMS Terror* and *HMS Erebus* became trapped by ice pressure and ultimately sank. When the Franklin party never returned, numerous search expeditions came to the same area. This eventually led to the complete mapping of the Northwest Passage in 1850-1854. More than 150 years later, in 2014 and 2016, the wreckages of the *HMS Erebus* and *HMS Terror*, respectively, were discovered south of King William Island.

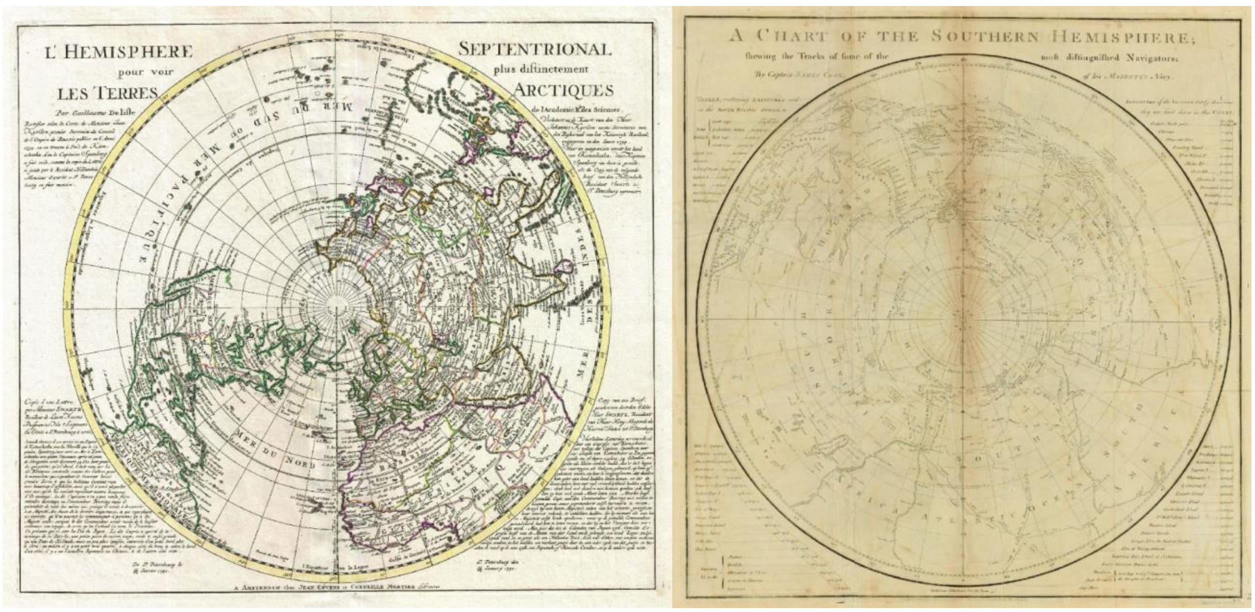

Figure 1. Left: A map of the Northern Hemisphere by Guillaume de L'Isle in 1714, updated by Coven's and Mortier in 1741. **Right:** A map of the Southern Hemisphere by Captain James Cook after his second voyage in 1772-1775.

In 1882, the first International Polar Year (IPY) was launched with the objective of collecting geophysical observations of the polar regions year-round through coordinated, multinational efforts [Barr and Lüdecke, 2010]. The first IPY and those that followed expedited knowledge of the polar climate systems, resulting in considerable improvements to weather forecasting and air and sea navigation capabilities. Numerous notable scientific accomplishments made during IPY influence our understanding of polar climate to this day.

Perhaps the most unprecedented accomplishment of its time was the *Fram* expedition of 1893-1896. Nine years prior to the expedition, the wreckage from the naval exploration vessel *USS Jeannette* was discovered off the southwest coast of Greenland three years after the ship sank in the East Siberian Sea [De Long, 1884]. This discovery led Fridtjof Nansen to hypothesize that there was an ocean current that carried the wreckage across the Arctic Ocean.

Today, this current is known as the Transpolar Drift Stream. To test his hypothesis, Nansen and his team deliberately froze the *Fram* into the pack ice, letting it drift with the ice at the whim of the winds and ocean currents. During the drift, Nansen and his team quantitatively measured Arctic sea ice and oceanic properties in their pursuit of the North Pole [Nansen, 1902].

Inspired by the *Fram* expedition, the 1918-1925 *Maud* expedition sailed through the Northeast passage with the intent of freezing into the pack ice to travel with the Transpolar Drift Stream to the North Pole. The expedition had an extensive scientific program, including measurements of ocean tides, vertical atmospheric profiles of temperature, and sea ice physical properties [Sverdrup, 1926]. Finn Malmgren, a research assistant to Harald Ulrik Sverdrup on the expedition, dedicated substantial time to carrying out multiple sea ice experiments. His findings were published in his thesis: *On the properties of sea ice* [Malmgren, 1927]. The findings give the first quantitative evidence of the saline nature of sea ice and its thermal effects on sea ice temperatures [Sverdrup, 1926; Malmgren, 1927]. He found that newly formed sea ice, which is quite saline, is composed of pure ice with pockets of brine. As temperatures neared the melting point, he observed the brine pockets expand and become interconnected, leading to subsequent brine percolation and the freshening of the upper ice surface (**Figure 2**) [Malmgren, 1927]. These studies have contributed greatly to the understanding of sea-ice salinity and its representation in modern-day sea ice models [e.g., Hunke et al., 2011]

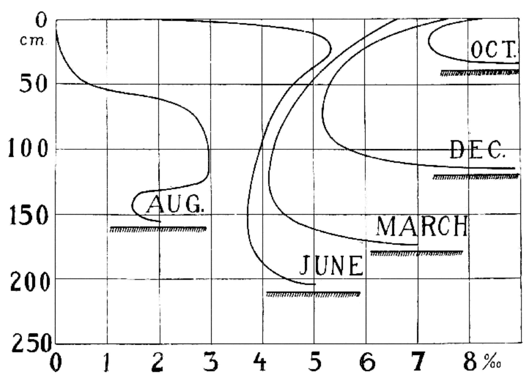

Fig. 2. Schematical representation of salinity of sea-ice as a function of depth in different months.

Figure 2. Results from one of the first quantitative studies on sea ice, from Malmgren [1927]. The schematic shows the evolution of sea-ice salinity with the seasons.

1.2 The Antarctic

Relative to the Arctic, the first encounter with sea ice in the Southern Ocean occurred much later. According to Polynesian narratives [Wehi et al., 2021 and references therein], Hui Te Rangiora (Ūi Te Rangiora), an explorer from Rarotonga, was the first person to navigate to the Southern Ocean in the early 7th century, where “rocks grow out of the sea…” and the “frozen sea of pia… a foggy, misty, and dark place not seen by the sun” [Smith, 1899]. While his voyage is not recorded in writing, it appears as stories in carvings and oral repositories [Hongi, 1925; Wehi et al. 2021].

The first written account of the Antarctic sea ice cover originated from the second scientific voyage of Captain James Cook in 1772-1775. Thereafter, several scientific expeditions in search of the Antarctic continent traveled to the margins of the Antarctic sea ice cover, with mixed success. For both the Arctic and Antarctic, the sealing and whaling era was particularly valuable in the systematic mapping of the edge of the Arctic and Antarctic sea ice covers (**Figure 1**), providing the first semblance of seasonal extent, much to the whales' disadvantage.

Until the early 1800s, sea ice was largely considered a hazard (e.g., **Figure 3, left**) rather than a topic of scientific study. The purposes of polar expeditions began to shift towards advancing understanding of the geophysical environment of the polar regions. One notable expedition was that led by James Clark Ross, who searched for the South Magnetic Pole in 1841. The naturalist on board, James Hooker, made extensive notes on the Antarctic sea ice cover, including the peculiar color of the ice itself. Upon closer inspection, Hooker discovered the presence of diatoms, which helped establish the earliest records of sea ice biota in the polar regions.

According to Weeks [1998], the first scientific paper on sea ice was published in 1874 by John Buchanan. While aboard the *H.M.S. Challenger* in the Southern Ocean, Buchanan explored the nature of freezing seawater, as well as the chemical and physical properties of sea ice. These included observations of "air bells" and "mechanically enclosed brine" within the sea ice structure, and Buchanan noted that sea ice "was very far from being a homogenous body" [Buchanan, 1874]. The 1878-1880 *Vega* expedition was the first to navigate through the Northeast Passage (**Figure 3, right**). On board, Otto Petterson conducted freezing point experiments using seawater and other saline solutions to pinpoint the differences in the physical nature of sea ice from freshwater ice [Petterson, 1883].

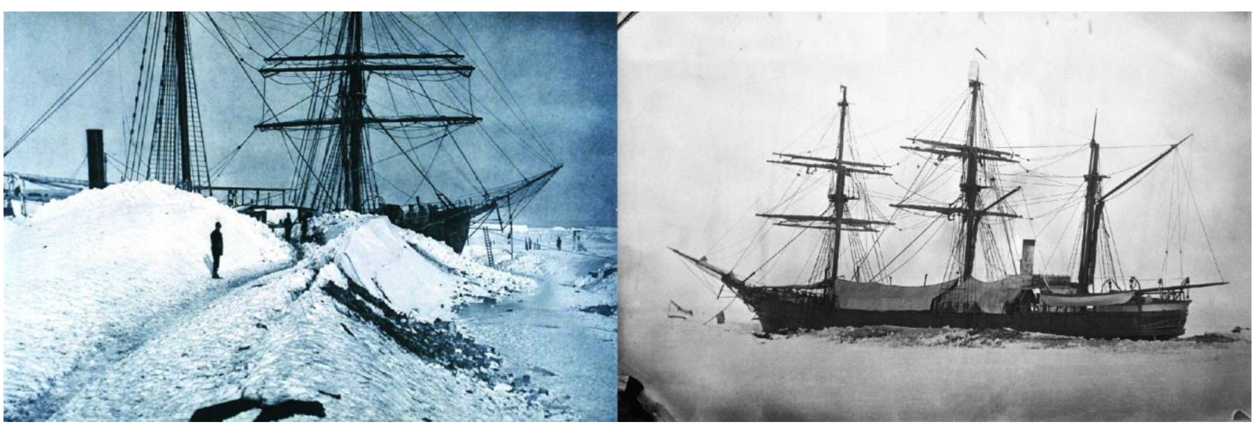

Figure 3. Left: The *Gauss* trapped in sea ice in the Southern Ocean in 1902. Despite the unintended encampment, geophysicists studied the meteorological, oceanographic, and sea ice conditions. Photo in: 'Deutsche Sudpolar-Expedition 1901-1903 Meteorologie I' by Erich von Drygalski. Plate 6, page 337. Bd. 3, I Halfte 1, Teil 1. **Right:** The *SS Vega* frozen into the pack ice near Siberia. Photo taken by Louise Palander during the 1878-1880 *Vega* expedition. Available at the Nordiska Museet.

2. Drifting Ice Stations

2.1 Technological Precursors to Ice Stations

Routine Arctic observing programs, including drifting ice stations, began with advancing technology and increased activity by air and sea in the Arctic. The looming gap of observations in the central Arctic imposed a logistical challenge for marine and air activities. There was a critical need for charts of real-time meteorological and sea ice conditions to aid navigation and weather forecasts. This need, together with the geopolitical environment at the time, motivated the proliferation of scientific pursuits on, over, and under Arctic sea ice beginning in the early 1900s.

The former Soviet Union spearheaded sea-ice observational programs. In 1898, the first icebreaker, *Yermak*, was constructed by the Imperial Russian navy with the purpose of charting sea-ice conditions and furthering the development of ship designs for ice-covered waters [Weeks, 1998]. Through the establishment of the Arctic and Antarctic Research Institute (AARI) in 1920, regular airborne reconnaissance surveys were conducted along the Northern Sea Route. These surveys guided ships to easy passages through leads within the pack ice. The spatial expansion made possible by aircraft augmented production of ice charts, which detailed sea ice thickness, consolidation, age, and other physical properties. Much of the modern-day sea ice nomenclature and subsequent ice chart categories are based on those charts (**Figure 4**) [WMO 1970].

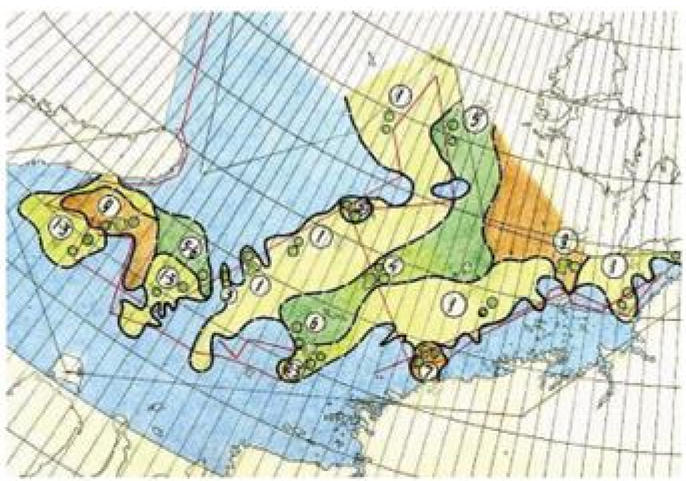

Figure 4. An Arctic and Antarctic Research Institute (AARI) ice chart of the Kara Sea for August 1933, courtesy of the National Snow and Ice Data Center and compiled by V. Smolyanitsky, V. Borodachev, A. Mahoney, F. Fetterer, and R. G. Barry. (2007) with dataset doi: 10.7265/N5D21VHJ.

The Soviet Union carried out routine airborne surveys over Arctic sea ice during the 20th century. In the early 1900s, the first successful aircraft landing on Arctic sea ice was achieved. Aircraft were especially equipped with skis and parachutes, the latter of which reduced the landing distance on sea ice. With these and other innovations, the Soviets expanded airborne operations to include *in situ* measurements on the ice landing runways and the surrounding areas up to the 1970s, albeit with periods of discontinuity, in the *Sever* program [Environmental Working Group, 2000; Fetterer and Radionov, 2000]. In addition to meteorological conditions, the measurement program included data collection of sea ice thickness, snow depth and density, the dimensions and areal coverage of ridges, hummocks, and sastrugi, as well as ocean temperature. The airborne operations typically occurred in spring prior to melt so that the frozen snowscape remained suitable for aircraft landings.

2.2 North Pole Station Program (1937, 1950, 1954-1991)

Widespread airborne operations in the Arctic were a leap forward in filling the observational gap of the Arctic Ocean. The Soviet Union's frequent ice landings provided numerous snapshots of a given place at a given time, but most landings occurred in spring when refrozen leads were sufficiently thick to support aircraft. Despite these valuable observations, the climatological picture of the Arctic was incomplete; it remained unknown how meteorological, oceanic, and sea-ice conditions evolved seasonally in the central Arctic. A time-series from a location on drifting sea ice was needed. To remedy this, and, as a show of technological prowess, the Soviet Union decidedly pushed the boundaries of polar observations. After many reconnaissance flights and repeated successful ice landings, the Soviet Union established the first drifting ice station at the North Pole in 1937 (**Figure 5**).

Figure 5. Mikhail Vodopyanov, the first pilot to successfully land at the North Pole to establish the first North Pole Station in 1937.

The camp, the first of many *Severny Polyus* or North Pole Stations (**Figure 6**), was set up on a multiyear ice floe initially averaging three meters in thickness. It lasted from 21 May 1937 to 20 February 1938, during which time it drifted more than 2,400 kilometers. During those nine months, four researchers carried out a relentless schedule of six-hourly meteorological observations around the clock, transmitting weather reports via radio to the mainland [Papanin, 1939]. The weather observations revealed new linkages between synoptic events originating in the northern Atlantic and those reaching the central Arctic. The researchers experienced numerous "blizzards" which caused sufficiently deep snow drifts to warrant snow tunnels between tents [Papanin, 1939].

In addition to meteorological data, the field measurements included a substantial oceanographic program. A total of 38 oceanographic depth soundings were conducted, with corresponding temperature, salinity, chemical, and biological measurements at depth [Papanin, 1939]. These measurements were the first indication of the Atlantic deep-water current in the central Arctic [Althoff, 2007]. They also revealed the Arctic to be a biologically-rich environment inhabited by phytoplankton and zooplankton [Papanin, 1939]. The measurement program at North Pole Station 1 became the standard for future "systematic geophysical studies… in the otherwise inaccessible northern polar region" [quote from Radionov in the Arctic Climatology Project, 2000]. In early February of 1938, the floe on which the North Pole Station was established began to fracture and crumble in the warm Atlantic waters in Fram Strait; the floe was reduced to an area less than 30 m by 50 m [Papanin, 1939]. On February 20, the Soviet *Taimyr* and *Murman* icebreakers evacuated the four-person team, which ended the drift of North Pole Station 1.

Figure 6. Historical photographs from the North Pole Drifting Ice Stations [Arctic Climatology Project, 2000]. Left: An overview of North Pole Station 6. Different tents were used for communications, magnetic readings, cooking, and sleeping. **Middle:** The use of dogs for travel and polar bear safety was common at the North Pole Stations. **Right:** Exploration of ridges on the boundaries of the level sea ice "platform".

During the same summer of North Pole Station 1, the *Georgy Sedov* and two other icebreakers became trapped in sea ice near the East Siberian Sea. The *Yermak* icebreaker freed two of the ice-bound ships, but the *Sedov* remained trapped in the ice. Rather than treating the situation as a loss, the *Sedov* was converted to a drifting science platform much like North Pole Station 1, albeit having the benefit of a ship as shelter. The *Sedov* drifted with the sea ice for two years in a similar track to Nansen's *Fram* drift expedition along the Transpolar Drift Stream. The *Sedov*'s research program was similar to that at North Pole Station 1 and included meteorological, magnetic, and oceanographic measurements. While never officially a part of the North Pole Station program, the observations during the *Sedov* drift added to the growing knowledge of the seasonal evolution of the Arctic weather and climate.

In the 1950s, the Soviet Union was at the forefront of sea ice studies. It reinitiated its continuous drifting North Pole station (1954-1991), airborne *Sever* (mostly continuous during

1950s - 1970s), and Drifting Automatic Meteorological Station (DARMS, 1953-1972) programs. The foundation to Arctic sea ice science came from the continuous time-series from the North Pole drifting ice station program (**Figure 7, left**). These stations were established on thick multiyear ice or glacial ice islands, ideally with refrozen leads nearby to serve as aircraft runways. In addition to 3-hourly meteorological observations, these stations and the associated *Sever* surveys conducted measurement programs that expanded sea ice studies. These measurements included ridge size and distribution [Romanov, 1995], snow depth and density [Loshchilov, 1964; Radionov et al., 1997], melt pond coverage [Nazintsev, 1964], sea ice drift, and several other relevant variables. These data have formed the climatological baseline (e.g., **Figure 7, right**) from which long-term changes in Arctic environmental conditions have been gauged. They have been especially informative for understanding the seasonal evolution of the Arctic sea ice environment.

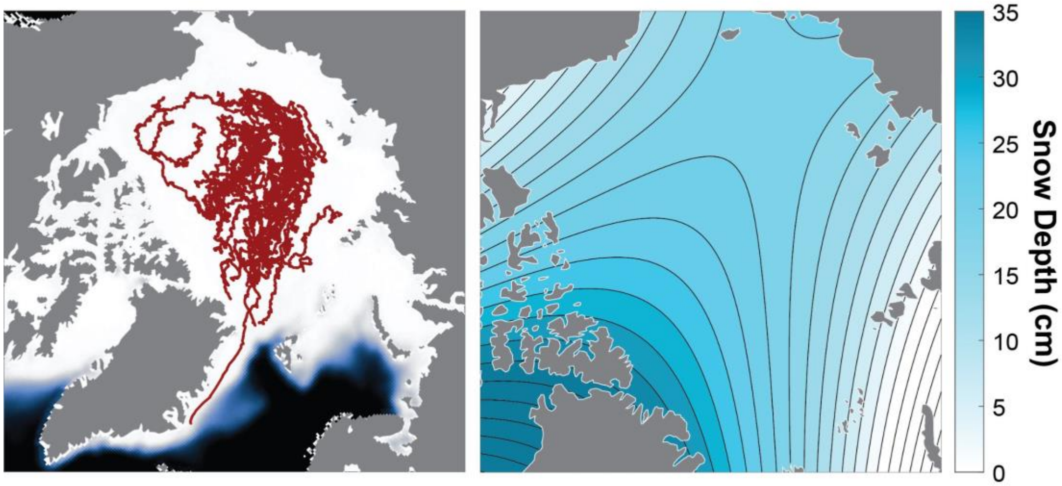

Figure 7. Left: Drift tracks of the former Soviet Union's North Pole ice stations from 1937, 1954-1991 in red with the mean sea ice concentration for March over 1979-1991. Station location data are available from the Arctic Climatology Project [2000] and the sea ice concentration from the NOAA/NSIDC Climate Data Record [Meier et al., 2021]. Station locations were determined by celestial fixes until 1980; thereafter satellite technology was used. **Right:** A zoomed-in subset of the 1954-1991 climatological snow depth distribution for March using a two-dimensional quadratic fit to station snow depth survey measurements following Warren et al. [1999]. Snow surveys were carried out every 10 days along 500-m to 1000-m transects [Radionov et al., 1997; Warren et al., 1999]. The climatology is actively used to this day to aid altimetry retrievals of sea ice thickness.

Despite experience and technology, the North Pole drifting ice stations were still subjected to the inherent unpredictability of the Arctic environment. Fracturing of the ice on which the stations were established was a common disruption. North Pole Station 8 in particular experienced more than 22 sea ice dynamic events, with floe breakup forcing the relocation of the camp and runway on numerous occasions [Althoff, 2007]. Even so, several North Pole stations persisted for multiple years. North Pole Station 22 lasted nine years, owing to its location on a glacial ice island.

Other logistical challenges were more predictable and expected. Every summer, melting snow and expansive pools of meltwater made travel and measurements difficult. Small rubber boats and canoes became the choice of transportation (**Figure 8**) [Arctic Climatology Project, 2000]. For context, on North Pole Station 1, the largest melt pond was 200 m x 400 m with a 2.4-m depth [Zubov, 1945]. The pedestaling instrumentation and infrastructure became increasingly precarious as surface melt thawed the sea ice underneath [Arctic Climatology Project, 2000]. In some instances, tents and instruments had to be relocated to more stable surfaces. The environmental challenges experienced by the North Pole Station scientists have plagued drifting ice stations throughout history, including the more recent 2019-2020 Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition.

Figure 8. Historical photographs from the North Pole Drifting Ice Stations [Arctic Climatology Project, 2000]. Left: Melt ponds posed a hazard for travel between tents and research sites. **Middle:** Rubber boats and "canoes" made travel and measurements feasible during the melt season when melt ponding became widespread. **Right:** Pedestaling of sea ice was a common occurrence during summer. Large objects shielded the underlying sea ice from direct solar radiation while the surrounding, exposed sea ice experienced greater ablation.

In 1957, the International Geophysical Year (IGY) injected momentous funds into Arctic and Antarctic science. The IGY initiative coordinated multinational efforts to expand polar observing programs. Leveraging IGY and technological advances, the Soviet Union devised a new plan, Drifting Arctic Remote Meteorological Stations (DARMS), to collect continuous time-series measurements without the need for staffed stations. Originally developed by Yu. K. Alexeyev at AARI, the DARMS automatically transmitted wind speed and direction, air pressure and temperature via radio. The data were transformed into radio signals using a code block and transmitted by Morse code [Arctic Climatology Project, 2000]. The DARMS locations were positioned by high-frequency radio-wave triangulation three times per month. An average of 11 stations per year were deployed throughout the marginal seas of modern-day Russia. During any given year, the number of DARMS was highest after the spring deployments (15) and decreased (9) in late winter. In addition to aiding weather forecasts, the widespread deployment of DARMS enabled a more comprehensive view of large-scale sea ice motion in the Arctic.

2.3 T-3 (1952-1974) and Ice Station Alpha (1957-1958)

After a hiatus during World War II, the Cold War in the 1950s reinvigorated scientific and geopolitical activities in the Arctic, much to the benefit of sea ice science. In 1952, the U.S. established its first multiyear drifting ice station: T-3, or Fletcher's Ice Island, named after Colonel Joseph O. Fletcher of the U.S. Air Force. As indicated by its name, the ice station was established on a large ice island (iceberg), which likely originated from Ellesmere Island. The project leaders posited that, by setting up on thick, glacial ice, one could avoid sea ice dynamics and thereby reduce the risks to the integrity of the drifting station. The argument held and the semi-permanent station was occupied off and on from 1952 to 1974.

Similar to other drifting ice station programs, meteorological observations were the primary objective of the T-3 science program [Crary, 1956; Fletcher, 1965], as the need for reliable forecasts were ever pressing with the increasing number of geopolitical activities in the Arctic. Oceanographic properties, bathymetric soundings, and acoustic tests were logged (**Figure 9**) to better understand the oceanic conditions and improve capabilities for under-ice navigation. Observations at T-3 advanced sea ice science by showing the relationship between surface winds, ocean currents, and sea ice motion.

Figure 9. The intensive meteorological and oceanographic measurement program at T-3. **Left:** Numerous images were collected of the sea floor, in addition to oceanic sampling and acoustic testing. **Right:** The drifting ice station was re-supplied by aircraft drops. Photographs from D. Scoboria/USGS.

The acoustic tests at T-3 were especially beneficial to the U.S. for sharpening under-ice survey and submarine monitoring capabilities. The 1950s gave rise to the development of under-ice sonar, which enabled submarine surveys in ice-covered waters. The first under-ice crossing of the Arctic Ocean was accomplished by the *USS Nautilus*, a nuclear-powered submarine, in 1958. The sonar data provided a means for avoiding thick ice. The trans-Arctic crossing of the

USS Nautilus gathered a plethora of information for under-ice navigation. Particularly useful were data to enhance under-ice sonars to detect sea ice, which later led to the capability of deriving sea ice draft and thickness.

With the help from IGY in 1957, the initiative for two U.S. ice stations became a reality. Ice Station Alpha was established on drifting pack ice, while Ice Station Bravo was established on the T-3 ice island. Ice Station Alpha was the most extensive western program on sea ice until the 1970s. It was also the first U.S. station on drifting pack ice. The sea ice measurement program included ice physical properties, seismic tests for ice strength and underwater acoustics, under-ice surveys of phytoplankton and zooplankton, and stake arrays to monitor the sea ice mass balance evolution (**Figure 10**) [Untersteiner, 1961]. The observations collectively formed the basis for the thermodynamic theory of sea ice in modern-day sea ice models [e.g., Maykut and Untersteiner, 1971; Hunke et al., 2015].

Several more insights gained from the field experiment inspired later works. For example, "firnification" of an ablating sea ice surface was observed [Untersteiner, 1961]; this process is now referred to as the surface scattering layer and contributes to the high albedo of sea ice [e.g., Light et al., 2008]. Other insights hinted at the influence of melt ponds in slowing sea ice freeze-up due to their high heat capacity [Untersteiner, 1961], a topic revisited more recently with MOSAiC observations in [Thielke et al., 2023]. Preliminary results also suggested that the heterogeneity in snow depth distribution may contribute to various sea-ice growth rates during freezing. Altogether, these findings inspired future generations of researchers to investigate the complexities of the sea ice system.

Figure 10. Left: the hydrohut provided a shelter for conducting oceanographic sampling. Photograph from April 1969. **Right:** the same view of the hydrohut in late June, with a field scientist "boating" on a wooden crate. Photographs from D. Scoboria/USGS.

2.4 Quiet Camps: ARLIS (1960-1971) and APLIS (1971-1993)

As the Cold War continued, the U.S. vied to maintain an Arctic presence despite dwindling funds to support such activities after IGY. The scientific priorities shifted to underwater acoustics with the establishment of the Arctic Research Laboratory Ice Station

(ARLIS) program by the U.S. Navy. These low-cost "ice bivouacs" were set up on both multiyear ice floes and ice islands in 1960-1971. Prefabricated hut materials, together with smaller-scale camps, reduced the total cost to ~$75,000 for ARLIS I [Althoff, 2007]. Early in the program, ARLIS observations consisted of underwater acoustics, heat flow, marine biology, physical oceanography, gravity and magnetics, sea ice strain, and meteorological measurements. While most ARLIS stations lasted 2-7 months, ARLIS II survived three summer melt seasons and included 14 scientific projects in total [Althoff, 2007].

In 1967, the ARLIS program transitioned to smaller camps with "quieter" activities to maintain a low ambient noise environment for acoustics studies. Low-frequency research was conducted for very long-range detection and tracking of submarines. In 1970, the ARLIS V, ARLIS VI, and (reoccupied) T-3 ice stations were strategically positioned ~250 km apart to carry out acoustic propagation tests using explosives [Althoff, 2007]. Building on the ARLIS program, in the spring of 1978, the U.S. Navy started the Arctic Polar Laboratory Ice Station (APLIS) program. The APLIS program's overarching goal was to advance understanding of high-frequency under-ice acoustics. The APLIS stations were typically deployed in spring and evacuated in mid-summer to investigate the acoustic response of the sea ice as melt progressed [Althoff, 2007]. A richer understanding of the acoustic signature of ice deformation and strain was gained through the ARLIS and APLIS programs, which has been especially foundational to sea ice seismic studies.

2.5 Autonomous Platforms and AIDJEX (1975-1976)

By the late-1960s, the advancements in satellite technology revealed unprecedented views of the globe and polar regions. Passive microwave remote sensing was especially useful for all-weather monitoring of the polar seas, elucidating the sea ice pack in both the Arctic and Southern Oceans. In 1972, with the advances in satellite technology, the US National Academy of Science recommended that a network of autonomous drifting buoys be deployed on the global and polar oceans to collect data for operational weather prediction, and for meteorological and oceanographic research [NRC, 1974]. The launch of the first Geostationary Operational Environmental Satellite (GOES) in 1975, and the Polar-orbiting Operational Environmental Satellite (POES) in 1978, by the United States National Oceanic and Atmospheric Administration (NOAA) allowed for near real-time observations of weather by the satellites, and the inclusion of Argos transceivers allowed remote autonomous drifting stations on the world's oceans to transmit weather data such as sea level pressure and temperature back to land, where these observations were assimilated in numerical weather prediction models. This capability allowed observations from remote *in situ* weather stations on the sea ice to transmit their data in real-time so these data may be assimilated into operational numerical weather predictions models and for research.

The Arctic Ice Dynamics Joint Experiment (AIDJEX) program in 1972 (pilot study) and 1975-1976 leveraged the combination of instrumented buoys, submarine surveys, ship surveys, aircraft overflights, and drifting ice stations to measure the atmospheric and oceanic forcings driving the motion and dynamics of the Arctic sea ice cover. This American-Canadian-Japanese partnership endeavored to carry out a unique design relative to traditional drifting ice stations: nested arrays of camps and buoys were strategically placed to collect coincident measurements of atmosphere-ice interactions on the synoptic scale to better understand atmosphere-ice-ocean momentum exchange. In total, there were 4 ice stations and 43 buoys deployed in the Beaufort Sea. The measurement program also included detailed measurements of the under-ice topography by diver and submarine, as well as microwave emission measurements for remote sensing applications (**Figure 11**). The success of AIDJEX led to the establishment of the Polar Science Center at the University of Washington, and provided the foundation for drifting buoy programs and ice camps for decades to come.

Figure 11. Historical photos from the Arctic Dynamics Joint Experiment by Tom Marlar [AIDJEX, 2023]. **Left:** Boundary-layer studies involved divers assembling current-meter masts under the water and mapping the under-ice topography. **Right:** Microwave emissivity measurements over different sea ice conditions were made to better understand the microwave signature of sea ice.

2.6 Arctic Ocean Buoy Program (1979)

The US National Academy of Science recommended the development of the global drifting buoy programs that exist today [NRC, 1974], motivating the establishment of Arctic Ocean Buoy Program (AOBP) in 1979, the first incarnation of the IABP [Thorndike and Colony, 1980]. One of the primary objectives of the AOBP was to support the Global Weather Experiment [Fleming, 1979]. In March 1979, a network of 15 Tyros Air Drop (TAD) buoys was deployed, spread out across the Arctic Ocean, to record sea level pressure and temperature, which were measured from inside the hull of the buoys. Heat from the electronics and insolation introduced a warm bias in these first TAD buoys. Collaboration between Norbert Untersteiner, Alan Thorndike and Roger Colony at the PSC/APL/UW with Torgny Vinje at the Norwegian

Polar Institute (NPI) led to the development of the ICEXAIR buoy in the early 1980s, which has a ventilated thermistor located at the top the buoy, allowing for more accurate measurements of temperature at about 1-m height. The ICEXAIR remains one of the primary buoys deployed by the IABP today (**Figure 12**), and the collaboration between PSC, NPI and the Atmospheric Environment Services of Canada (now known as Environment and Climate Change Canada) led to the renaming of the AOBP to the Coordinated Arctic Ocean Buoy Programme (CABP) in 1986.

Through the 1980s, the CABP expanded to include many international collaborators interested in polar operations and research, and in 1991 the IABP was formed as an Action Group of the Data Buoy Cooperation Panel of the World Meteorological Center and Intergovernmental Oceanographic Commission. The IABP's basic objective remains – to maintain a network of drifting instrumented buoys on the Arctic Ocean to provide meteorological and oceanographic data for real-time operational requirements and research purposes, including support to the World Climate Research Programme, the World Weather Watch Programme, and the Arctic Observing Network (AON).

The locations of these early remote drifting buoys were positioned by the Argos satellites using the Doppler shift in their data transmissions, which were typically accurate to 300 m [Thorndike and Colony, 1980]. Satellites also led to the Global Positioning System (GPS), enabling far-reaching telecommunications, which further supported maritime and scientific activities in the polar regions. In comparison to GPS, Lindsay and Stern [2003] estimated the error for Argos positioning to be 158 m in the polar regions, almost half the estimate of Thorndike and Colony [1980].

In time, the Iridium satellite constellation would surpass the Argos network for transmission of remote weather and oceanographic observations given its denser coverage and ability of one satellite to transmit data to other satellites in the network so that the data reaches the terrestrial download stations in real-time so data can be transmitted more frequently and efficiently. The capability of the Iridium network to locate the remote stations was less accurate (usually tens of kilometers), which required remote drifting stations to include GPS in their suite of sensors. This improved the location accuracy of remote polar stations to just a few meters, which, in turn, allowed scientists to study higher temporal and smaller spatial scale processes, such as inertial oscillations [Kwok et al., 2003]. The new Iridium-NEXT and Starlink satellite constellations promise to be the next evolution for communications in the global observing systems, with their ability to transmit orders of magnitude more data from remote stations back to land.

Figure 12. ICEXAIR buoy deployed by the Alaska Air National Guard from a C-17. From left to right, U.S. Air Force Senior Master Sgt. Brian Johnson, Tech. Sgt. Chris Eggleston and Senior Master Sgt. Cecil Dickerson, loadmasters assigned to the 144th Airlift Squadron at Joint Base Elmendorf-Richardson, deploy an ICEXAIR buoy during an airdrop mission over the Arctic Ocean, July 12, 2023. The IABP and Office of Naval Research partnered with the 144th AS to deploy five different types of data-gathering buoys across more than 1,800 kilometers of the Arctic Ocean. U.S. Air Force photo by Airman 1st Class Shelimar Rivera Rosado.

2.7 Ice Station Weddell (1992)

After several successful research cruises to the Southern Ocean in the 1980s, an idea for a drifting ice station was conceived in 1988 in a joint effort between the former Soviet Union and U.S. [Gordon et al., 1993]. Ice Station Weddell became the first drifting ice station in the Southern Ocean, and was strongly motivated by the largely unexplored region of the western Weddell Sea. The ice station's objective was to study the atmosphere, sea ice, and ocean in the Weddell Gyre, a significant feature influencing Earth's thermohaline circulation by way of deep-water formation. Up to that point, the perennial presence of sea ice in the western Weddell sector had prevented exploration.

In February 1992, Ice Station Weddell was established on a ~1.8-m thick floe in a location not far from where Shackleton's *Endurance* became trapped in the ice in 1915 [Gordon et al., 1993; Althoff, 2007]. The floe itself was a mixture of perennial and seasonal ice [Gordon et al., 1993]. The ice station drifted over 700 kilometers to the north, in a similar drift track to that of the *Endurance* [Althoff, 2007]. A total of 60 researchers rotated to the ice camp by aircraft or ship. While an intensive measurement program was carried out at the station, helicopters offered expanded coverage for measurements including the deployment of instrumented buoys and geophysical measurements of the surface by airborne sensors [Dierking, 1995].

Ice Station Weddell drifted until June 1992, and was a highly successful campaign in expanding knowledge of the coupled atmosphere-ice-ocean system in the Weddell Gyre region. In particular, the suite of measurements made a strong contribution to understanding large-scale ice motion and dynamics [Kottmeier et al., 1992; Geiger et al., 1998], thermodynamic processes [Lytle et al., 1996], snow characterization [Massom et al., 1997], ice-ecosystem studies [Garrison and Close, 1993], in addition to numerous atmospheric and oceanographic studies. The expedition also made use of a wider range of remote sensing technology to study the composition and large-scale motion of the Antarctic sea ice cover in the Weddell Sea.

2.8 SHEBA (1997-1998)

In October 1997, the *Des Groseilliers* icebreaker began its year-long drift in the Beaufort Sea for the Surface Heat Budget of the Arctic Ocean (SHEBA) expedition. SHEBA had two overarching goals: (1) to determine the atmosphere-ice-ocean processes that control the ice albedo and cloud radiation feedbacks, and (2) to develop models that improve simulations of Arctic climate [Uttal et al., 2001]. With a collective team of over 160 participants, the expedition was the largest of its kind. The expedition was strongly motivated by the need for improved realism of global climate models through the incorporation of process-oriented observations. Accordingly, the observational program was designed to collect measurements that could be used to develop parameterizations of physical processes and improve representation of physical properties.

The SHEBA observational program was interdisciplinary in nature, and strategically collected coincident measurements of atmospheric, sea ice, and oceanic properties (**Figure 13**). The sea ice program made major advancements in the understanding of Arctic sea ice mass balance (**Figure 14**) and the critical role surface albedo has in the summer evolution of the surface energy budget [Perovich et al., 2002; 2003; Light et al., 2008]. Summer melt processes were also investigated, revealing how complex networks of meltwater accumulation, percolation, and drainage strongly influence the surface albedo evolution [Eicken et al., 2002; 2004]. New understanding of the physical properties of snow and their insulating effects on sea-ice growth rates was obtained [Sturm et al., 2002a; 2002b]. As with other drifting stations, SHEBA was no exception to frequent dynamic events. The integrative deployment of buoy arrays and satellite data greatly contributed to a stronger understanding of sea ice dynamics from local to aggregate scales [Richter-Menge et al., 2002; Stern and Moritz, 2002],

SHEBA was highly successful in integrating the knowledge gained from observations into climate model development. Specific to sea ice studies, major advancements were made to model parameterizations of sea ice optical properties and processes [e.g., Holland et al., 2012], snow processes on sea ice [Sturm et al., 2002b], melt pond evolution [e.g., Flocco et al., 2010], and cloud radiative feedbacks [Intrieri et al., 2002]. The suite of SHEBA data sets continues to make valuable contributions to this day: as a validation source for model development [e.g., Vancoppenolle et al., 2009] and as a comprehensive forcing data set for model experiments. Collectively, the suite of observations from SHEBA have transformed our understanding of the surface energy balance of the Arctic.

Figure 13: The SHEBA expedition had an extensive multidisciplinary and sea ice program. **Left:** autonomous platforms were deployed to monitor the meteorological, sea ice, and oceanic conditions. **Middle:** Routine measurements of lateral ice melt were conducted for investigations of sea ice mass balance. **Right:** Networks of ice thickness gauges enabled continuous monitoring of sea ice mass balance. Photographs courtesy of Don Perovich.

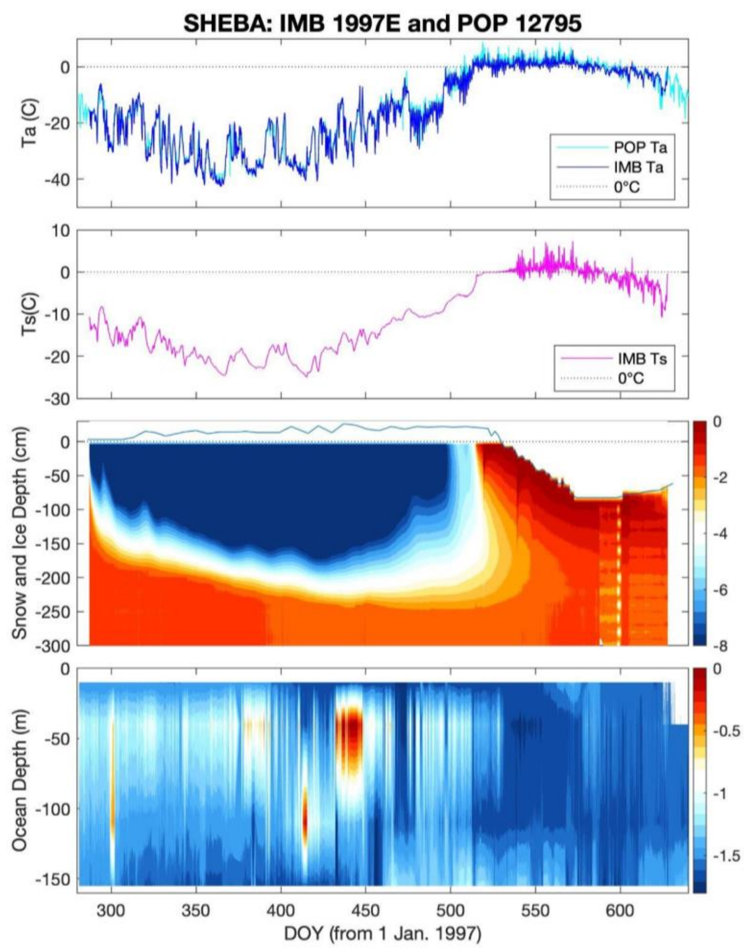

Figure 14: Measurements from Ice Mass Balance Buoy (IMB) 1997E and Polar Ocean Profiler (POP) 12795 at SHEBA [Perovich et al., 2023]. The top panel shows surface temperatures from the POP (cyan line) and IMB (blue line) buoys. The second panel shows surface temperature measurements from the IMB. The third panel shows snow depth (black line) and temperature

measurements from the IMB string. The fourth panel shows ocean temperature measurements at nominally 10-m, 40-m, 110-m, and 155-m depth from the POP buoy [Morison et al., 2007].

2.9 ISPOL (2004-2005)

In November 2004, a coordinated team from 11 nations set out to the Weddell Sea on the Ice station POLarstern (ISPOL) drift experiment to investigate the coupled processes between the atmosphere, sea ice, ocean, and ecosystem [Hellmer et al., 2008]. The experiment consisted of 12 along-transit ice stations preceding and following a 36-day period of a Lagrangian drift to a 10-km-by-10-km ice floe. The main floe was 2-m thick second-year ice, with sections of seasonal ice ranging 0.9-1.8 m in thickness [Haas et al., 2008]. The ice station drifted more than ~290 km from November 2004 to January 2005 in a largely northerly direction with several loops [Hellmer et al., 2008]. The suite of data filled the observational gap in Ice Station Weddell's seasonal time-series by capturing the transition to summer melt. The data suite provided new information on the spatial transition between the seasonal and perennial ice zones with regard to sea ice physical properties and biological and biogeochemical characteristics. It also revealed linkages between ice dynamics, ocean heat flux processes [e.g., McPhee, 2008], and primary productivity.

The studies involving ice thickness and floe size distributions were particularly informative for understanding sea ice processes in the Weddell Sea. Similar to Ice Station Weddell, an array of instrumented buoys was deployed to study the large-scale motion and deformation of sea ice in the broader vicinity of the main floe [e.g., Heil et al., 2008]. Together with airborne imagery, the evolution in floe size distribution was investigated; researchers observed an increasing distribution in smaller floes and brash ice during the drift, which was attributed to large-scale divergence of the pack ice and melt-induced weakening of ridges, which reduced the integrity of floes [Steer et al., 2008]. These ice processes revealed important linkages to factors governing the Antarctic melt processes, as well as environmental conditions that contribute to the timing of phytoplankton blooms in the Weddell Sea.

2.10 N-ICE2015 (2015)

The Norwegian Young Sea ICE (N-ICE2015) expedition was a drifting ice experiment with the goal of investigating the energy fluxes of a younger, thinner sea ice regime in the Atlantic sector of the Arctic [Granskog et al., 2018]. Given the decline in Arctic sea ice due to anthropogenic warming [Meier et al., 2014], there was a critical need to better understand the atmosphere-ice-ocean interactions when sea ice is young and thin. The interdisciplinary expedition took place over five months, and was a series of four separate drifts in the Transpolar Drift Stream north of Svalbard. The ship relocated to new, northerly floes after each site met its demise at the ice edge.

The expedition captured the winter to spring transition (**Figure 15**), and experienced frequent storms and rapid ice drift [Granskog et al., 2018]. While frequent storms were logistically disruptive, they also proved to be scientific opportunities to better understand the response of a thinner sea ice cover to synoptic events. The effects of storms on turbulent ocean heat fluxes and the surface energy budget were investigated [Peterson et al., 2017; Walden et al., 2017], revealing that the enhanced ocean heat flux was sufficiently strong to cause rapid basal ice melt [Koenig et al., 2016; Provost et al., 2017]. The combination of enhanced basal melt and heavy snowfall caused flooding and snow-ice formation to occur [Merkouriadi et al., 2017; Provost et al., 2017], a phenomenon more commonly associated with Antarctic sea ice [Massom et al., 2001]. The effects of large ocean swell and strong winds on sea ice were also investigated; the resulting studies showed irrevocable weakening of the ice cover and greater free drift of the ice floes due to the thin nature of the sea ice pack [Itkin et al., 2017].

The N-ICE2015 observation program also made strong contributions to the understanding of ice–ecosystem processes. Studies found that, despite the sea ice cover having an optically thick snow cover, the phytoplankton bloom occurred relatively early in spring; the early timing was attributed to the open leads that had formed from ice dynamics [Assmy et al., 2017]. Investigations also revealed the importance of the bio-optical feedback between under-ice phytoplankton blooms and solar heating [Taskjelle et al., 2017]. Although the drift experiment had a shorter duration relative to historical drifting ice stations, the scientific output was relatively high owing to the thoughtful coordination across disciplinary measurements.

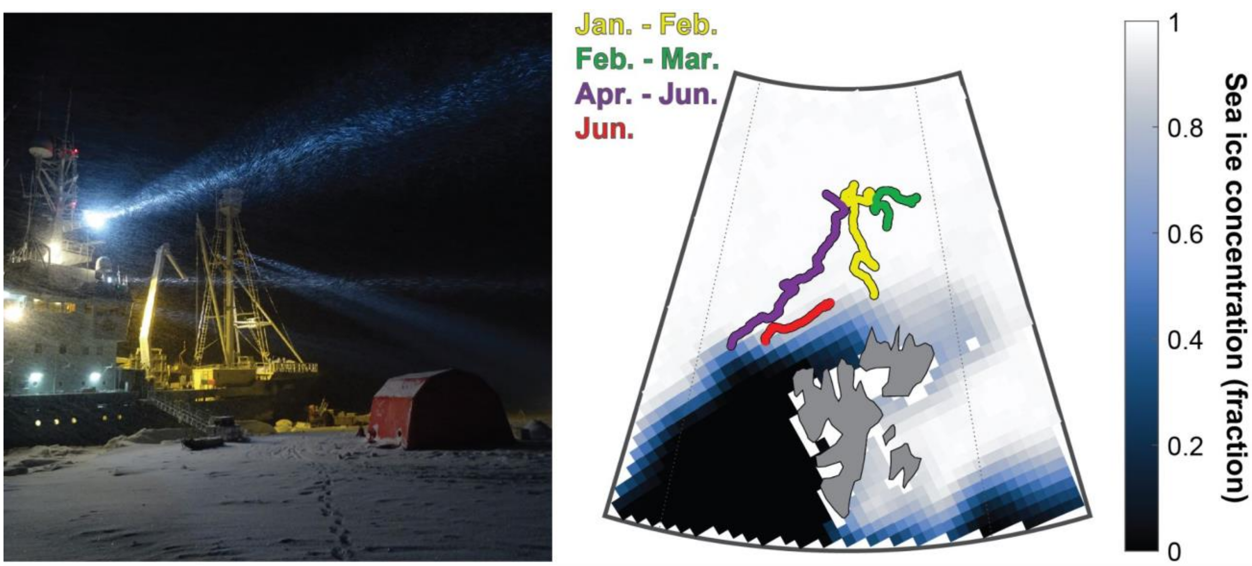

Figure 15. Left: N-ICE2015 was unique in collecting coincident atmosphere-ice-ocean-ecosystem observations during the late winter season, a period when interdisciplinary observations are limited [Photo credit: Mats Granskog/ Norwegian Polar Institute]. **Right:** The approximate tracks of the four drifts during the N-ICE2015 campaign overlaid onto sea ice concentration for March 2015. The sea ice concentration from the NOAA/NSIDC Climate Data Record [Meier et al., 2021]

2.11 MOSAiC (2019-2020)

More than 125 years after the start of the *Fram* expedition, the largest drift experiment in history was conducted on the *Polarstern* icebreaker in 2019-2020: the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC). With over 300 participants from more than 20 nations working together, the overarching goal was to investigate how the atmosphere, sea ice, ocean, and ecosystem interact over the course of an entire year on a floe composed of perennial and seasonal ice [Shupe et al., 2020]. The design of the study allowed for process-oriented analyses of the evolution of atmosphere-ice-ocean-ecosystem interactions for second-year and first-year sea ice (**Figure 16**). The tightly coordinated effort was especially successful in linking disciplinary measurements and modeling efforts to conduct interdisciplinary studies of the Arctic climate system. In fact, many of the *in situ* observations and sampling plans were tailored towards developing and improving parameterizations in sea ice and fully coupled climate models.

The sea ice observational program had a wide range in scope [Nicolaus et al., 2022]. It included under-ice ROV surveys, ridge mass balance [Lange et al., 2023; Salganik et al., 2023], drone surveys of surface conditions [Calmer et al., 2023], stress tests and ice mechanics, lidar-based surface topography [Clemens-Sewall et al., 2022], microstructure [Macfarlane et al., 2023], snow mass budget [Wagner et al., 2022], optical properties and albedo evolution (**Figure 16, c**) [Light et al., 2022], sea ice mass balance [Raphael et al., in review], snow and ice thickness and pond depth surveys (**Figures 16, f and 17**) [Webster et al., 2022; Itkin et al., 2023], as well as an array of airborne measurements [e.g., von Albedyll et al., 2022; Thielke et al., 2023]. *In situ* measurements with remote sensing sensors were used to improve understanding of spaceborne remote sensing of sea ice [Nicolaus et al., 2022]. These measurements have been especially insightful for interpreting the electromagnetic signal from sea ice when its surface undergoes rapid changes, such as with rain on snow [e.g., Stroeve et al., 2022].

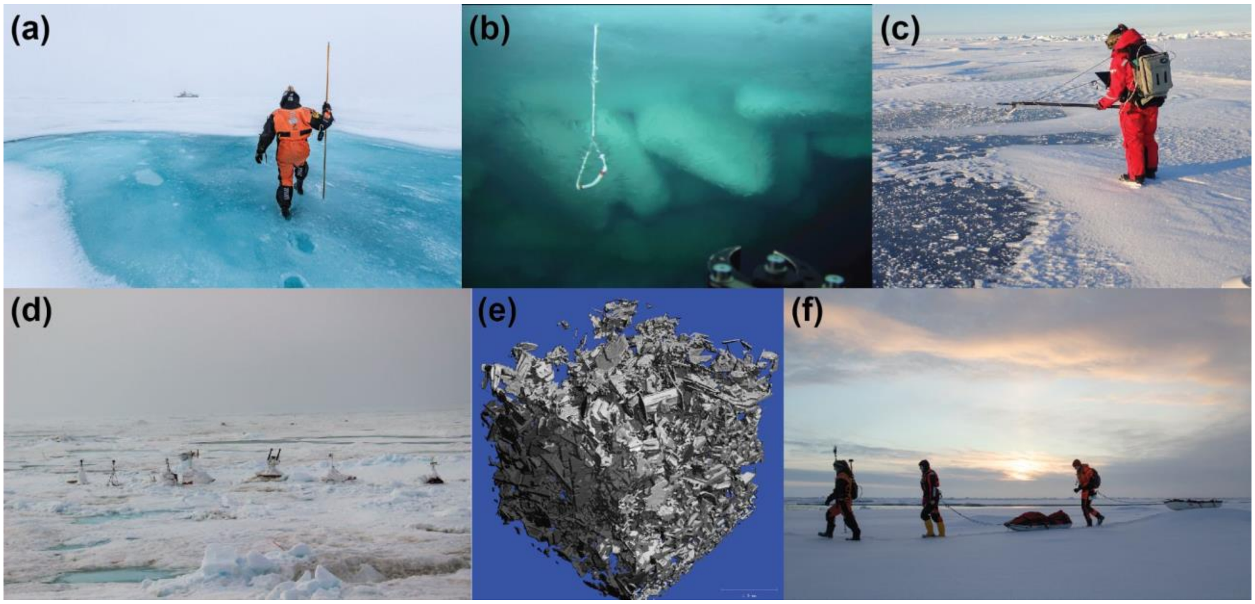

Figure 16. The MOSAiC sea ice measurement program was vast in scope. **(a):** Surveys of melt pond depths captured the progression of melt pond evolution (Photo credit: Lianna Nixon). **(b):** Platelet ice crystals were observed using an ROV during winter on MOSAiC [Katlein et al., 2020; doi:10.1594/PANGAEA.919398]. **(c):** Optical measurements were conducted on a frequent basis to capture the seasonal evolution of surface albedo (Photo credit: Felix Linhardt). **(d):** The array of remote sensing instruments measured the changes in the geophysical signals as the ice surface seasonally evolved (Photo credit: Aikaterini Tavri). **(e):** Microtomography scans of the snow surface enabled new understanding of processes driving snow grain evolution (Image credit: Schneebeli/WSL). **(f):** Snow depth and ice thickness surveys were repeated in the same location to monitor the seasonal evolution in the sea ice mass balance during the MOSAiC expedition (Photo credit: Marcel Nicolaus).

In similar fashion to AIDJEX, buoy deployments were made over nested spatial scales to study the multi-scale dynamics of the sea ice cover with the ever-changing winds and ocean currents [Bliss et al., in review]. A wide range in buoy instrumentation allowed for autonomous measurements of radiative fluxes, snow and ice thickness, and meteorological conditions at strategic distances from the Central Observatory to enable synoptic and meso-scale studies of atmosphere-ice-ocean interactions [Shupe et al., 2020]. Additionally, routine observations of surrounding ice and weather conditions were logged during the MOSAiC drift as well as during relocation transits, which further broadened the observational coverage of the MOSAiC program.

Several sea ice studies from MOSAiC build upon the classical understanding of sea ice physics, with some results confirming long-standing hypotheses while others revealed new insights. One unexpected result was the prevalence of platelet ice formation in winter [Katlein et al., 2020], a phenomenon that occurs in supercooled conditions and is more commonly associated with ice shelves (**Figure 16, b**). Other MOSAiC findings were both a surprise and a confirmation of prior results, as was the case with albedo (**Figure 17**). The seasonal evolution of the surface albedo was similar to that of the SHEBA expedition (1997-1998), despite measurements taking place on seasonal ice at MOSAiC [Light et al., 2022]. The similarity may have implications for the variability in albedo across different sea ice types. Other MOSAiC studies made connections to science further back in history. At MOSAiC, the preceding summer's melt ponds were observed to have a measurable thermal effect on sea ice during the winter season [Thielke et al., 2023]. These results substantiate the speculations by Norbert Untersteiner on the thermal persistence of refreezing ponds during Ice Station Alpha (1957-1958). At the time of this writing, MOSAiC observations continue to be processed and analyzed, and the results published. A key component of the MOSAiC program is the incorporation of observational findings into climate model development, which is currently underway.

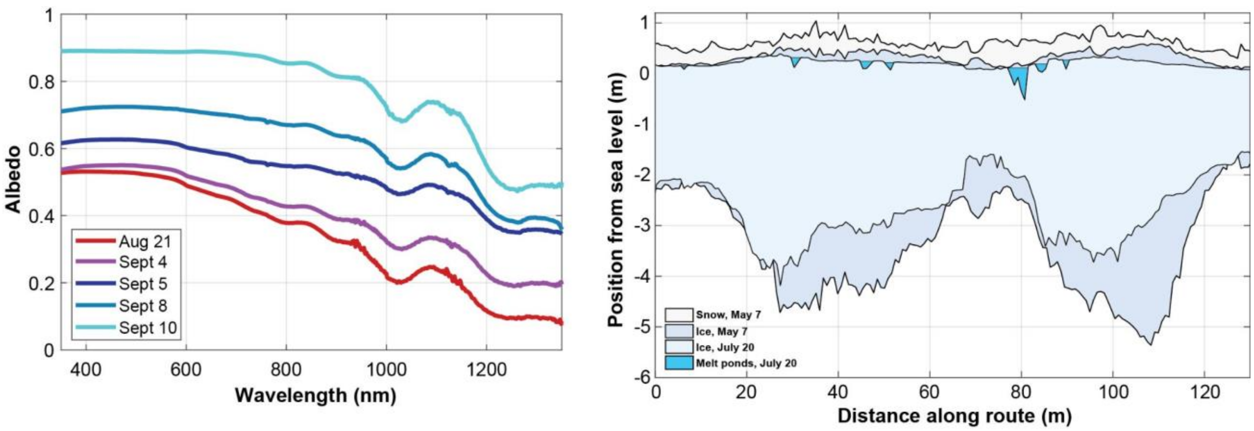

Figure 17. Left: The MOSAiC expedition captured the seasonal evolution of surface albedo, including the transition into the freeze-up season as shown in this panel. Data available at: https://doi.org/10.18739/A2FT8DK8Z. **Right:** Sea ice mass balance was measured in a variety of ways on MOSAiC. Transect measurements of snow depth, sea ice thickness, and melt ponds along repeat surveys revealed the seasonal evolution. Here, two points in time illustrate the pre-melt season state (May 7) and the advanced melt season state (July 20). Figure adapted from [Webster et al., 2022].

3. Legacies of Past Observational Programs

3.1 SCICEX (1995-2020 with discontinuity)

In the early 1990s, the military and scientific communities of the U.S. embarked on a joint program that provided unprecedented oceanographic and sea ice measurements. After a successful trial cruise with scientists aboard the *USS Pargo* in 1993, the SCience ICe EXercise (SCICEX) program was formally established in 1994 [SCICEX Science Advisory Committee, 2010]. As motivation for this program, nuclear-powered submarines were recognized as a unique observational platform that could be leveraged for cross-Arctic surveys of ice draft, oceanic hydrographic and nutrient properties, and bathymetry. They could travel far distances in relatively short periods of time and were unimpeded by ice conditions, inclement weather, or time of year. The submarines were specially equipped with conductivity and temperature sensors, through-hull water samplers, and used existing sonar equipment for ice draft retrievals. The SCICEX measurement program conducted annual surveys from 1995 to 1999, and continued surveys off and on through the Science Accommodation Missions to 2020 (**Figure 18**).

The scientific findings from the SCICEX surveys were compelling. Rothrock et al. [1999] combined the SCICEX ice draft data set with those from surveys in prior decades to reveal, for the first time, that the Arctic sea ice cover had undergone widespread thinning. Sea ice thickness in the central Arctic had decreased from 3.1 m to 1.8 m between the 1958-1976 and 1993-1997 periods [Rothrock et al., 1999]. Further discoveries helped pinpoint the areas where water mass exchange takes place between the continental shelves and deep ocean basins [Morison et al., 2000 and references therein]. Both the sea ice thickness time-series and oceanographic data continue to be of value to this day for model development and evaluation, as well as for the validation of sea ice retrievals from satellite data [e.g., Kwok and Rothrock, 2009] and studies of Arctic sea ice change [e.g., Kwok, 2018].

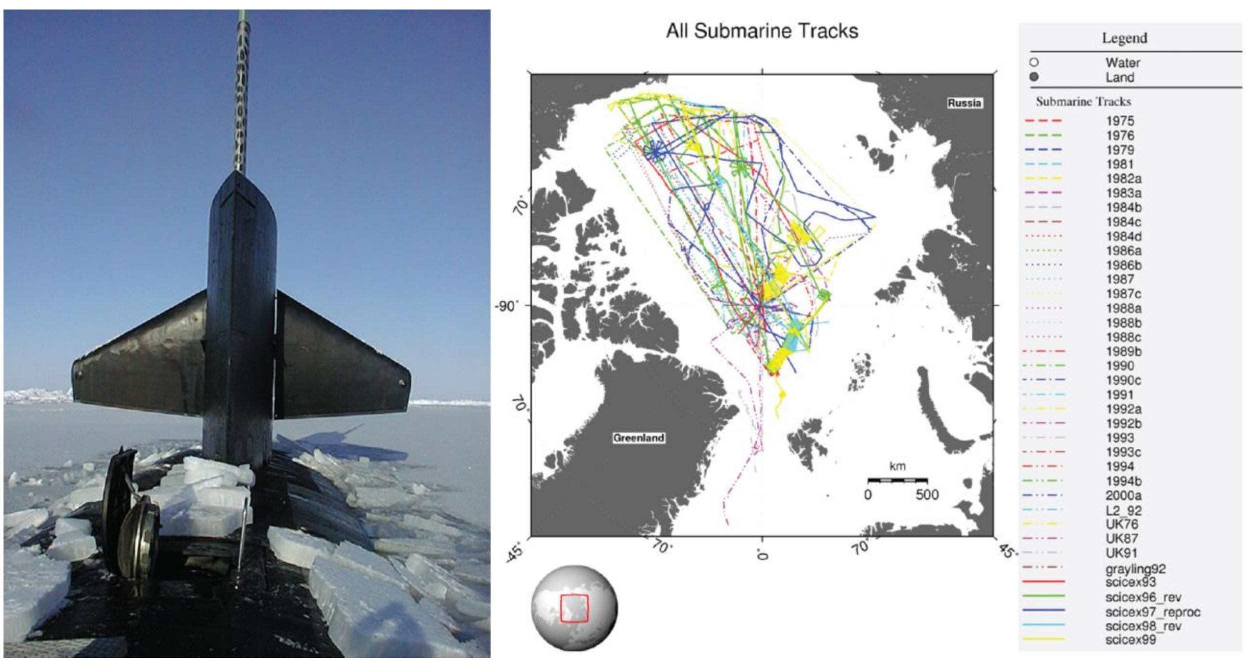

Figure 18. Left: The *USS Hawkbill* surfacing at the North Pole during SCICEX 1999 (Photo credit: Arctic Submarine Laboratory/NSIDC). **Right:** Submarine tracks from the SCICEX and SAM programs (Map credit: NSIDC G01360 user guide; SCICEX Science Advisory Committee, 2014, https://doi.org/10.7265/N5930R3Z).

3.2 North Pole Environmental Observatory (2000-2015)

Climate change in the Arctic was becoming an emerging scientific topic in the early 2000s, as records were showing a thinning ice cover [Rothrock et al., 1999] and warming ocean temperatures [Morison et al., 2000]. It was argued that to better understand these changes in the context of global climate change, an observational program of atmospheric, sea ice, and ocean conditions in the central Arctic was needed. With the cessation of the North Pole Drifting Ice Stations in 1991, coincident measurements of atmospheric, sea ice, and oceanic conditions were lacking. Thus, the North Pole Environmental Observatory (NPEO) program was created in 2000, with the objective of providing long-term multidisciplinary research stations equipped with autonomous instruments [Morison et al., 2000].

From 2000 to 2015, annual expeditions to the North Pole were conducted each April to deploy instrumentation for recording measurements throughout the remainder of the year. The NPEO stations typically had a deep-sea mooring, automated weather instruments, and instrumented buoy clusters fixed to the drifting ice; the station was further complemented by airborne hydrographic surveys. The instrumented buoys recorded images (**Figure 19**), meteorological conditions, snow depth and ice thickness [Perovich et al., 2014], as well as vertical profiles of sea ice and ocean temperatures. The resulting data provided a rich time-series to investigate ocean heat flux processes [McPhee et al., 2003], sea ice mass balance evolution [Perovich et al., 2014], and long-term trends in Arctic temperatures and warming events [Overland et al., 2008; Moore, 2016].

Figure 19. Webcam imagery from the North Pole Environmental Observatory from (**Left**) July 25 and (**Right**) July 28 showing the effects of melt pond drainage. Image Credit: North Pole Environmental Observatory, National Science Foundation.

3.3 2007-2008 IPY

In 2007, 125 years after the IPY in 1882, the fourth IPY was launched. The 2007-2008 IPY was the most ambitious to date, with ~50,000 researchers, local observers, educators, students, and support personnel from more than 60 countries involved [International Science Council, 2011 report]. There were an estimated 228 international IPY projects in total [International Science Council, 2011 report]. At the core of the fourth IPY objectives was to advance scientific knowledge and understanding of the polar regions through international collaboration and coordination [NRC, 2012]. Relative to earlier IPYs, the fourth IPY was unique in successfully incorporating stakeholders in IPY activities, engaging with policymakers, creating programs to facilitate early career development and mentorship (**Figure 20**), including Indigenous organizations in polar science at all levels, and founding several integrative observing programs.

Figure 20. One of the outcomes of the 2007-2008 IPY was the engagement of early career researchers in polar science. As a case example, the 2009 Interdisciplinary IPY Field School taught undergraduate and graduate students about the disciplinary components (e.g., terrestrial ecology, oceanography, sea ice, and more) of the polar climate system. Photographs courtesy of Graham Simpkins.

The 2007-2008 IPY spearheaded the establishment of several observational initiatives. The Sea Ice Mass Balance in the Arctic (SIMBA) initiative was one of the major international observing systems resulting from the IPY Antarctic sea ice program in 2007-2008. The objective of SIMBA was to investigate the atmosphere-ice-ocean mechanisms governing the mass balance of sea ice in the Bellingshausen and Amundsen seas in spring-summer. The *Nathaniel B. Palmer* drifted with an ice floe approximately 2.3 m in thickness from October to December in 2007, veering close to the drift track of the *Belgica* expedition, which had been trapped in the ice in 1898-1899 [Lewis et al., 2011; Ackley et al., 2016]. The SIMBA sea ice program included ice core analysis of temperature, salinity, brine volume, and oxygen isotopes, gauges for recording sea ice thickness changes, snow property characterization, ice mass balance buoys, and surveys of snow surface elevation, snow depth, and sea ice thickness. The SIMBA observations revealed new insights on the response of sea ice to storm-driven temperature cycling [Lewis et al., 2011], as well as improved understanding of wind-driven snow redistribution and snow loss into leads [Leonard and Maksym, 2017]. Building on SIMBA activities, the planning for the Southern Ocean Observing System (SOOS) was initiated during IPY [https://www.soos.aq/]. The SOOS is a multidisciplinary, international observing program to monitor essential climate variables in the Southern Ocean. Ongoing SOOS activities continue to expand the suite of observations and enable better understanding of the state of the Southern Ocean.

In the Arctic, the Sustaining Arctic Observing Networks (SAON) was formed through IPY to pool together smaller observational networks into a broader, international coalition [NRC, 2012]. The overarching objectives of SAON are to facilitate collaboration and coordination across international observing communities, and to archive high-quality observations of the atmosphere, ocean, sea ice, land, and ecosystem across the Arctic. SAON has been particularly impactful in the collection of a wide range of observations essential for monitoring the changes in the Arctic atmosphere-ice-ocean system and identifying specific environmental drivers of ecosystem change [NRC, 2012].

Sea ice science greatly benefited from the proliferation of research cruises, airborne surveys, station upgrades, and instrument deployments in the Arctic and Southern Oceans. Combining these observations with earlier data, one of the major outcomes from the fourth IPY was an updated, comprehensive assessment of the polar regions at a time of rapid change. New insights were gained on the rate of Arctic sea-ice loss. Rothrock and Kwok [2009] combined SCICEX ice draft data with spaceborne ice thickness retrievals to show a thinning of ~1.X m in Arctic sea ice. During the IPY, the September minimum sea ice extent set a new all-time low record in the 1979-2007 satellite record (and remains the second lowest extent on record as of 2023) [Meier et al., 2014]. The decreasing coverage in Arctic sea ice was observed to increase the amount of solar absorption and heating of the Arctic Ocean due to the ice albedo feedback [Perovich et al., 2007]. Additionally, the GPS tracks of drifting buoys combined with passive microwave data revealed the shift from a multiyear to a seasonal ice regime [Rigor and Wallace, 2004; Maslanik et al., 2007].

In the Southern Ocean, the scientific findings on sea ice during IPY were confounding. Sea ice loss in the Amundsen and Bellingshausen Seas occurred in tandem with the increasing trend in air temperatures in the Antarctic Peninsula; however, sea ice coverage in the West Antarctic was increasing [Cavalieri and Parkinson, 2008; Stammerjohn et al., 2008], and the factors contributing to this increase were not well understood. Altogether, the Arctic and Antarctic studies resulting from the IPY were compiled into peer-reviewed reports to promote community understanding of the changing polar regions and to help inform policy decisions. These reports, including the Antarctic Climate Change and the Environment (ACCE), the Climate Change and the Cryosphere and the Snow, Water, Ice and Permafrost in the Arctic (SWIPA) are available to the public.

The involvement of Indigenous groups in observing programs was a major outcome of the 2007-2008 IPY. One such success was the development of the Sea Ice for Walrus Outlook (SIWO) product [https://www.arcus.org/siwo; Eicken et al., 2011], which provides weekly forecasts of the spring sea ice breakup and walrus migration each spring. Sea ice scientists in partnership with the Eskimo Walrus Commission and several local village monitors brought together a diverse group of sea-ice experts to discuss sea ice conditions and exchange knowledge of sea ice predictions to promote the enhancement of forecasting capabilities [Eicken et al., 2011]. The forecasts were shared with Alaska native subsistence hunters in communities along the coasts of the Beaufort, Chukchi, and Bering seas in a format that is helpful to local users.

Observations of the weather and sea ice conditions encountered during subsistence hunting were then shared with model forecasting groups to contribute to the improvements in the 10-day weather forecasts.

Model-observation synthesis was another key priority of IPY 2007-2008 [NRC, 2012], which is showcased by the creation of the Sea Ice Outlook (SIO) [https://www.arcus.org/sipn]. The SIO is an international initiative to provide and discuss annual sea ice forecasts to facilitate improvements in sea ice predictability, integrate observations with modeling, and provide predictions across spatial and temporal scales. The SIO remains an active community to this day and has extended its prediction efforts to both hemispheres, providing annual forecasts of Arctic and Antarctic sea ice coverage.

Through the support from the International Arctic Science Committee (IASC) and Scientific Committee on Antarctic Research (SCAR), the next IPY is planned for 2032-2033.

4. Ongoing Observing Programs

4.1 IABP/IPAB (1979 - present)

Observations from the IABP and its predecessors have proven to be invaluable for research, as many of the changes in Arctic and global climate were first observed and studied using IABP data. For example, Walsh et al. [1996] showed that sea level pressure (SLP) over the Arctic Ocean had dropped by over 4 hPa when comparing 1979-1986 and 1987-1994 IABP SLP fields (**Figure 21**). Walsh et al. [1996] may be the first paper published on Arctic climate change. We know now that this change in SLP is related to the Arctic Oscillation (AO) [Thompson and Wallace, 1997], which is highly correlated to the North Atlantic Oscillation (NAO) [Hurrell, 1996]. The changes in wind related to the decrease in SLP were found to drive a corresponding weakening of the clockwise circulation of sea ice in the Beaufort Gyre (**Figure 21**) [Rigor et al. 2002]. Proshutinsky and Johnson [1997] and Steele and Boyd [1998] showed that these anomalies have propagated down into the ocean where the circulation has become more cyclonic (anti-clockwise). The changes in SLP and wind also modify the advection of heat into the Arctic by the atmosphere. Using IABP data, Rigor et al. [2000] showed the warming observed over land and lower latitudes [e.g., Jones et al., 1999] extended out onto the Arctic Ocean (**Figure 22**). The integrated effect of all these changes were studied by Rigor and Wallace [2004] who showed that the average age (thickness) of sea ice has decreased dramatically (**Figure 23**), which explains the recurring records of melt and low summer sea ice extent despite colder years. All of these results relied heavily on IABP data.

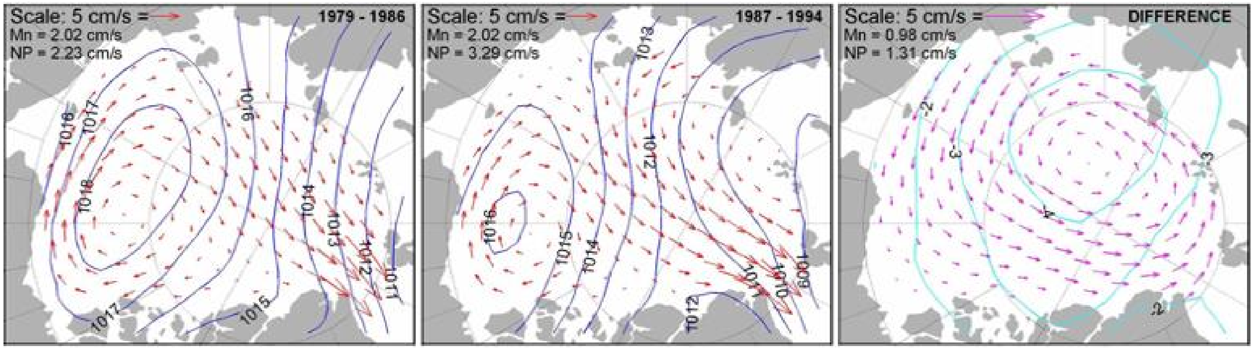

Figure 21. Using IABP data, Walsh et al. [1996] showed that sea level pressure (SLP) over the Arctic Ocean decreased by over 4 hPa (right), when he took the difference between SLP from 1979 – 1986 (left), and 1987 – 1994 (middle). These changes in SLP (winds) drive a cyclonic anomaly in ice motion (vectors), e.g., Rigor et al. [2002].

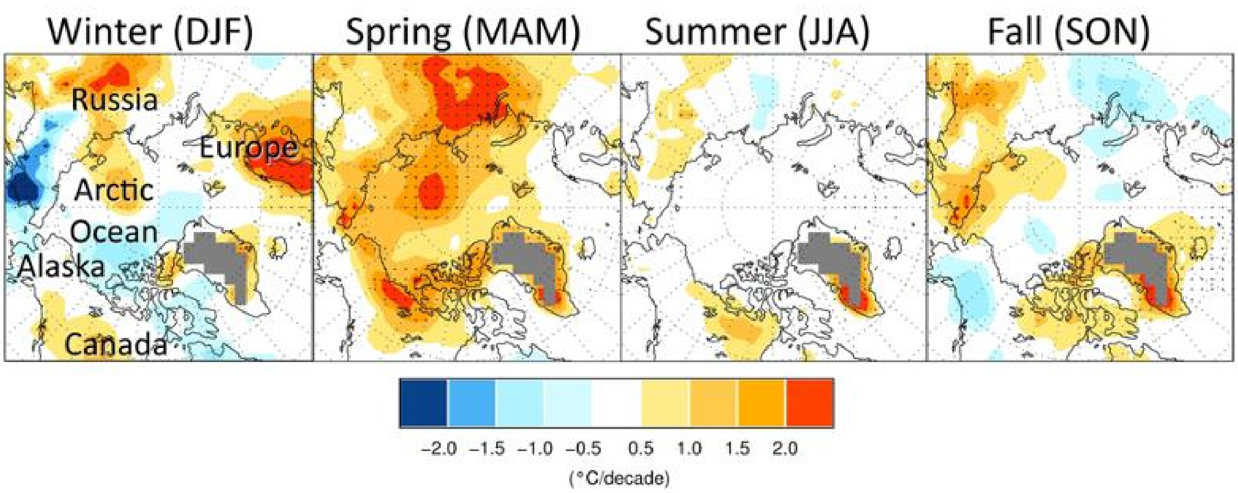

Figure 22. Surface air temperature trends for 1979 – 1998. This figure shows that the warming trends found over land extend over the Arctic Ocean and are strongest during spring. Black dots show areas where the trends are significant at the 95% confidence limit. From Rigor et al. [2000].

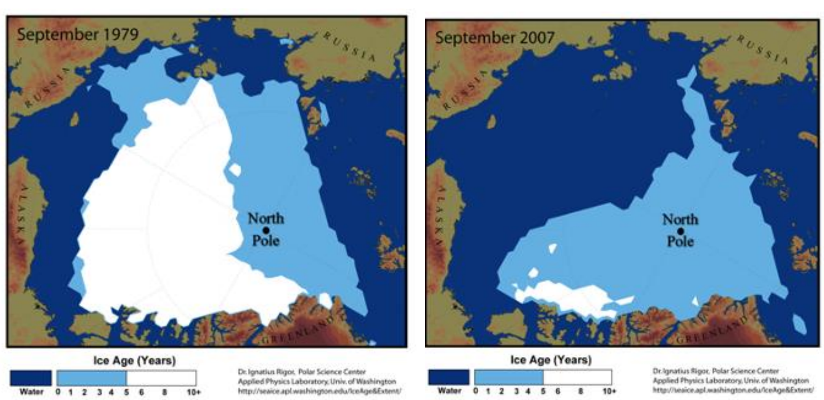

Figure 23. These maps compare the age (thickness) of sea ice between September 1979 (**left**) and September 2007 (**right**) estimated from buoy data as presented by Secretary Kempthorne during

his press announcement to list polar bears as a threatened species. The decrease in the area of older, thicker sea ice (white areas on left compared to right) suggests a decrease in the area and amount of thicker, ridged ice, which polar bears prefer for habitat. These maps helped justify this decision, were adapted from Rigor and Wallace [2004] by David Douglas (USGS) and used data from the IABP.

The retreat of Arctic sea ice during the last couple of decades has forced the IABP to continually evaluate the types of instruments deployed by the program. During the 1980s, a buoy could be deployed on a thick multi-year ice floe, which provided a robust platform for the weather station and would report for many years. With the loss of multi-year sea ice and the increasing area of open water during summer, the IABP began deploying Surface Velocity Program (SVP) buoys in the polar regions in 2006. SVP buoys evolved from the World Ocean Circulation Experiment [Niiler, 2001], and have long been used to measure ocean circulation, sea surface temperature and air pressure in all the world's wet oceans. The IABP found that the ocean drogue on the SVP buoys tended to pull the buoy under the sea ice, especially during the fall freeze up, which led the IABP to deploy more "Ice Balls", i.e., SVP buoys without the drogue, and develop the Air-Deployable Seasonal Ice Buoy (AXIB) (**Figure 24**). Similarly, the IMB buoys have been redesigned to operate in the seasonal ice zone [Planck et al., 2019], and buoys to observe increasing areas of fetch (open water) and waves are being deployed in the Arctic [Thomson, 2021].

Figure 24. Lt. Cmdr. John Woods, Office of Naval Research (ONR) reserve component, and Ignatius Rigor, University of Washington, prepare an Air-Deployable Seasonal Ice Buoy (AXIB) for deployment in the high Arctic near the North Pole from a Royal Danish Air Force C-130 aircraft operating out of Thule Air Force Base in Greenland, as part of the International Arctic Buoy Program (IABP). (U.S. Navy photo by John F. Williams/Released)

The IABP observations from 1979–present (**Figure 25**) provide the longest continuous record of *in situ* observations over the Arctic Ocean and its peripheral seas, and recent papers continue to show the importance of these *in situ* observations. The data are assimilated into many long-term atmospheric reanalyses such as the NCEP/NCAR Reanalysis [Kalnay et al., 1996], Modern-Era Retrospective Analysis for Research and Applications [MERRA, Rienecker et al., 2011] and in climate data records such as the Ice Motion and Ice Age analyses by Tschudi et al. [2020]. The observations from drifting buoys were found to provide the largest benefit in improving weather forecasts in the Arctic [Gelaro et al., 2017]; Inoue et al. [2009] showed that the standard deviation in gridded SLP reanalysis fields over the Arctic Ocean was over 2.6 hPa in areas where there were no buoy observations to constrain the reanalyses (**Figure 26**). Inoue et al. [2009] also showed that the uncertainty in the SLP fields spreads to cover the entire Arctic when the observations from buoys are removed from the reanalyses.

Given the critical role the IABP has played in documenting the changes in Arctic climate, the IABP has been identified as a fundamental component of the Sustained Arctic Observing Network [National Research Council, 2006].

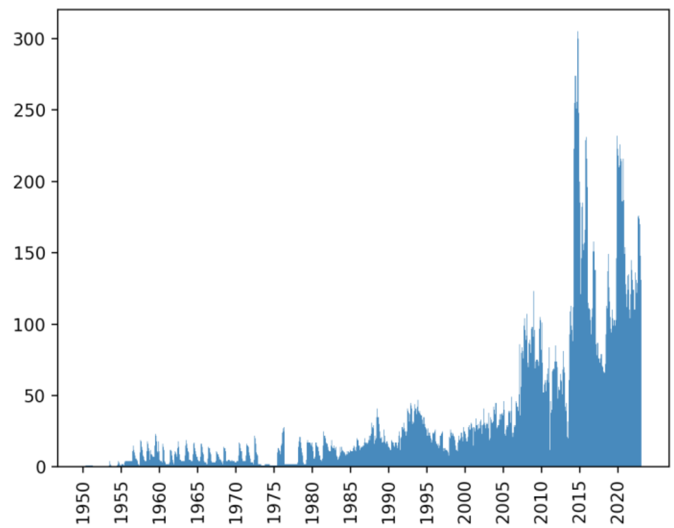

Figure 25. Histogram of observing stations reporting during any given month from the 1950s to the present. During the 1950-1970s, the number of stations deployed by the Russian North Pole Stations, DARMS and other programs ranged from a couple at the end of winter to as many as 15 after the spring and summer deployments. The deployments during AIDJEX can be seen in the late 1970s, and the establishment of the AOBP in 1979 was the beginning of continuous, year-round observations of the Arctic environment. Other notable increases in deployments include the 2007-2008 IPY, 2014 and 2015 Office of Naval Research (ONR) Marginal Ice Zone (MIZ) experiment, and the 2019-2020 MOSAiC expedition.

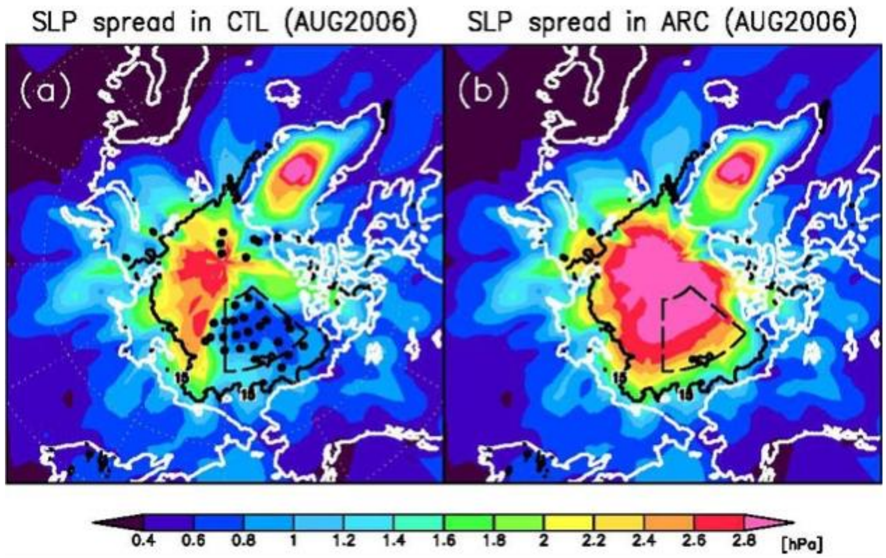

Figure 26. Standard deviation (SD) of sea level pressure measurements from various atmospheric reanalyses. The SD is low in areas where there are buoy observations (**left**). The spread increases to cover the whole Arctic when the observations from the buoys are removed from the reanalyses (**right**).

4.2 ASPeCt (1996 - present)

In 1996, the Scientific Committee on Antarctic Research established a multidisciplinary expert group called the Antarctic Sea-ice Processes and Climate (ASPeCt) to promote understanding of the Antarctic sea ice system. The key objective of ASPeCt, which is still active to this day, is to better understand and model Antarctic sea ice in the atmosphere-ice-ocean system. Accordingly, ASPeCt helps coordinate targeted field programs to complement and contribute to other international science programs, advance remote sensing capabilities, and enhance numerical modeling of the coupled Antarctic climate system. Given the dearth of routine observations in the Antarctic, one of the primary activities of ASPeCt has been to establish observed distributions of sea ice physical properties, such as snow depth, ice thickness, floe size, leads, and other variables relevant to atmosphere-ice-ocean processes in climate models. These observations have proven valuable for assessing climate model output and advancing model parameterizations, and are the beginning to create a spatial climatology of the Antarctic sea ice environment.

There have been notable successes through ASPeCt activities, including the standardization of shipborne observations of sea ice and meteorological conditions through open-source software [available at https://aspect.antarctica.gov.au], data rescue projects for securing historical observations [e.g., Ackley et al., 2003], as well as integrated autonomous platforms for seeding an observational network across the Southern Ocean. ASPeCt activities have also led to greater understanding of the Antarctic ecosystem, including disruptions associated with recent Antarctic sea ice loss.

4.3 Contemporary North Pole Stations (2003 - present, with discontinuity)

In 2003, Russia re-initiated its drifting ice station program beginning with North Pole Station 32, which lasted for nearly one year. From 2003 to 2013, a total of nine drifting ice stations were established to continue the routine meteorological, oceanographic, and sea ice geophysical studies from the 1937, 1954-1991 program. The new research program was expanded to include biological observations and pollution sampling.

By the early 2000s, however, the Arctic sea ice cover had thinned substantially due to anthropogenic climate change [Meier et al., 2014]. Thicker, older sea ice, which is optimal to support an ice camp, was in record decline and being replaced by thinner, seasonal ice. As was the case in 2012, the search was extensive and prolonged for a suitable ice floe to build an ice station due to the absence of older, thicker, more resilient sea ice. Arctic sea ice coverage in 2012 was exceptional in that it had the lowest areal extent throughout the 1979-2023 passive microwave satellite record [Meier et al., 2014]. Because of Arctic sea-ice loss, the more recent drifting ice stations were established on thinner, weaker sea ice that fractured prematurely. This led to early, and costly, evacuations of the drifting ice stations. Similarly, North Pole 2015, Camp Barneo in 2018, and the 2019 Transarktika expedition were subjected to early ice breakup and necessary evacuation.

Given the state change of Arctic sea ice cover, stations on drifting ice floes are becoming increasingly risky and costly. To counter these issues, ship-based platforms are becoming attractive alternatives. As a case example, the *Severny Polyus* icebreaker was specially designed to serve as a drifting station, outfitted with 15 laboratories and enough supplies to drift for two years. The *Severny Polyus* (North Pole Station 41) began its first test drift in October 2022 north of the New Siberian Islands. As of this writing (November 2023), its field tests and scientific experiments are ongoing and may possibly continue into 2024.

5. Future Directions and Conclusion

Over the decades, *in situ* observations of sea ice have transformed with emerging technologies, model-observation synthesis, cross-disciplinary linkages, and an ever-growing array of stakeholder needs. Surface-based measurements have been key to unlocking knowledge of the thermodynamics and dynamics of sea ice. This knowledge has led to a more holistic view of the role of sea ice in Earth's climate system, which can help society prepare for the consequences of anthropogenic climate change. However, there are still numerous knowledge gaps that remain in sea ice science and, in particular, about the role of sea ice in a warming climate.

Earth system models project sea-ice loss to continue in the Arctic and Antarctic [Notz and SIMIP Community, 2020]. The projected rates of sea-ice loss across Earth system models have a wide spread, which suggests imperfect model representations of atmosphere-ice-ocean interactions and sea ice physical processes. Accordingly, it is crucial to leverage surface-based measurements of the sea ice environment to improve process-oriented understanding of the interactions between the atmosphere, sea ice cover, ocean, and ecosystem. Model sensitivity experiments and coupled model simulations can help guide the experimental design of field programs to prioritize sampling of specific environmental properties and processes. Furthermore, observations can aid the assessments of model physics and advance model development by compiling forcing and diagnostics packages of coincident atmospheric, oceanic, ecological, and sea ice observations.

Continued monitoring of Arctic and Antarctic sea ice is critical for accelerating improvements to Earth system and weather forecast models, but reseeding observational networks (e.g., IABP) and filling observational gaps (e.g., SOOS) is becoming increasingly challenging with sea-ice loss. Sea ice measurement programs face obstacles including more frequent instrument loss, the environmental impact of instrument loss, and the logistical cost of deployments in a remote location. Despite these challenges, there are opportunities to enhance observational assets in the near future:

1. Environmental impact studies can elucidate the true consequences of instrument loss, which can help prioritize resources
2. Harmonization of instrument sensors can enable interdisciplinary investigations to further understanding of the coupled atmosphere-ice-ocean-biological system
3. Development of low-cost instruments can be achieved through the revamping of instrument design (i.e., seasonal IMBs) and employing alternative deployment methods
4. Scalable instrument deployments can be accomplished through coordination across international communities and collaboration across stakeholder groups with sea ice interests
5. Coordination and collaboration across modeling, remote sensing, and observational communities can pinpoint physical processes that warrant further investigation.

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