Recent Evolution of Techniques for Studying the Physical Oceanography and Sea Ice of the Arctic Ocean

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Dramatic progress has been made over the past quarter century in our understanding of oceanographic and sea ice processes in the Arctic Ocean. The availability of new platforms, including highly capable icebreaking research vessels, remote instrumented buoys, and satellites, has allowed us to observe in detail those processes that dominate this climatologically crucial, and observationally difficult, part of the global ocean. Technological advances have allowed miniaturization of highly reliable components with low power usage, leading in turn to packaging of entire sensor and computer systems within autonomous instrument packages. Satellite-borne sensors now provide high-resolution information on ocean surface and sea ice conditions. These sensors are far more critical in the Arctic than elsewhere in the global ocean, as the logistical and environmental constraints of Arctic operations severely limit the means by which we gather information.

Physical oceanography encompasses studies of ocean circulation and mixing processes that allow us to understand the conditions that we observe in the ocean and to better predict changes in these conditions. The Arctic Ocean is one of several regions where dense water may form that impacts deep circulation and water characteristics in the global ocean. The upper layers receive a large amount of fresh water as both river runoff from the surrounding continents and as ice melt, and the distribution of this fresh water is believed to play a primary role in the formation of the deep waters and also in the maintenance of the permanent pack ice cover. These processes vary seasonally, interannually, and in response to longer-term climate change. A major internal warming event, with concurrent shifting in the distribution of fresh water in the upper ocean, started in the late 1980s and continues to the present. The pack ice cover has decreased in both thickness and geographical extent over recent decades. Understanding these processes in sufficient detail to predict likely future conditions requires a firm base in in situ observations of the conditions undergoing change.

Ocean Temperature and Salinity

Our ability to assess conditions and change in the ocean depends critically on our ability to measure the spatial distributions of various properties, such as temperature and salinity, as well as circulation. By the mid-1970s, instrumentation had developed to a state where it was possible to obtain reasonably accurate, continuous vertical profiles of oceanic temperature and salinity that could be used to derive the three-dimensional spatial distributions of these variables. These profiles revealed that older data, obtained using discrete sampling bottles spaced from 10 m to several hundred meters apart vertically, were missing a tremendous amount of information. Discretely sampled data failed to provide consistent or realistic values for maxima in properties such as temperature, and they were incapable of detecting smaller-scale vertical features that we now realize are related to ocean mixing and other important internal processes. Profilers have evolved further since the 1970s, with greatly increased measurement accuracy and with the ability to measure quantities such as dissolved oxygen and chlorophyll concentrations. We can now routinely observe vertical water column structures down to a resolution of 1 m or less, adequate for assessing the small-scale processes such as mixing that help control the ocean's response to external forcing.

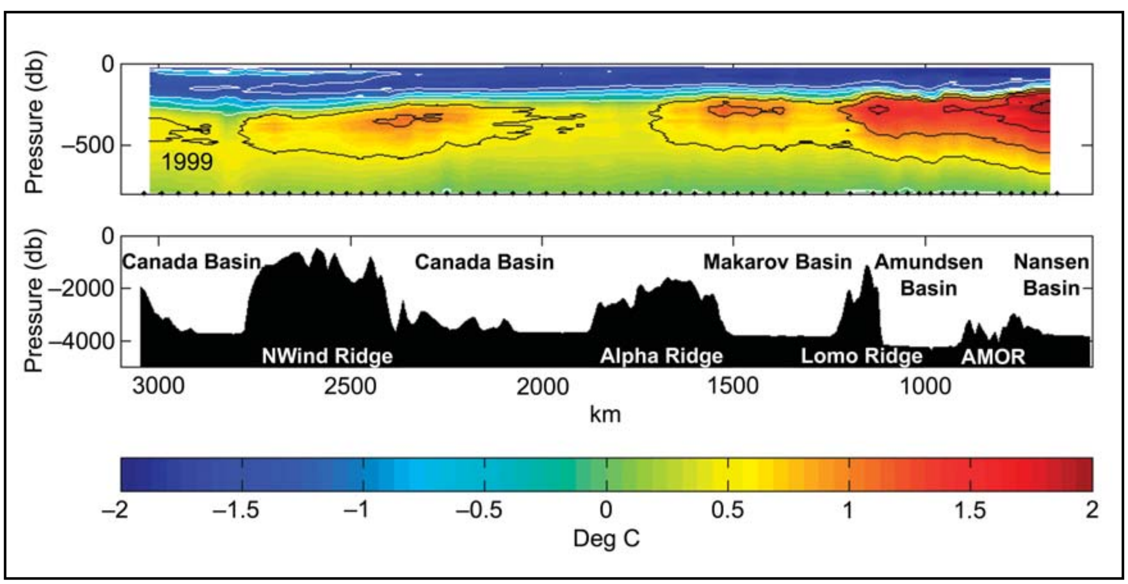
To measure vertical property profiles in the Arctic Ocean, we must use aircraft to reach the desired location and drill a hole in the ice through which to sample, or else we must reach the sampling location using an ice-breaking research vessel. Such operations are costly, time consuming, and potentially risky. Surface vessels and aircraft are still used and are generally crucial to research efforts. However, the development of autonomous profilers over the past few decades has lessened our reliance on such elaborate, costly, and potentially hazardous operations.

Bottom-moored, internally recording profilers are now available that can be left in place to record conditions continuously during the entire mooring period. Earlier versions of these devices were available in the early 1980s and profiled vertically by varying their own buoyancy while cycling upward and downward along a moored cable. Newer and more reliable versions cycle vertically on a moored cable by using a small electrically powered traction device. While the use of an icebreaking vessel is necessary to moor such instruments, the time series of vertical profiles can extend through the winter when the ice cover makes data acquisition using a surface vessel difficult or impossible. These bottom-moored instruments record data internally, allowing the data to be downloaded when the instrument is recovered by a surface vessel. Such profiling instruments also have the potential for deployment beneath surface buoys that are mounted on, and drift with, the pack ice.

Instruments mounted from surface buoys can transmit their data in near-real time through communications satellites. Satellites now available for this purpose have a much higher data transfer rate than older systems, making it feasible to transfer much larger amounts of data than was possible even a decade ago. Other profiling instruments cycle upward and downward while drifting freely in the open ocean, measuring vertical profiles of water properties as they cycle. Versions of these instruments are being modified for use beneath the Arctic ice. Such instruments might be deployed either through leads or in the marginal ice zone, then programmed to drift beneath the ice to obtain profiles there.

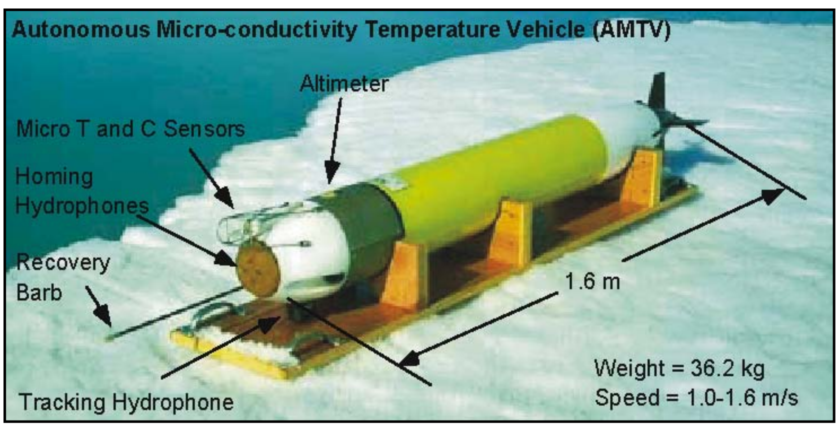
In the early 1990s, an agreement was reached among research funding agencies and the U.S. Navy enabling a program that allowed the use of U.S. fleet submarines for basic oceanographic research activities. This program, titled SCICEX (for SCientific ICe EXercise), carried out a broad suite of oceanographic observations from submarines that traversed the Arctic Basin underneath the pack ice. The first such deployment was in 1993, and subsequent traverses were made on nearly an annual basis through 1999. During this period, civilian scientists were able to participate in sampling aboard the submarines. The program of sampling by submarines along cross-Arctic transects continues to the present. Sampling is now being carried out by trained Navy personnel rather than by civilian scientists; however, the data are made available to the ocean research community. Sampling along a cross-Arctic transect by submarines has allowed us to monitor, over more than a decade to date, the internal warming event and associated changes that have been occurring in the Arctic Ocean since the late 1980s.

The 1990s warming was also measured with a new technique that utilized the transmission of a beam of sound waves across the Arctic Basin. This technique, called acoustic tomography, entails the transmission and receipt of acoustic signals in such a way that analyses of the data



Vertical distribution of temperature (ºC) in the upper Arctic Ocean (0–800 m deep) measured from a U.S. Navy submarine in the spring of 1999 under the auspices of the SCICEX program. The Bering Strait lies to the left (the Pacific Ocean side) and Fram Strait to the right (the Atlantic Ocean side). The core of warm water centered at 250–300 m deep originates from the Atlantic. Warm cores coincide with currents that flow along the flanks of mid-ocean ridges.

can provide information on water temperature along the pathway over which the acoustic signal is transmitted. Since sound velocity depends on water temperature, tomography provides a means for estimating water temperature along the pathway. Sound also reflects downward from an ice cover, and the resultant scattering during reflection can provide information on the roughness of the underside of the ice and, by implication, the ice thickness. In the late 1990s, a pilot experiment tested the feasibility of using a powerful acoustic source in the Russian Arctic to transmit sound across the entire Arctic Ocean to north of Alaska. This experiment was highly successful, demonstrating that sound transmission could in fact provide information on the internal temperature of the Arctic Ocean and on the roughness and thickness of the pack ice cover. Long-term deployment of such a tomographic system would allow multiyear monitoring of ocean conditions internal to the Arctic Ocean, as well as pack ice cover thickness. Combined with satellite imagery capable of defining the lateral extent of the ice cover, thickness information would contribute to the construction of a viable observational, multiyear pack ice budget.



An Autonomous Micro-conductivity Temperature Vehicle (AMTV) resting on pack ice at the SHEBA Ice Station in August 1998. The altimeter is used to determine the distance to the overlying pack ice when the instrument is operating beneath the ice.

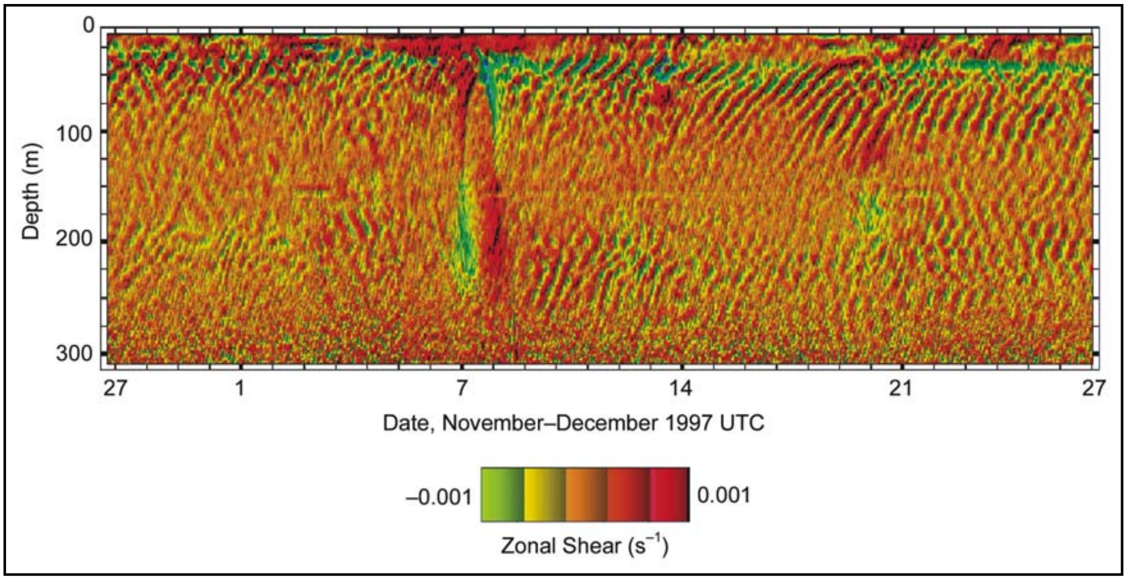
The methods summarized above have been useful for large-scale studies. However, many smaller-scale process studies have investigated properties unique to an ice-covered ocean. The pack ice can be viewed in many ways as beneficial, rather than as a hindrance, to small-scale studies because it provides a highly stable platform for carrying out measurements and allows rapid access to remote regions using aircraft equipped to land on the ice. Miniaturization has led to the development of much smaller and lighter versions of many instruments, such as profilers, that could previously only have been deployed from ships. The same advances that led to miniaturization have allowed the development of sophisticated velocity, temperature, and salinity sensors useful for measuring, for example, turbulent fluxes of heat and salt in the upper ocean beneath the ice cover.

Such sensors have been deployed from autonomous underwater vehicles (AUVs), which can sample horizontal as well as vertical profiles and can operate beneath the pack ice. These vehicles are especially well suited for studying small-scale features such as leads, which are believed to play significant roles in many Arctic Ocean processes. The highly discontinuous nature of processes in the upper Arctic Ocean produces spatial variability that is, in fact, difficult to impossible to sample without an AUV.

Ocean Currents

Prior to the 1980s, instrumentation for measuring ocean currents was limited to mechanical or electromagnetic current meters that were capable of measuring water motion only at the single point where the instrument was located. Vertical strings of many such instruments were required to obtain estimates of the vertical profile of horizontal currents needed to better understand the Arctic Ocean circulation. The development in the 1980s of acoustic Doppler current profilers (ADCPs) allowed, for the first time, the measurement of continuous vertical profiles of currents using a single instrument. These instruments use beams of transmitted sound, rather than mechanical or electromagnetic sensors, to measure current speed. Such instruments lend themselves to suspension beneath an ice cover, where they measure currents in the upper ocean beneath the ice. Mounted on vessel hulls, they have been used to map currents from ships both underway and stopped while sampling at measurement sites.

The development of ADCPs has continued to advance technologically. More recently developed systems allow the measurement of currents in greater detail and over greater ranges than ever before. The transport of materials from the shelves that surround the Arctic Ocean into the central basin depends in part on so-called mesoscale features such as eddies. The energy that drives internal mixing between waters having different sources is derived in part through the propagation of internal gravity waves through the ocean. Results from newly developed technology such as ADCPs are of critical importance in improving our understanding of processes internal to the ocean.



The zonal (east–west) component of vertical current shear measured in late 1997 from a drifting ice station in the central Beaufort Sea, well seaward of the continental shelf break, using an ADCP. The red areas correspond to an increase in eastward current speed with increasing depth. The complex patterns show the presence of internal gravity waves, generated in part by a storm on 5 December, that redistributed energy and led to mixing in the ocean. The vertical pattern on 7–8 December shows a large vortex or eddy over which the ice station drifted. Understanding these complex smaller features is crucial to our ability to predict ocean response to larger-scale, longer-period forcing.

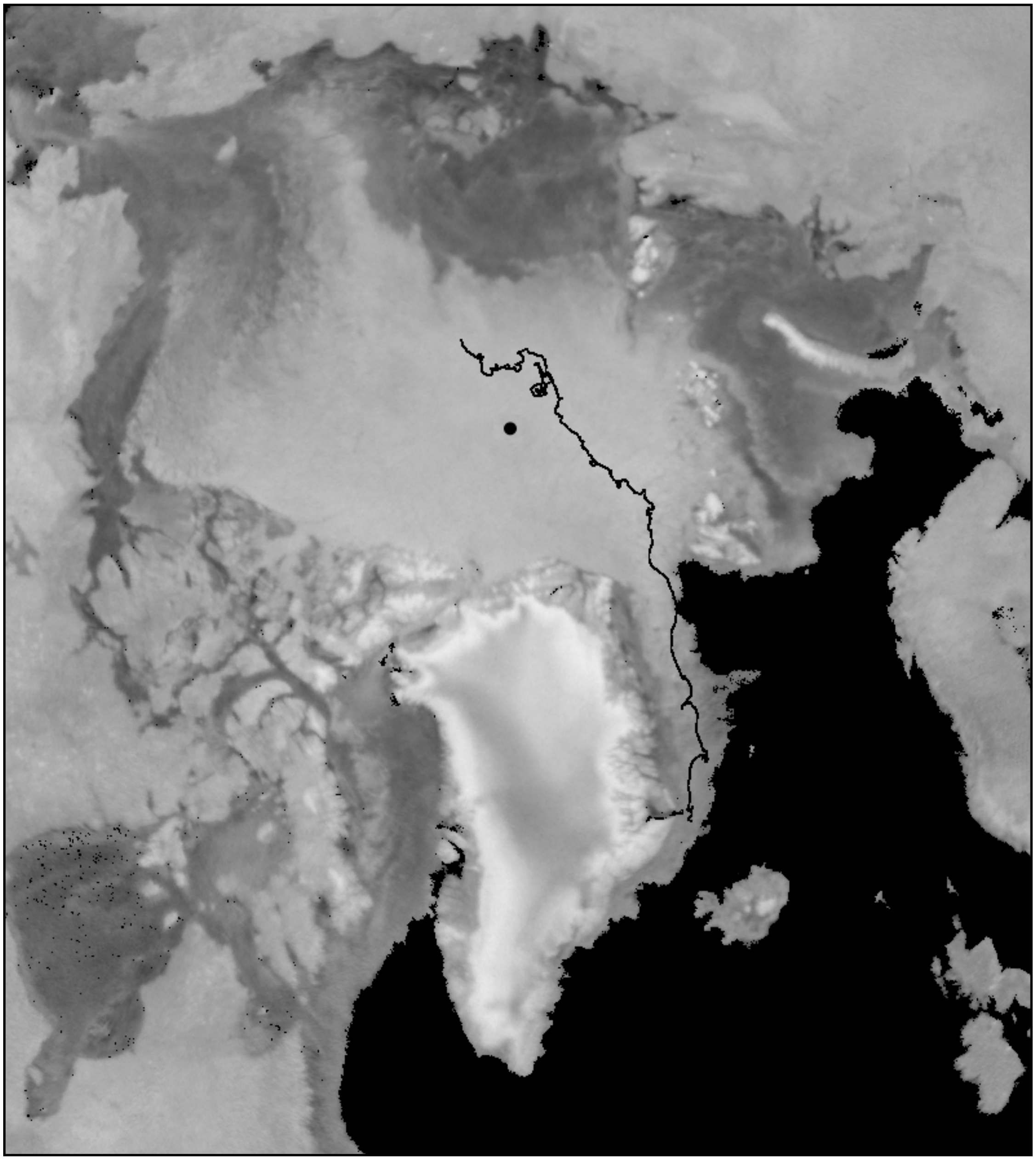
The Pack Ice Cover

The Arctic Ocean perennial pack ice cover comprises the ocean–atmosphere interface. It interacts closely with the underlying ocean through the transfer of wind energy, the provision or uptake of fresh water (depending on whether ice is freezing or melting), and effective thermal insulation of the upper ocean from the atmosphere. Large-scale movement of the pack ice internal to the Arctic Basin varies interannually in response to the Northern Hemisphere atmospheric pressure and wind fields. These variations exert a strong control over the ice budget, which is determined by freezing, melting, and export of ice from the Arctic Ocean, primarily southward through Fram Strait.

By the early 1980s, satellite-tracked buoys had become available and were being deployed on the pack ice to track large-scale ice movements under the auspices of the International Arctic Buoy Programme (IABP). (See the article on the IABP on p. 21.) Buoy location information, along with other data collected by attached sensors, is telemetered through Argos or other satellite systems. This program, with several satellite-tracked buoys deployed on the ice at any given time, has continued up to the present and has provided a priceless multi-year record of the ice movement and its interannual variability. Additional sensors provided on the ice buoys have allowed measurements of sea-level air temperature and pressure that have been used, in turn, to greatly improve predictions of the surface winds that drive the ice motion. The buoys can also support salinity, temperature, and depth observations at discrete intervals along a cable suspended beneath the buoy. In fact, instruments deployed from these buoys represented one of the earliest uses of conductivity cells, used to derive ocean salinity, in a moored or long-term drifting mode. Data from these and similar buoys have played an increasing role in operational observations, process studies, and long-term monitoring.

By the mid-1970s, satellite-borne remote sensing was becoming a useful tool for studying the Arctic pack ice. The sequence of NOAA satellites equipped with multi-band, very high resolution radiometers was underway, and analyses of the resulting imagery provided new information on ice extent and percent coverage and allowed estimation as to whether ice was first-year or multi-year. The radiometer data, which were passive and relied on the reception of energy radiated from the ocean surface, were limited, though, by a fairly coarse resolution of about 1 km and by their inability to penetrate cloud cover.

More-recent satellites carrying instruments that actively transmit multiband signals and then acquire the reflected signals for analyses have allowed us to derive far more information on sea ice cover. The transmitted signals fall in the radar, or microwave, frequency bands and allow us to determine, through the use of algorithms generated by comparing satellite data with ground truth data, ice characteristics such as overlying snow cover and roughness. These newer satellite-borne sensors also allow us to determine the geographical distribution of sea ice much more accurately (down to tens of meters) than the older passive radiometers. This better resolution has allowed more robust estimates of broad geographical



Ice drift trajectory (black line) derived from International Arctic Buoy Programme (IABP) data, superposed on a sea ice distribution derived from QuikScat/SeaWinds satellite data using the method reported in Haarpaintner et al. (2004). The land mass in the bottom center is Greenland, and the black dot is the North Pole.

variables, such as the percentage of open water as leads for a given season, than in the past. Automatic ice tracking can be performed on high-resolution SAR (synthetic aperture radar), as well as on low-resolution, Arctic-wide passive microwave and scatterometry, to assist in determining ice characteristics and drift.

Satellite-borne sensors designed for communications and for providing geographical locations have proven extremely useful for sea ice research. For the past two decades, geographical positions and recovery of data were possible using the ARGOS satellite system. These satellites returned geographical coordinates of buoys that were equipped with ARGOS receivers with an accuracy of approximately 100 m. They allowed for transmittal of data from the buoys at what is today considered a very slow rate, but, for years, they provided the only feasible means of data recovery from remotely deployed, non-recoverable instruments such as ice-mounted buoys. This system allowed us to recover not only the drift track of such a buoy, but also a time series of data such as surface temperature measured by sensors mounted on the buoy. This was the technology used for the Arctic Data Buoy System, which has been in use for several decades and has allowed a rigorous mapping of ice motion throughout the Arctic Ocean.

More-recent satellites provide considerably more-accurate positioning capabilities for remote instruments such as ice-mounted buoys. The GPS (global positioning system) satellites are in use everywhere and by virtually everyone from the military to mountain hikers. These satellites provide geographical locations to within a few meters. They are proving invaluable for studying ice motion because they can resolve the smaller-scale, shorter-period movements driven by tides and inertial oscillations that impact larger-scale properties such as ice strength and percentage of open water. The high accuracy of these satellites has also allowed some elegant studies of ice deformation in response to wind forcing over scales of a few kilometers. Such studies provide information on ice strength and response to forcing that is essential for our capability to numerically model and predict the distribution and motion of the pack ice, which has implications for the upper ocean freshwater balance and for climate change issues.

Newer-generation communications satellites such as Iridium provide us with much higher data transfer rates from remote instrumented platforms than were possible using the older ARGOS system. It's now feasible to design remote instruments capable of recording, and transmitting in real time, a broad range of environmental parameters. These parameters might include geographical position, surface air temperature and pressure, incoming solar radiation, and, from the underlying water, vertical profiles of temperature, salinity, and current velocity. Real-time transmittal of such data allows immediate inclusion into predictive models such as the U.S. Navy's PIPS (Polar Ice Prediction System).

Summary

The past few decades have witnessed tremendous advances in our ability to carry out both detailed, process-oriented studies and longer-term, monitoring-level observation programs in the Arctic Ocean. Most of these programs would not, in fact, have been possible prior to about 1980. The advances have paralleled much-larger-scale developments in instrumentation that have reduced the size and power requirements while improving reliability. Instrument development has been paralleled by greatly improved observational platforms, especially icebreaking research vessels and satellites. Serindipitously, these advances have coincided with, and have helped us understand, the many changes, dominated by both oceanic and atmospheric warming and the loss of the pack ice cover, now taking place in the Arctic.

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