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Sustaining observations in the polar oceans

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Polar oceans present a unique set of challenges to sustained observations. Sea ice cover restricts navigation for ships and autonomous measurement platforms alike, and icebergs present a hazard to instruments deployed in the upper ocean and in shelf seas. However, the important role of the poles in the global ocean circulation provides ample justification for sustained observations in these regions, both to monitor the rapid changes taking place, and to better understand climate processes in these traditionally poorly sampled areas. In the past, the vast majority of polar measurements took place in the summer. In recent years, novel techniques such as miniature conductivity-temperature-depth (CTD) tags carried by seals have provided an explosion in year-round measurements in areas largely inaccessible to ships, and as ice-avoidance is added to autonomous profiling floats and gliders, these promise to provide further enhancements to observing systems. In addition, remote sensing provides vital information about changes taking place in sea ice cover at both poles. To make these observations sustainable into the future, improved international coordination and collaboration is necessary, to gain optimum utilization of observing networks.

1. Introduction

The polar oceans are some of the most remote and inhospitable areas of the World Ocean. Sea ice prevents access to most research vessels for a large part of the year, leaving both the Arctic and Antarctic regions consistently undersampled, with strong seasonal biases toward their ice-free summer seasons. In recent years there have been concerted efforts to increase year-round measurements in the polar oceans, especially under the auspices of the International Polar Year 2007–2008 (IPY) and its legacy projects. This has been made possible by developments in autonomous platforms and the deployment of seal-borne CTD tags.

In connection with the Prospectus 2013 meeting, organised by the Challenger Society for Marine Science and the UK Scientific Committee on Oceanic Research at the Royal Society in September 2013, I was asked to speak about sustained observations in the polar oceans.

In this context, sustained observations are defined as long-term observations aimed at monitoring the state of the ocean and changes occurring, as opposed to shorter-term process-oriented studies. Traditionally, these have primarily consisted of repeat hydrographic sections, oceanographic moorings, and remote sensing. In recent years, novel platforms for data acquisition such as profiling floats, gliders, and seal-borne CTD tags have emerged, and promise to provide data from polar regions at significantly lower cost per profile than conventional ship-based measurements. The main drawback to these platforms is their irregular spacing and coverage. However, with improvements in data assimilation techniques in global or regional ocean state estimates [1, 2], these platforms will become increasingly important in ocean observing systems, and are thus being included here.

I have structured this paper by outlining some elements of polar ocean observing systems, including remote sensing and in situ measurements using conventional and autonomous platforms, and discussing how these measurements can be drawn together. As a more specific case study of how these different techniques can be used, I have included some discussion of the decline in Arctic sea ice leading to the minimum in 2007. Finally, I outline some future developments and ideas for sustaining observations into the future.

2. Elements of observing systems

Observing systems in polar oceans can use many techniques from other regions. However, the presence of sea ice prevents many surface measurements being made, and the risk of icebergs prevents the use of moored instruments in much of the upper water column in some regions. While it is impossible to touch on all possible aspects of polar oceanographic observing systems, some examples of measurements and techniques used in the polar regions are given here, along with some discussion of combining these measurements.

(a) Conventional platforms: Arctic

Warm Atlantic water reaches the Arctic Ocean through two pathways: Fram Strait and the Barents Sea. The upstream volume and heat transport is being monitored at the RAPID mooring array at 26.5° N [3, 4], and there are plans to extend monitoring in the South Atlantic [SAMOC, 5] and in the Subpolar North Atlantic [OSNAP, 6]. Mooring arrays have been deployed to monitor the flow through Fram Strait [7] and the Barents Sea Opening [8] since 1997. Combined with repeat hydrography going back to the 1950s [8], they give a good overview of variability in Atlantic water properties over the years.

It has long been known that the heat transported northward along the Norwegian coast affects sea ice extent in the Barents Sea. Helland-Hansen & Nansen [9] traced temperature anomalies along the coastline, and found a good correspondence between higher temperatures and increased areas of open water in the Barents Sea with a lag commensurate with the flow speed of the Norwegian Atlantic Current. This is also supported by more recent studies using modern oceanographic data [10].

In the Arctic Ocean itself, annual sections extending across the shelf break have been made for several years in both the Eurasian and Canadian basins [11]. Combined with moored instruments at some of these locations, variability in the temperature and depth of the Atlantic water layer can be observed. Polyakov *et al.* [11] found that a temperature maximum observed in 2007 in Fram Strait propagated around the Arctic, resulting in a maximum in 2008 at 105° E and in 2009 at 125° E.

Historical measurements in the central Arctic Ocean are fairly sparse. Occasional expeditions such as Nansen's *Fram* expedition (1893–1896) did cross and winter in the Arctic Ocean,

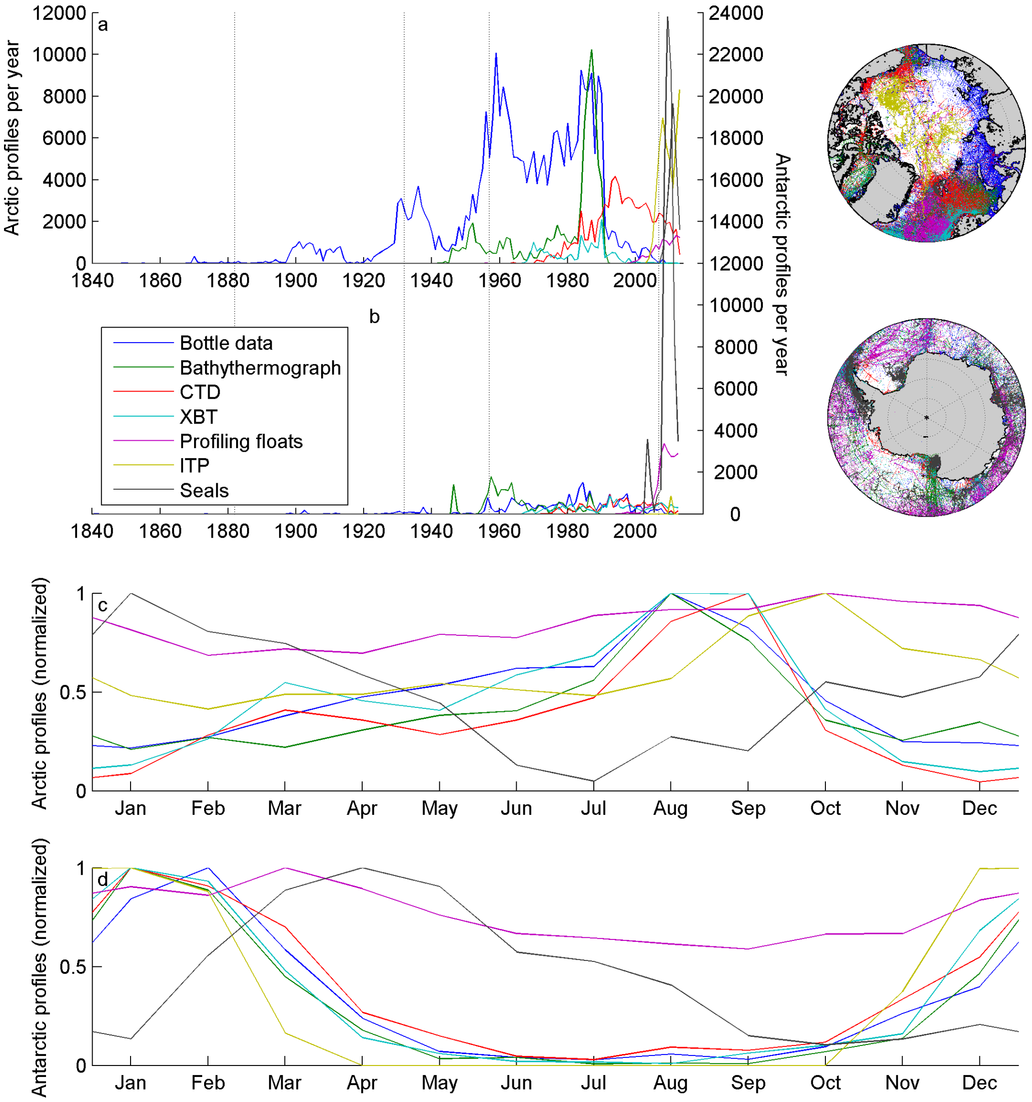

Figure 1. a and b show the number of profiles per year from different observing platforms from the World Ocean Database (WOD) 2013 [13] and http://www.whoi.edu/itp in the Arctic and Antarctic, and their locations. The dotted lines indicate the International Polar/Geophysical Years in 1887, 1932, 1957, and 2007. c and d show the normalized monthly distributions of data from these platforms in the Arctic and Antarctic, respectively. The boundaries used to delineate Arctic and Antarctic measurements in this context are 66° 33.73′ N (the Arctic circle) and 60° S, respectively.

but the first systematic measurements were taken from a sequence of Soviet and Russian drift stations operating nearly continuously from 1950–1991 [12] and from 2003–2013 (see http://www.aari.nw.ru).

(b) Conventional platforms: Antarctic

The Southern Ocean plays a unique role as a link between the Atlantic, Pacific, and Indian Oceans, as well as being an important region for bottom water formation and modification [14, 15]. The Antarctic Circumpolar Current (ACC) is the only uninterrupted circumpolar current, and is generally delineated by the Subantarctic Front, Polar Front, and Southern ACC Front; most of the ACC transport occurs along these three fronts [16].

In many areas of the Southern Ocean, the boundaries of the ACC can be difficult to locate, as the locations of the fronts are variable [17]. But Drake Passage is a natural place to measure the currents, as it is well constrained by the Antarctic Peninsula to the south and South America to the north. For this reason, Drake Passage has been monitored regularly since the mid-1970s [18, 19]. Meredith *et al.* [19] have written a review of sustained monitoring at Drake Passage. This extends from the International Southern Ocean Studies (ISOS) in the second half of the 1970s through the World Ocean Circulation Experiment (WOCE) in the 1990s, to current measurements. Many research stations are located on the Antarctic Peninsula and nearby islands, and the resupply of these stations provides opportunities for measurements across the passage. *RRS James Clark Ross* has made annual hydrographic sections along the WOCE "SR1b" line in connection with the resupply of Rothera Research Station in all but two years since 1993 [19], while *RV Laurence M. Gould* has collected expendible bathythermograph (XBT), expendible CTD (XCTD) and acoustic Doppler current profiler (ADCP) data en route to Palmer Research Station several times a year since 1996 [20, 21].

(c) Floats

The immensely successful Argo programme currently has over 3600 floats deployed in the World Ocean, profiling down to 2000 m depth [22, 23]. However, these floats were not designed to operate in ice-infested waters; if under sea ice, they cannot transmit their data, and they can become damaged from impacting the ice [24]. By incorporating an ice-sensing algorithm into their Argo floats, the Alfred Wegener Institute for Polar and Marine Research (AWI) were able to increase the over-wintering survival rate of floats that encountered sea ice from less than 40% to 80% [24]. Combined with sub-sea sound sources for positioning when surface positions were not available, this can yield year-round measurements in ice-covered regions — as long as the floats that drift into these areas are equipped with suitable hardware and software.

An alternative approach is to tether profiling floats to the sea ice itself. Here they can profile along a wire and transmit their data to the surface, where they are relayed to satellites. Two different types of profiler have been used in this way: the Ice-Tethered Profiler (ITP), which crawls along the wire [25], and the Polar Ocean Profiling System (POPS), which uses a buoyancy-driven Argo float loosely tethered to the wire [26]. Both of these systems require considerable effort to install on ice floes, in contrast to regular Argo floats, which can be readily deployed from most ships in minutes. However, they are capable of providing time series of hydrographic profiles over extensive distances, and sometimes for multiple years, when deployed on ice that survives a summer's melt.

ITPs have been used more extensively in the Arctic Ocean than the Antarctic. Here the thicker sea ice that flows around the Beaufort Gyre and through the transpolar drift is particularly suited to their use.

(d) Gliders

In recent years buoyancy-driven ocean gliders such at the Slocum [27], Seaglider [28], and Spray [29] have become more common in many regions. These vehicles' low power consumption, giving them long operating ranges and endurances, makes them a very attractive proposition for monitoring remote areas. However, these vehicles surface regularly to establish their position and to send back data and receive new commands. In ice-covered waters this presents a serious risk of damage. One approach is to pilot these gliders to keep them away from the ice [e.g. 30]. This method may work well in areas of open water, but does carry risks if the ice edge changes rapidly during a mission, or if the area in which the gliders are operating freezes up entirely. Another approach is to include ice avoidance and acoustic positioning capabilities in the gliders, enabling them to establish their position from moored acoustic beacons without surfacing. This method has been used in Davis Strait, where a glider was able to stay submerged for 51 days, operating completely autonomously, and similar deployments have been attempted in Fram Strait [31]. Gliders have been deployed in Marguerite Bay, Antarctica, where the highest perceived risk is from impacts with and entrapment beneath icebergs [H. J. Venables, pers. comm.]. In the future, improved ice avoidance algorithms, combined with improved algorithms for coping with entrapment beneath icebergs will hopefully decrease the risk and increase the use of gliders in polar regions.

(e) AUVs

Conventionally propelled (as opposed to buoyancy-driven) autonomous underwater vehicles (AUVs) have been deployed beneath sea ice to map the underside of the ice, and of ocean properties beneath it; Wadhams & Doble [32] provide a good summary of the history of using AUVs beneath sea ice. However, beneath ice shelves, where the ice can be hundreds of metres thick, and where the possibility of recovery in the case of failure is low if not impossible, more specialised AUVs are needed. The Autosub-2 AUV, developed at the National Oceanography Centre, Southampton (and preceding institutes), was specifically modified for under-ice use for the Autosub Under Ice programme [33]. Here it was deployed both beneath sea ice off the coast of Greenland and beneath Fimbul Ice Shelf, where it unfortunately was lost in 2005 [34]. However, in 2009 Autosub-3 was successfully used beneath Pine Island Glacier [35], where it has yielded valuable insights into the sub-ice bathymetry, with important implications for the ocean circulation and ice dynamics of the ice shelf [36]. Compared with gliders, AUVs like Autosub-3 have a very large science payload for high-power instruments, but the trade-off for the high power consumption is limited operating time and range, and the size of the vehicle requires a specialised crane and considerable deck space. However, ongoing developments of the Autosub AUVs will lead to longer ranges and endurances, permitting them to be used for longer-term monitoring as well as for short-term surveys [37].

(f) Seals

One novel approach to obtaining measurements in ice-covered areas is to attach CTD satellite relay data loggers (CTD-SRDLs) to seals that live in these regions [38, 39]. The tags measure temperature, conductivity, and pressure during the seals' dives, which, in the case of elephant seals, can reach up to 2000 m depth. The resulting temperature and salinity profiles are compressed and transmitted back by satellite when the seal is at the surface or on sea ice, as well as being stored on the tag, where the full data can be downloaded if the tag is recovered. The tags are glued to the seals' fur and fall off when they moult, after a maximum of one year. In addition to measuring oceanographic data, they also provide information about the seals' diving and foraging behaviour, and even their physical condition [40].

Southern elephant seals *(Mirounga leonina)* [41] and Weddell seals *(Leptonychotes weddelli)* [42, 43] have both been used in the Antarctic. The elephant seals are usually tagged on beaches on sub-Antarctic and Antarctic islands, while the Weddell seals are tagged on sea ice. Seal data have been used together with Argo floats to determine the positions of the fronts in the ACC [17]. This is helped by the fact that many of the frontal areas are biologically productive, and therefore are good feeding grounds for the seals. While it is possible to target ocean regions and types of area (frontal zones vs. shelf break) by selecting seals by area, age, and sex, seals do have a mind of their own and it can be difficult, if not impossible, to predict exactly where the seals will travel and obtain data. However, even if seals do not venture far from the location in which they are tagged, they can still provide very useful time series [44] or sections [43] in areas where winter-time data are lacking, and where oceanographic moorings stand a high chance of being damaged or destroyed by icebergs.

In total, seals have yielded more than 270,000 CTD profiles, accounting for more than 70% of CTD profiles south of 60° S in the NOAA National Oceanographic Data Center (NODC) World

Ocean Database (WOD) [13, 39]. These instruments do have lower accuracy than most ship-borne CTDs, and much lower resolution, because of the high levels of compression required to transmit the data back by satellite. However, they are currently the only practical way to obtain large numbers of year-round measurements from areas of the ocean which even the most powerful ice breakers can struggle to access. Seals are almost ubiquitous around Antarctica, and as long as a sustained effort is made to fit a variety of seals with CTD-SRDLs across a wide geographical area annually, they can provide valuable winter-time hydrographic information from extensive areas of the Southern Ocean.

(g) Remote sensing

In the polar regions there is one major obstacle to using remote sensing to study the sea for much of the year: sea ice. However, the extensive coverage of satellites is ideal for monitoring the sea ice itself, providing measurements of ice concentration (and, by extension, ice extent), thickness, and motion.

(i) Measurements of sea ice concentration

The Barents Sea has been regularly visited by ships for hundreds of years, mainly in connection with whaling and sealing, and sea ice extent in this region can be reconstructed going back to the mid-19th century from ships' log books [e.g. 45]. However, much of the Arctic and Antarctic has not been visited this frequently, and very little is known about historical ice extent.

Since 1978 a succession of passive microwave imagers from the Scanning Multichannel Microwave Radiometer (SMMR) on the Nimbus-7 satellite to the Special Sensor Microwave/Imager (SSM/I) and Special Sensor Microwave Imager Sounder (SSMIS) on the Defense Meteorological Satellite Program (DMSP) satellites have provided near-real-time images of sea ice concentration calculated from brightness temperatures [46]. This has provided a near-continuous time series of sea ice concentration in the Arctic and Antarctic, with daily coverage since 1987 (to save power, SMMR only measured on alternate days). The different sensors do have slightly different characteristics such as frequency, orbit, and footprint size, but by analysing overlapping periods of measurements these differences can be taken into account when producing longer time series [47]. More recently, sensors such as the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E; 2002–2011) and Advanced Microwave Scanning Radiometer 2 (AMSR2; 2012–present) have provided higher-resolution data, continuing these time series [48, 49].

(ii) Measurements of sea ice thickness

While the sea ice extent and area has been measured for decades, it is more difficult to accurately quantify changes in sea ice volume. By installing sensors above and beneath an ice floe it is possible to measure the thickness of sea ice directly, and indeed such measurements have been made from ice mass balance buoys (IMBs) in the Arctic [50]. Estimates of ice thickness can also be made either from the draft or freeboard of the ice, though that requires some assumptions about snow loading on the surface of the ice. The draft is most readily measured using upward-looking sonar, either from submarines [e.g. 51] or moored sonar [e.g. 52]. Both methods have limitations as to their temporal and spatial coverage, respectively, though decreases in ice thickness have been observed both in Fram Strait in 1990–2011 [52] and in the central Arctic from 1958–2000 [51, 53].

Measurements of ice freeboard can be made either from aircraft or satellites. The laser altimeter on the National Aeronautics and Space Administration's (NASA) ICESat (Ice, Cloud, and land Elevation Satellite) has been used to estimate sea ice thickness [54] and compared with measurements from submarines [55]. In addition, data from radar altimeters on the European Space Agency's (ESA) European Remote Sensing satellites (ERS-1, 1991–2000 & ERS-2, 1995–2011) [56], Envisat (2002–2012) [57], and CryoSat-2 (2011–present) [58] have provided measurements

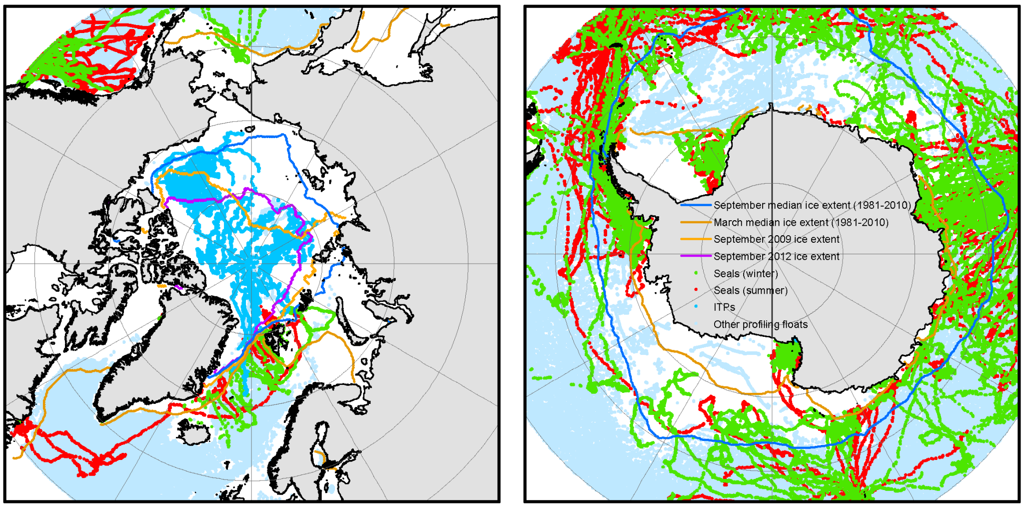

Figure 2. Maps showing the distribution of seal-borne CTD profiles (green and red dots), profiling floats (light blue), and ice-tethered profilers (blue), from WOD [13] and http://www.whoi.edu/itp. In addition, the 1981–2010 median sea ice extent in March and September is indicated, along with the September Arctic sea ice extent in 2007 and 2012 (from Fetterer *et al.* [61]).

of freeboard from the 1990s to today. These time series are not yet as long as those of ice concentration, but they do show promise for monitoring future changes in sea ice thickness if continued.

The PIOMAS ice/ocean model [59] uses the long time series of ice concentration to deduce ice volume using a dynamic and thermodynamic sea ice model to calculate sea ice thickness, assimilating the satellite-derived ice concentration data. The resulting time series of ice thickness in the Arctic compares quite well with the available satellite and submarine data when these are available [59]. Perhaps by also assimilating sea ice thickness data into the model further improvements can be made to estimates of ice volume.

(h) Putting it all together

Traditional repeat hydrographic data aim to be taken at the same positions on every visit (ice and weather permitting), making comparisons of successive measurements fairly straight forward. In contrast, the paths of drifting ITPs and Argo floats and foraging seals can be erratic, with uneven temporal and spatial coverage. To obtain a better overall estimate of the ocean state from these data, they can be used to constrain general circulation models [1]. For the Southern Ocean, this has been done as the Southern Ocean State Estimate [2], incorporating remote sensing data, ship-based observations, and autonomous platforms.

The impact of adding seal-borne profiles into the state estimate has been evaluated by Roquet *et al.* [60]. By comparing a version of the state estimate incorporating only Argo floats with a version using both Argo and seals, they found that errors in the model were considerably reduced compared with independent observations.

The spatial and temporal distribution of different measurement types is shown in figure 1. Profiling floats appear to provide the most consistent year-round measurements. However, from figure 2 we can also see that there are large areas in the perennial and marginal ice zones where few or no profiles are available from this source. The conventional bottle data, CTD, mechanical bathythermograph (MBT) and XBT casts all show roughly similar patterns biased toward the summer months. In the Arctic there are slightly more winter- and spring-time bottle/MBT measurements, largely stemming from airborne and drift station measurements in past years.

The seal-borne measurements have a completely different time distribution, yielding most data in early winter, and then dropping off over the spring as more tags fail or fall off. The ITPs provide a relatively stable number of profiles throughout the year in the Arctic, with most in autumn (shortly after deployment); in the Antarctic there was only one deployment, so the distribution there is not statistically representative. From figure 2 we can see that the spatial distribution of seal data in the Antarctic complements the profiling float data well: seals have provided measurements in many of the ice-covered areas that are not accessible to floats — though there still are gaps in large areas, such as the perennially ice-covered western Weddell Sea and parts of the Amundsen and eastern Ross seas (though seals have been tagged in the Amundsen Sea in February 2014, promising to plug one of these holes). In the Arctic the ITP dataset from the central Arctic Ocean complements the seal data in the marginal seas, and profiling floats further south.

Looking at the number of profiles from different platforms, the relative abundance of historical data in the Arctic compared with the Antarctic is immediately apparent: until the early 2000s there are very few Antarctic data. In both hemispheres, there is a clear effect from the International Polar or Geophysical Years: measurements do increase noticeably in conjunction with these events. In the case of the latest International Polar Year, 2007–2009, there is a large increase in ITP data in the Arctic, and a large increase in float and especially seal data in the Antarctic. Suddenly the number of annual profiles from the Antarctic has, for the first time, surpassed the number in the Arctic.

3. Sea ice decline in the Arctic

One of the most significant changes in the polar regions in recent years is the decline of Arctic sea ice. Different techniques have provided observations of the sea ice itself, as well as the forcing that is behind these changes, making it a good case study of how some of these methods can be used.

In recent years, a marked decrease in sea ice extent (typically defined as the area with >15% sea ice concentration) has been observed in the Arctic Ocean, with the most extreme minima observed in 2007 and 2012 [61] (see figure 2). This has significant implications not only for regional climate, but also for ecosystems, where shifts in the ice edge and changes in seasonal ice cover can have large effects on organisms at all trophic levels [62, 63]. In addition, the retreat of sea ice is spurring an increased interest in Arctic oil exploration and shipping [64], with consequences for international relations [65]. Unlike the Antarctic, which is governed under the Antarctic Treaty, much of the Arctic falls into the territorial seas and exclusive economic zones (both established and claimed) of the Arctic coastal states [66].

Changes in the sea ice extent have been quantified from satellite-derived data. By 2000 the observed rate of decline in the annual minimum sea ice extent was 6.4% per decade [67]. In subsequent years, the ice extent continued to decline at an accelerating rate[68], with minima observed in 2002, 2005, 2007, and 2012 [61].

Different explanations for the decline in Arctic sea ice have been offered, and indeed there are probably many different contributing causes, acting on different time scales. The circulation of sea ice in the Arctic is largely dependent on atmospheric circulation [69], while its melting is controlled by solar radiation both directly and through heat absorbed in the surrounding open water [70], as well as by heat fluxes from deeper waters [71, 72]. Many of these processes are summarised by Stroeve *et al.* [73], who provide a review of recent changes to the Arctic sea ice cover and the underlying processes.

In 2007 different processes worked together to cause the record minimum ice extent. A larger-than-normal sea ice export was observed through Nares Strait [74] and Fram Strait [75, 76], driven by anomalous wind patterns [77]. At the same time, a record volume of warm Pacific water was imported through Bering Strait [78].

The low ice concentration caused significant ice albedo feedback, leading to an estimated four–five times increase in solar heat input into the upper ocean in the Beaufort Sea, causing increased ice melting from below [79]. And the warming of the Atlantic Water observed over the preceding years would also have caused an increased upward heat flux into the overlying halocline waters, contributing to the decrease in sea ice thickness [71].

These measurements have come from a multitude of sources, including repeat hydrographic sections, moorings, and IMB and ITP data. Although it was fortuitous that the 2007 event took place in IPY, when more observations than usual were being made, the time series from the inflow and outflow regions and the boundaries of the Arctic Ocean, combined with drifting buoys in the interior, are critical to understanding the context of the event.

4. The future

The third International Polar Year took place in 2007–2009 [80, 81, 82], leading to a marked increase in measurements over that time period (see Figure 1). Since then, levels of observation have decreased, but many of the novel methods that were introduced or whose use was expanded during IPY, such as ITPs and seal tags, continue to provide larger numbers of data than ever before from the polar regions [13]. IPY did lead to an increase in funding for polar research in many countries [83]. However, in the current economic climate, levels of funding are under increasing pressure in many nations, and it is difficult to see how sustainable the current level of activity is, if changes are not made to how observations are performed.

One method of increasing the efficiency of observations is to increase international collaboration, making better use of ship time, and decreasing duplication of effort, as well as improving data management, distribution and sharing. In addition, as autonomous platforms and novel sensors become more capable, they can replace some measurements previously done from ships. However, there is still a need for ships to deploy and recover these instruments, and to transport personnel and supplies to the polar regions.

Sustained observations are necessary to enable us to quantify the rapid and significant changes that are occurring in the polar oceans. However, it is also necessary to perform more focused process-oriented and curiosity-driven research in these regions. These studies help interpret long-term time series and understand the processes driving the observed changes. Although this type of research should not be constrained by the locations of sustained observations, it can be beneficial to both shorter and longer-term measurements to co-locate them, reducing the cost of logistics necessary to reach the study areas, and even using long-term observing networks as test platforms for novel sensors and instruments.

It is also necessary to optimise observing networks. While this can lead to reductions in some types of measurements, increased use of autonomous vehicles can also mean that some fixed instruments can be replaced by more flexible AUV or glider surveys. If properly coordinated, these platforms could also be deployed to fill gaps in surveys done by less predictable platforms such as floats and seals.

(a) Chemical sensors

Currently physical data are sparse in the polar oceans, but chemical and biological data are even rarer. Optical sensors for nitrate do already exist, and have been used in the Arctic Ocean in conjunction with more widely used dissolved oxygen sensors [84]. Although the response is slower than conductivity and temperature sensors, continuous profiles of these properties have yielded new information about features that otherwise could easily be missed or be mistaken for outliers when sampling using discrete water bottles.

Recently fluorometers have been added to seal-borne CTD tags [85], opening the possibility of measuring primary production in otherwise poorly sampled regions and times of year. And an increasing number of Argo floats are being equipped with bio-optical and chemical sensors [86, 87], with miniaturized CO_2 sensors recently tested on profiling floats[88]. As novel sensors are developed and existing technologies become miniaturised, with reduced power consumption and higher stability, more chemical data will undoubtedly become available from the polar regions in years to come, as they can be added to gliders, floats, and seal tags. This can be used to address a multitude of problems including the role of the polar regions in the carbon cycle [e.g. 89] and other nutrient cycles.

(b) Coordination of observing systems

Both in the Arctic and in the Antarctic, there have been concerted efforts to coordinate and expand observing networks in recent years. In the Southern Ocean this is primarily through the Southern Ocean Observing System (SOOS) [90]. This is envisaged as an integrated system incorporating data from both conventional and autonomous sources and remote sensing, assimilating them into physical and biogeochemical models. SOOS is designed around six key questions or themes [91]. At this stage, key variables and observing platforms have been identified, and broad guidelines for data management have been set out, but there is still a long way to go before the observing system is operational. Meredith *et al.* [90] recommend implementing a regional pilot study as a first step toward a full circum-Antarctic observing system.

In the Arctic there are also efforts to coordinate observations, both nationally [e.g. 92] and on an international scale. The integrated Arctic Ocean Observational System (iAOOS) originated as a coordination of Arctic Ocean observations during IPY [81]. In the future it is envisaged as a network of both Lagrangian (ITP/POPS buoys and gliders) and Eulerian (moorings) platforms monitoring the Arctic Ocean [93].

5. Conclusions

The oceans in both the Arctic and Antarctic are undergoing changes unprecedented in observational records. While developments in remote sensing, autonomous and seal-borne platforms are providing increasing quantities of data from areas previously unsampled and unreachable, the polar oceans are still undersampled compared with much of the World Ocean. Bringing research vessels to the polar regions is still necessary, both to continue existing time series and to deploy autonomous systems. And conventional measurements will be necessary for the foreseeable future to assess the performance of observing systems using novel methods, in order to ensure continuity of existing long-term records in key locations such as the inflow/outflow regions of the Arctic, and in Drake Passage.

However, it is important to develop and improve autonomous platforms for use in ice-covered regions if we are to continue measurements in the future, as well as expanding the array of sensors that can be used on these platforms to include chemical and biological properties. As these technologies mature, it is likely that they will need to supplant an increasing number of conventional measurements. And as more data are collected from these regions, increased international coordination and collaboration are required both to optimise the observation networks themselves and to enable optimal utilisation of the data to provide state estimates of the ocean.

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