

Observing the polar oceans during the International Polar Year and beyond

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Introduction

Leaving behind a legacy is a key aim of the International Polar Year (IPY) 2007-2008 (Allison *et al.*, 2007). One of the key legacies from the International Geophysical Year (IGY) of 1957-1958 was the establishment of a network of bases in the Antarctic that would provide springboards for a greatly enhanced programme of exploration of the interior of the continent. Most of these bases are still active today and, as a result of the ever increasing scientific interest in the polar regions, they have been augmented with bases emplaced by yet other nations that were not participants in the IGY.

In the case of IPY 2007-2008, we will be focusing on a different kind of scientific legacy, the establishment of observing systems for detecting and monitoring changes in the ice/ocean/atmosphere system at high latitudes and for providing the data essential for forecasting future change. This difference of approach between the IGY and the IPY has come about through the massive increases in robotics, automation, miniaturization, communication and computing

power that have taken place in the last 50 years, enabling us for the first time to begin to sample hitherto unsampled or extremely poorly sampled regions like the polar oceans. In the preparations for IPY, WMO, in partnership with the International Council for Science (ICSU) and UNESCO's Intergovernmental Oceanographic Commission (IOC), promoted the notion that Arctic and Southern Ocean Observing Systems should be key outcomes of the investment in the IPY 2007-2008. Parts of these oceans are difficult to access for the six months of the year that the sea's surface is covered in sea ice and are commonly hard to work in because of high winds, high seas, poor visibility, sub-zero temperatures, 24-hour winter darkness and the icing of ships' superstructures.

Yet, with automated approaches combined with remote measuring and communications systems such as subsurface floats, moorings, gliders and autonomous underwater vehicles, automated devices deployed on other autonomous platforms and advanced underwater acoustic communication systems, there is now vastly increased

potential to collect previously missing *in situ* data for combination with the now well-established satellite data. Exploiting these potentials should allow us to do routinely what has been difficult to do before—to make in-water measurements year-round, and to make them beneath the sea ice.

In the Arctic, the idea is to develop and sustain an integrated Arctic Ocean Observing System (iAOOS), while, in the Antarctic, a Southern Ocean Observing System (SOOS) is planned. Both iAOOS and SOOS will provide knowledge, understanding and prediction: knowledge of the state of the system at any one time; understanding of the processes at work; and the ability to combine that knowledge and understanding in advanced numerical models to predict change. These two new systems will contribute directly to the Global Ocean Observing System, sponsored by IOC, WMO and UNEP, and through that the Global Climate Observing System (GCOS), for which GOOS provides the ocean component. GOOS and GCOS are in turn components of the Global Earth Observing System of Systems (GEOSS), providing advice to

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global policy-makers. Neither iAOOS nor SOOS is a regional GOOS body; rather, they are technical designs for implementation by nations working together or separately, as appropriate.

Observations of the Arctic and Southern Oceans will be made by a diverse array of tools, including—and expanding on—the observing methodologies developed by the ocean research community, and deployed and coordinated operationally under the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM), which includes, for example, operations by ships, by drifting and moored buoys, and by sea-level stations.

The development of ocean observing systems for the polar oceans is complementary to the establishment of a Global Cryosphere Watch (GCW), which was proposed to, and welcomed by, Fifteenth World Meteorological Congress. The concept of GCW is based on the recommendations of the Integrated Global Observing Strategy (IGOS) Theme on Cryosphere (CryOS) recently developed by the World Climate Research Programme (WCRP) through its Climate and Cryosphere project and the Scientific Committee on Antarctic Research (SCAR). The Theme report was approved by the IGOS Partnership in May 2007. It includes, among other things, recommendations for the observation of sea ice (for details see <http://igos-cryosphere.org>).

The need for sustained and integrated observing systems, especially in the polar regions, where the effects of global warming are happening more rapidly than elsewhere, has been recognized for well over a century. It was the Austrian architect of the First International Polar Year, Carl Weyprecht, who first publicly appreciated the need to study the Earth as an integrated system and that to do so we require “coordinated and synchronized observations to provide information on characteristics,

changes and the distinctive nature of phenomena in space and time” (Weyprecht, 1875). He was ahead of his time.

Governments are keen to see the science community take these developments forward. The Arctic Council Ministerial Meeting of 26 October 2006 provided a mandate for sustained Arctic observing networks by urging “all member countries to maintain and extend long-term monitoring of change in all parts of the Arctic, and request[ing]... efforts to create a coordinated Arctic Observing Network that meets identified societal needs”. The Antarctic Treaty Consultative Meeting on 11 May 2006, resolved to urge Parties “to maintain and extend long-term scientific monitoring and sustained observations of environmental change in the physical, chemical, geological and biological components of the Antarctic environment; to contribute to a coordinated Antarctic observing system network during the IPY (2007-2008); and to support long-term monitoring and sustained observations of the Antarctic environment and the associated data management as a primary legacy of the IPY, to enable the detection, and underpin the understanding and forecasting of the impacts of, environmental and climate change”.

A Southern Ocean Observing System (SOOS)

The coordinated nature of Antarctic and sub-Antarctic change

Society’s ability to adapt to or mitigate the threat of climate change requires, first and foremost, an understanding of how the climate system works. The ocean stores immense amounts of heat and of the greenhouse gas carbon dioxide and moves both of them slowly around the world, thus

influencing climate both regionally and globally. The Southern Ocean is the key connector in this global circulation: it receives climate signals from the rest of the world’s oceans and exports the climatic imprint of the Antarctic region. North Atlantic Deep Water arrives with signals from the Norwegian-Greenland and Labrador Seas. In the Antarctic Circumpolar Current (ACC), the world’s largest ocean current with a transport of 130 million m³/s, this water is integrated with other deep water into the Circumpolar Deep Water (CDW). Under the influence of the strong prevailing westerly winds the surface waters are pushed northwards, allowing CDW to well up near the continent. On the continental shelf it is cooled enough to become dense and sink down the continental slope, forming the Antarctic Bottom Water (AABW) that aerates and cools the abyssal layers of the world’s oceans. Further north in the ACC, processes involving the sinking of surface waters lead to the formation of Sub-Antarctic Mode Water and the denser Antarctic Intermediate Water. These water masses occupy the region below the surface and thermocline waters to a depth of several hundred metres or more and are known to be susceptible to changes in climatic forcing, including those of anthropogenic origin.

Understanding these oceanographic processes and their connections with the rest of the climate system is one of the bases for predicting the timing, magnitude and direction of future change and therefore demands that we monitor the physical properties of the Southern Ocean (Figure 1).

Change is evident over much of the Southern Ocean. Since the mid-1960s, the east coast of the northern Antarctic Peninsula has warmed rapidly in summer, with near-surface atmospheric temperatures increasing by more than 2°C, leading to the collapse of the two northern sections of the Larsen Ice Shelf. The warming is attributed to westerly

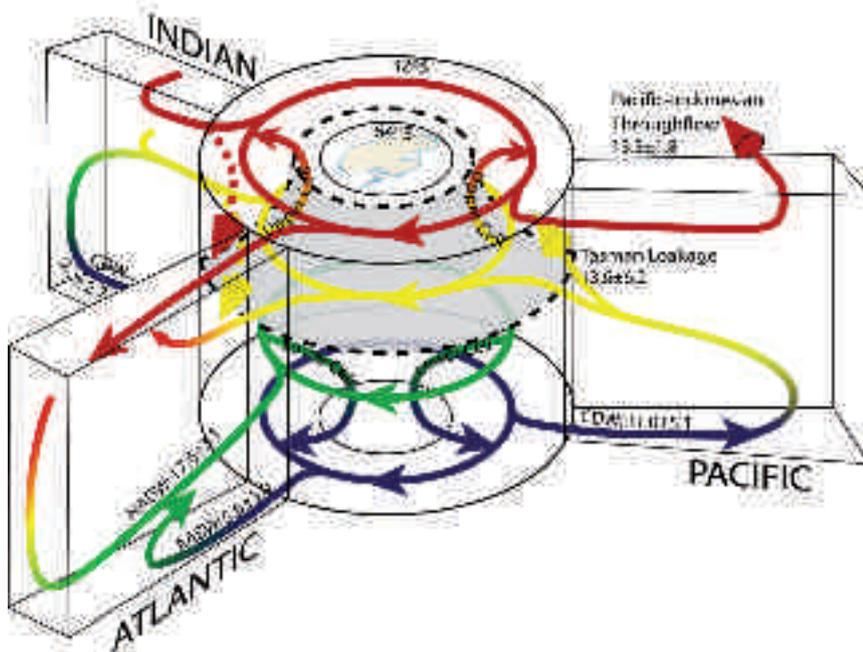


Figure 1 — The global overturning circulation, showing the key linking role of the Southern Ocean (Lumpkin and Speer, 2006)

winds becoming strong enough in summer to carry warm maritime air from the west over the barrier presented by the Antarctic Peninsula. Strengthening of the westerly winds results from a shift of the dominant meteorological pattern—the Southern Hemisphere Annular Mode (SAM)—into its positive phase, in which surface pressures drop over the Antarctic and rise in mid-latitudes. The shift and the observed rapid warming on the eastern Antarctic Peninsula appear to be a response to anthropogenic forcing by greenhouse gases (Marshall *et al.*, 2006).

It has been suggested that the increasing SAM may have led to a latitudinal shift and increase in transport of the ACC (Fyfe and Saenko, 2006). While there is good observational evidence that the ACC transport depends strongly on the SAM on time-scales from days and weeks (Aoki, 2002; Hughes *et al.*, 2003) to years (Meredith *et al.*, 2004), it has also been argued that the trend in winds is more likely to result in a trend in circumpolar eddy activity rather than one in ACC transport (Meredith and Hogg, 2006).

Gille (2002, 2003) has shown that in recent decades there has been a large-scale warming of around 0.2°C within the deep waters of the ACC. This was recently extended to show that this warming is surface-intensified, reaching as much as +1°C at the surface (Gille, 2007). Some of the warming could be attributable to a southward shift of the ACC current cores, essentially reflecting a redistribution of heat rather than an increase, though other interpretations are possible. For example, it could be explained by an increase in eddy activity in the Southern Ocean transporting more heat southward towards the Antarctic as a consequence of the strengthening of the circumpolar westerly winds (Meredith and Hogg, 2006; Hogg *et al.*, 2007).

Advanced numerical models can now reproduce a warming comparable to that observed in the Southern Ocean, which is more rapid than elsewhere in the world ocean. Analyses show that the Southern Ocean would by now be even warmer than it is but for the masking effects of volcanic and other aerosols (Fyfe, 2006).

Regional change is also observed in the Southern Ocean. Robertson *et al.* (2002) found that the warm deep water (WDW) layer within the Weddell Sea warmed by around 0.3°C. Boyer *et al.* (2005) noted large decreases in salinity south of 70°S in the Pacific Sector of the Southern Ocean and in the Weddell Sea. Freshening of the Ross Sea has been detailed and the Amundsen shelf and upper slope freshened and cooled between 1994 and 2000 (Jacobs, 2006). These waters include source waters for the AABW of the Indian and Pacific sectors of the Southern Ocean, which have shown a consequent rapid freshening (Rintoul, 2007). Thompson and Solomon (2002) attribute a regional decrease in ice extent in the Weddell Sea/Antarctic Peninsula area to an air-temperature-driven ice retreat effect caused by the shift in SAM. Continued decreases in sea ice in that region are balanced by an increase in sea ice in the Ross Sea (Gloersen *et al.*, 1992).

Warming on the west side of the Antarctic Peninsula appears linked to a decrease in sea ice in the adjacent Bellingshausen Sea, where the summertime surface and near-surface ocean has warmed by more than 1°C, faster than most other parts of the world ocean. The sea has also become more saline in summer. These changes are both positive feedbacks, acting to promote further decrease in ice production and further atmospheric warming. As the ocean warms only near the surface, the cause is likely to be meteorological, rather than oceanic. Further warming may lead to losses in species and populations of marine biota (Meredith and King, 2005).

Modelling suggests that over the next 80–100 years, we are likely to see the marginal sea-ice zone warm during the winter by up to 0.6°C/decade. Sea ice is projected to decrease by 25 per cent. Westerly winds will strengthen over the ocean, mostly in autumn, but coastal easterlies will weaken (Bracegirdle *et al.*, in press).

Southern Ocean observations

JCOMM is responsible for coordinating routine ocean observations in the polar oceans and elsewhere as part of GOOS, currently by the following means:

- The Voluntary Observing Ship (VOS) programme measures the properties of the ocean surface and the lower atmosphere. A subset of these data, with associated extensive metadata, is collected to the higher standards required for climate observations, through the climate subset of the VOS, known as VOSCLim;
- The Ship of Opportunity Programme (SOOP) deploys expendable bathythermographs (XBTs), largely from research and Antarctic supply vessels on routes across the Southern Ocean, to measure upper-ocean heat content;
- The Global Sea Level Observing System (GLOSS) uses tide gauges and the global positioning system (GPS) to measure the height of sea-level around the Arctic Basin and at the coast of the Antarctic and its offshore islands and uses bottom pressure recorders to measure the height of sea-level above the deep sea floor of the Southern Ocean;
- The International Programme for Antarctic Buoys (IPAB), and the International Arctic Buoys Programme (IABP) (both Action Groups of the Data Buoy Cooperation Panel) deploy buoys that drift with the currents at the ocean surface, or on the sea ice, and collect data on the properties of the surface water and lower atmosphere; elsewhere, other DBCP Action Groups, including the Global Drifter Programme, deploy buoys in the Southern Ocean and near-polar regions of all the other ocean basins;

- In ice-free waters, the Argo float programme deploys instrumented floats that move through the ocean at a depth of 1 000 or 2 000 m, ascending every 10 days or so to collect a vertical profile of temperature and salinity that is sent back to base via satellite when a float reaches the surface, upon which the float repeats the cycle;
- The reference buoy network of stations at which measurements are collected of ocean properties through the water column at the same site several times a year to provide a picture of change with time;
- Observations made of the ocean surface by remote-sensing from satellites using instruments of various kinds that can measure changes in sea-ice extent and characteristics, ocean surface height (by altimetry), sea-surface temperature (by infrared radiometry), sea-surface roughness (by scatterometry) and ocean colour (by visible wavelength radiometry).

The global climate module of GOOS was 58 per cent operational in May 2007 and is planned to be fully operational by 2014, though serious challenges to achieving this goal remain (Alverson and Baker 2006). One of the most formidable of these challenges will certainly be achieving comprehensive coverage of the remote Southern Ocean (see Figure 2). Monitoring the Southern Ocean is a formidable challenge, because it is so geographically remote, is such a harsh environment in which to work—especially in the southern winter—and is so far away from major oceanographic centres and shipping lanes. Much more effort than is available at present will be needed to expand present observations into a viable SOOS. Until that effort is made, the Southern Ocean will represent a gap in the knowledge required to predict climate change accurately.

Within the IPY, Southern Ocean physical observations will be made by a variety of means, principally through the IPY programmes given in the table overleaf.

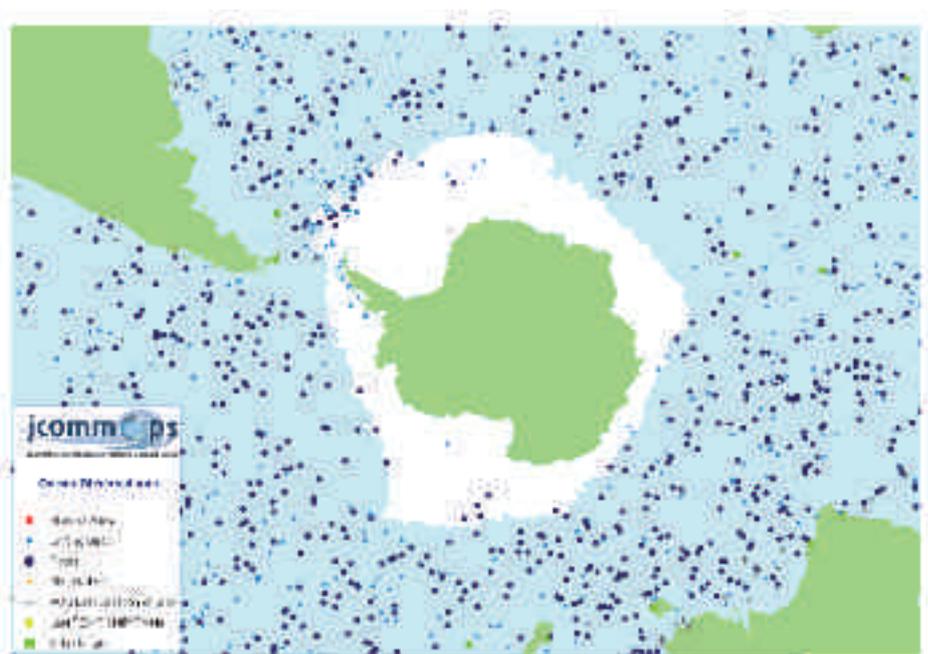


Figure 2 — Southern Ocean and Antarctic observations available in near real time, 23 July 2007

*IPY ocean programmes making physical measurements
(A = Arctic; B = Bipolar; S = Antarctic)*

- 8 (S) Synoptic Antarctic Shelf-Slope Interactions (SASSI)
- 13 (B) Sea Level and Tidal Science
- 14 (A) Integrated Ocean Observing System (iA00S)
- 23 (B) Atlantic Thermohaline Circulation (BIAC)
- 40 (A) Developing Arctic Modelling and Observing Capabilities for Long-term Environmental Studies (DAMOCLES)
- 70 (S) Upper Ocean: Africa to Antarctica
- 132 (S) Climate of Antarctica and the Southern Ocean (CASO)
- 141 (S) Antarctic Sea Ice Processes and Climate (ASPeCT)
- 153 (B) Marine Mammal Exploration of the Oceans Pole to Pole (MEOP)
- 305 (A) Consortium for coordination of Observation and Monitoring of the Arctic for Assessment and Research (COMAAR)
- 379 (A) IPY Operational Oceanography for the Arctic Ocean and adjacent seas (IPY Arctic GOOS)

costly—impacts of climate change on human society, so gathering accurate data on sea-levels worldwide is vitally important. Although sea-level is monitored at hundreds of sites through the IOC-WMO Global Sea Level Observing System, there are large gaps in data from the Arctic and the Southern Ocean because measuring sea-level along remote polar coastlines is a huge technical challenge. By enhancing existing sea-level gauges in the Antarctic and installing new, high-tech devices in the Arctic and on the Southern Ocean islands that will provide high-frequency, real-time data, this project will provide the missing piece of the jigsaw for scientists monitoring sea-level rise across the globe. The same sea-level data can also be used to monitor changes in the circulation of the high-latitude oceans, including transport variability of the Antarctic Circumpolar Current itself (Figure 4). This, in turn, may provide clues as to why sea-level is rising.

IPY 8: Synoptic Antarctic Shelf-Slope Interactions Study (SASSI)

Involving a team of scientists from 11 countries, this project will measure the temperature, salinity and flow speed of the water on the continental shelf and slope, including under ice environments, along short transects across the Antarctic continental shelf and slope (see Figure 3). This is something scientists know very little about but the data are crucial for developing better global climate models.

The few recent measurements we have suggest that the water close to the Antarctic is getting fresher. But where is this extra freshwater coming from? Only by measuring—especially during winter—the properties of the water and how fast it is flowing will we be able to understand the processes that are going on and make sure that these are put into our climate models correctly. There has never been a concerted effort to make measurements on the Antarctic continental shelf and slope during the winter. IPY is enabling everyone to work together to make this happen, by leaving instruments on the sea bed and in the water for a year, even when the ice is covering the sea surface above them. Each nation is going to deploy instruments so that a circumpolar coverage can be obtained for the first time. As well as gathering

data during IPY, some of the SASSI instruments will be left in place after IPY, providing an important legacy for future research.

IPY 13: Sea-level and tidal science in the polar oceans

Sea-level rise will be responsible for one of the most profound—and

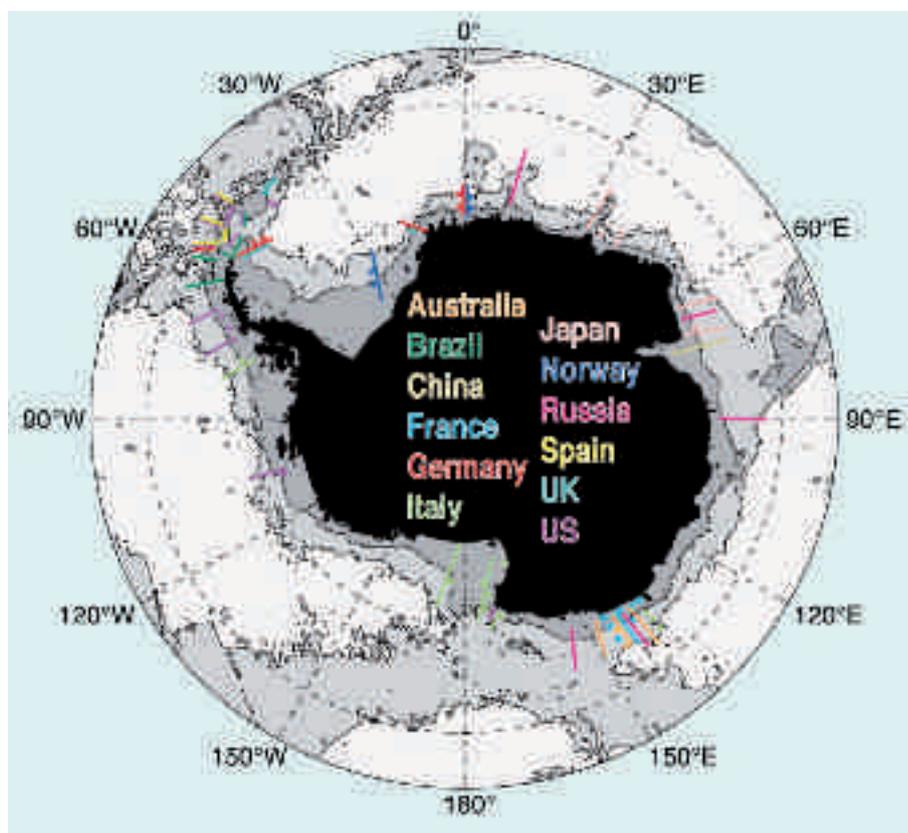


Figure 3 — SASSI conductivity-temperature-depth recorder/Acoustic Doppler Current Profiler sections and moorings planned for the IPY

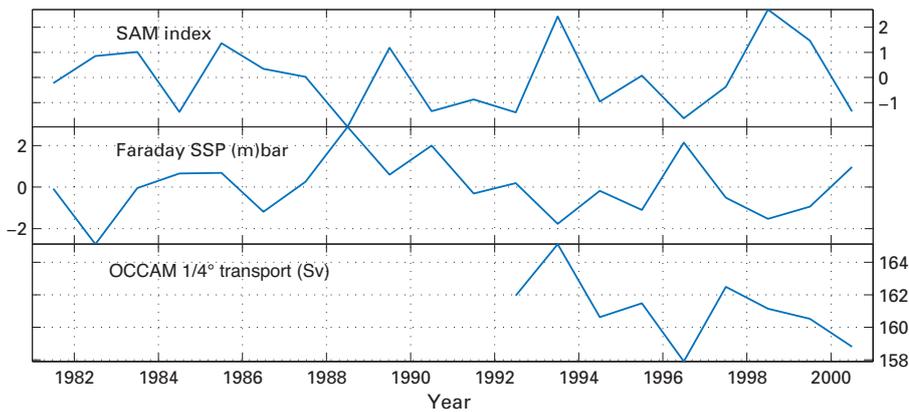


Figure 4 — Transport variability of the Antarctic Circumpolar Current (ACC) at Drake Passage, as measured by the tide gauge at Faraday/Vernadsky on the Antarctic Peninsula (middle line): the top line denotes the changing circumpolar westerlies over the Southern Ocean, which drives the transport changes of the ACC; the bottom line shows the corresponding transport changes in a global oceanographic model (from Meredith et al., 2004).

IPY 23: Bipolar Atlantic Thermohaline Circulation (BIAC)

This international team of oceanographers will embark on expeditions to the Polar Oceans with ice-going vessels to measure ocean temperature, salinity and currents, ice formation and distribution, especially in the Barents Sea and Weddell Sea. They will employ remote-sensing, as well as bottom-anchored instrument moorings to feed global numerical models. The project will try to estimate the impact of dense water formation in the polar regions on the global ocean circulation and climate. Ice-breakers will be equipped with state-of-the-art instrumentation for ocean and sea-ice studies, especially those on mechanisms, manifestations and impacts of bottom water formation on the bipolar Atlantic Ocean shelves.

IPY 70: Monitoring of the upper ocean circulation, transport and water masses between Africa and the Antarctic

An Indian contribution to CASO (see below)

Indian scientists will use expendable bathythermograph/expendable con-

ductivity, temperature and depth (XBT/XCTD) observations in the Indian sector of the Southern Ocean to map the present state and interannual variability of the oceanic environment. They will monitor the circulation, zonal and meridional transport, surface atmospheric heat budget and linkage between Pacific and India Ocean, and devise a framework for understanding climate variability. Year-to-year variability will be monitored, using repeated sampling from the Indian Antarctic expedition's logistic support vessels sailing between Africa and India's Antarctic station, Maitri. Additional hydrographic work will be carried out in areas of water-mass formation in the Ross and Weddell Seas and sub-Antarctic zone.

IPY 132: Climate of the Antarctic and the Southern Ocean (CASO)

CASO aims to obtain a synoptic circumpolar snapshot of the physical environment of the Southern Ocean (collaboration with other IPY activities will extend the snapshot to include biogeochemistry, ecology and biodiversity). CASO also aims to enhance understanding of the role of the Southern Ocean in past, present and future climate, including connections between the zonal

and meridional circulation of the Southern Ocean, water-mass transformation, atmospheric variability, ocean-cryosphere interactions, physical-biogeochemical-ecological linkages, and teleconnections between polar and lower latitudes.

The objectives are to:

- Improve climate predictions, from models that incorporate a better understanding of southern polar processes;
- Provide proof of concept of a viable, cost-effective, sustained observing system for the southern polar regions (including ocean, atmosphere and cryosphere);
- Establish a baseline for the assessment of future change.

CASO involves a number of major field programmes:

- A circumpolar array of full-depth multi-disciplinary hydrographic sections and XBT/XCTD sections, extending from the Antarctic continent northward across the Antarctic Circumpolar Current, including key water-mass formation regions;
- An enhanced circumpolar array of sea-ice drifters, measuring a range of ice, ocean and atmosphere parameters;
- Profiling floats deployed throughout the Southern Ocean, including acoustically-tracked floats in ice-covered areas;
- Current-meter moorings to provide time series of ocean currents and water-mass properties at key passages, in centres of action of dominant modes of variability, and in areas of bottom water formation and export;
- Environmental sensors deployed on marine mammals;

- Direct measurements of diapycnal and isopycnal mixing rates in the Southern Ocean;
- Analysis of ice cores, sediment cores and deep corals to extend observations of Southern Ocean variability back beyond the instrumental era;
- Bottom pressure gauges near Drake Passage to monitor ocean currents, validate tidal models, and improve regional corrections to satellite altimeter products;
- Automatic weather stations, flux measurements in the boundary layer and drifters to measure atmospheric variability (pressure, winds, heat and freshwater flux).

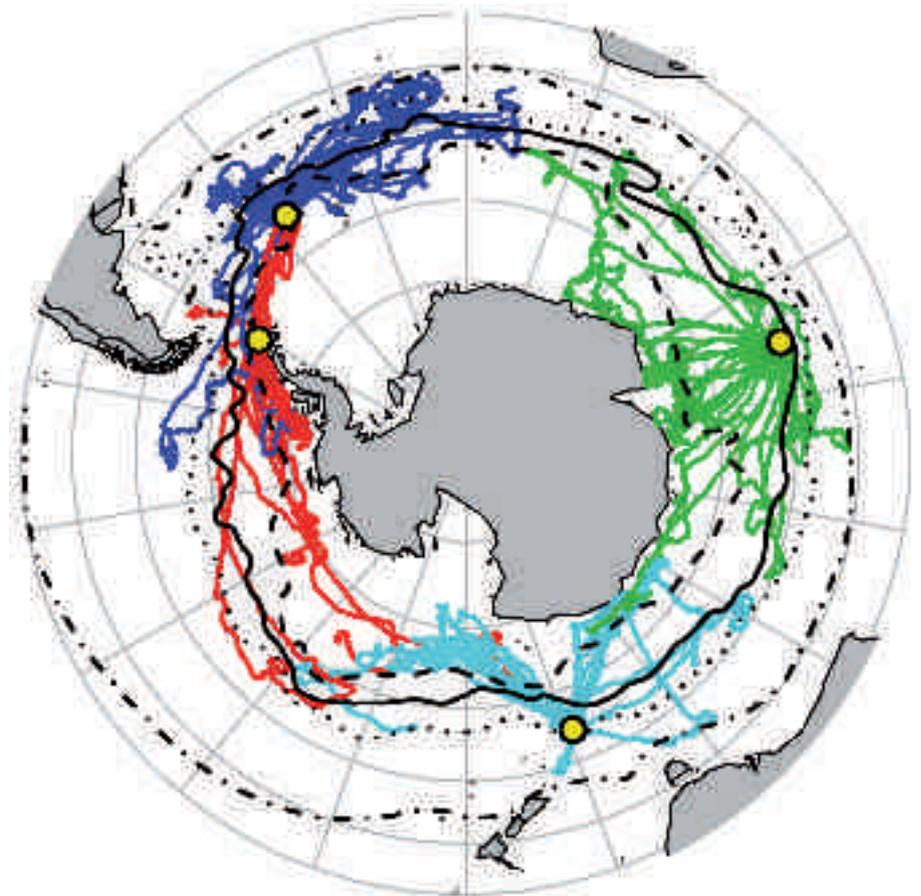


Figure 5 — Tracks of elephant seals tagged with instruments to record temperature and salinity profiles in the Southern Ocean (from Biuw et al., 2007)

IPY 153: Marine Mammal Exploration of the Oceans Pole to Pole (MEOP)

Collecting oceanographic data from ice-filled polar waters is costly and logistically challenging. Rather than relying solely on human scientists, this project uses beluga whales and four seal species as ocean explorers to collect information about the conductivity (salinity), temperature and depth (CTD) of Arctic and Antarctic waters. By fitting state-of-the-art CTD tags on dozens of these deep diving marine mammals, scientists will be able to gather a rich new dataset that will extend our knowledge of the world's oceans as well as of the behaviour of the top predators that live in them.

MEOP will provide a unique source of fundamental physical and biological data from the polar oceans. Its approach will complement efforts in many other IPY projects and will leave a legacy of useful biological and ocean data, along with new approaches to understanding the interaction of marine predators and their ecosystem. An example of the

huge potential of this technology for oceanographic observing systems in the polar regions is given in Figure 5, which shows the data coverage obtained across the Southern Ocean by this method during 2004-2006.

IPY 141: Sea-ice (ASPeCt)

The sea-ice programme will establish a quantitative base for circumpolar ice thickness to enable comparison between ice thickness distributions derived from ship observations and those available from validated satellite altimetric observations. Antarctic sea-ice cover can then be quantitatively evaluated for response to global climate change in the future. A principal legacy will be the development of validated satellite technology for sea-ice thickness monitoring in the Antarctic that can be used to elucidate interannual and longer variability in Antarctic sea-ice cover after IPY.

An integrated Arctic Ocean Observing System (iA00S)

The coordinated nature of Arctic and sub-Arctic change

When the Atlantic water core temperatures across the Arctic Ocean are reconstructed over the whole of the past century, as Polyakov *et al.* (2004) have done (Figure 6), we find, to our surprise, that, despite a very variable data-density with time, each of the main episodes in the hydrographic history of the Norwegian Sea over the past century (e.g. Dickson and Osterhus, 2007) is represented. Thus, as in the Norwegian and Barents Seas (see Helland Hansen and Nansen, 1909), the series begins with conditions of extreme cold around the turn of the last century, recorded by Nansen (1902) during the long

polar drift of the *Fram*. This is plainly followed by a period of sustained warmth after the 1920s, consistent and concurrent with the “warming in the north” that pervaded the Atlantic northern gyre (reviewed in Dickson, 2002). Then a sharp re-imposition of cooling in the late 1960s/early 1970s, accompanying the passage of the Great Salinity Anomaly around the northern gyre and the associated extreme southeastward shift of the Ocean Polar Front. Thereafter, successive pulses of warmth spread along the eastern boundary to produce the warmest conditions of the century in the Atlantic-derived sublayer of the Arctic Ocean—an increase of ~9 per cent in the heat content of the Atlantic water core between the 1970s and the 1990s, according to Polyakov *et al.* (2004, 2005).

The implication of Figure 6 is that a whole Arctic/sub-Arctic system of change is involved here; that the sub-Arctic seas have been a continuing source of multi-decadal Arctic change over the past century; that the same complex of causes that drove these changes in the Nordic Seas has contributed to change in the Atlantic water core temperature of the Arctic; and that the input of warmth from the Norwegian Sea to the Arctic Ocean appears to be continuing. The Arctic freshwater balance is also involved, of course. Hakkinen and Proshutinsky (2004) find that “changes in the Atlantic water inflow can explain almost all of the simulated freshwater anomalies in the main Arctic basin”.

The fate of the Arctic perennial sea-ice cover is a central focus of the International Polar Year and of many of the research programmes contributing to it—understandably so. Most computer simulations of the ocean system in a climate with increased greenhouse-gas concentrations predict a weakening thermohaline circulation in the North Atlantic—the so-called Atlantic Conveyor—as the subpolar seas become fresher and warmer (milestones for this prediction might run from the

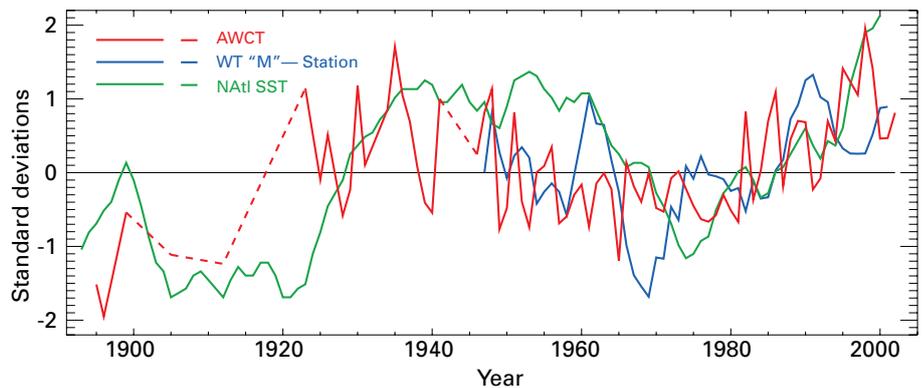


Figure 6 — Century-long comparison between the Atlantic Water Core Temperature (AWCT) at subsurface depths of the Arctic Ocean, the normalized six-year running mean temperature at 10 m depth at Ocean Weather Station Mike (66°N, 2°E) in the Norwegian Sea and normalized North Atlantic sea-surface temperature anomalies for the region bounded by 0°-90°N, 70W°-30°E (reproduced from Polyakov *et al.*, 2004, with their kind permission)

pioneering modelling work of Bryan (1986) and Manabe and Stouffer (1988) through the intermediate complexity of Rahmstorf and Ganopolski (1999), Delworth and Dixon (2000) and Rahmstorf (2003) to the full complexity of Earth system modelling by Mikolajewicz *et al.* (2007)); and the dwindling of sea-ice extent over the past three decades (Figure 7) will have made its contribution to the vast outpouring of freshwater from the Arctic to the Atlantic that has taken place since the mid-1960s

(Curry and Mauritzen, 2005). Second, we can anticipate radical changes in the ecosystem of the Arctic and sub-Arctic seas following the retraction, thinning and perhaps disappearance of the perennial sea ice; the recent Arctic Climate Impact Assessment (ACIA) Report suggests that a 2.5-fold increase in primary production may result from the removal of light limitation in areas presently covered by perennial ice. Third, it seems likely that the reduction in albedo of the Arctic Ocean from > 0.8 to < 0.2 over

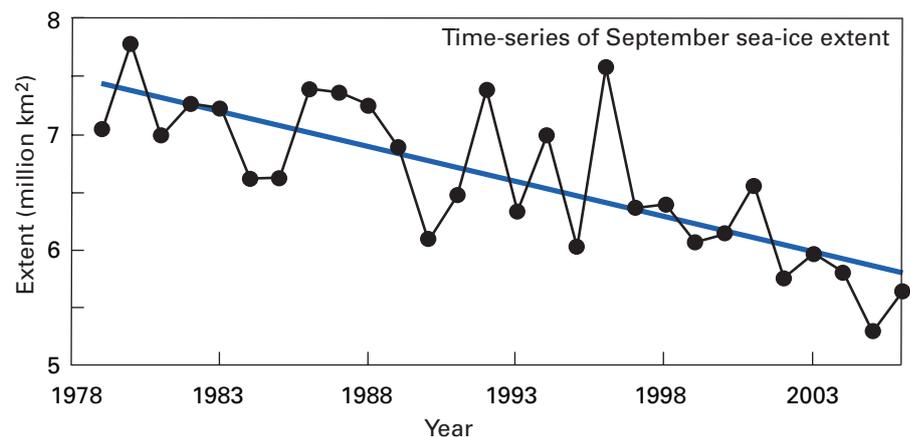


Figure 7 — Northern hemisphere sea-ice extent in September, remotely measured from passive microwave instruments, showing a long-term decline to a record minimum in 2005 (source: Mark Serreze and Julianne Stroeve, National Snow and Ice Data Center (NSIDC), Boulder, Colorado, personal communication, July 2007). Though the estimate for September 2007 is not yet complete, the ice extent of 4.42 million km² reported by NSIDC for 3 September 2007 is already so far below the previous minimum (5.32 million km² on 20-21 September 2005) that a new record absolute minimum seems highly likely (see http://nsidc.org/news/press/2007_seaiceminimum/20070810_index.html).

an area the size of Europe through the projected total loss of the late summer sea-ice cover will have some regional-to-global effect on climate.

With such a broad range of environmental and climatic effects, it is no surprise that the major research efforts in the Arctic during IPY, such as the medium-term European Commission (EC) DAMOCLES Project (involving 45 research institutions in 12 European countries and coordinated with Canada, Japan, the Russian Federation and the USA), the long-term US National Science Foundation Study of Environmental Arctic Change (SEARCH) and many of the national research efforts such as the United Kingdom's Arctic Synoptic Basin-wide Oceanography programme (ASBO) and the Norwegian flagship programme "iAOS for Norway" all draw their primary focus on the present state and future fate of the Arctic perennial sea ice. (It should be noted that the integrated Arctic Ocean Observing System is not a funded programme in its own right but a pan-Arctic framework designed to achieve optimal coordination of funded projects during the IPY. The overarching structure is itself set up to focus on the Arctic sea ice; see Dickson, 2006.)

In this article, we have space to provide only a brief summary of the present extreme state of the warm saline inflow passing poleward along the boundary of the Nordic seas before going on to describe plans to understand the changing sea-ice cover within the Arctic Ocean itself.

The recent spread of extreme warmth along the eastern boundary of the Norwegian Sea and the interconnected "system" of processes responsible

Very recently, the temperature and salinity of the waters flowing into the Norwegian Sea along the Scottish

shelf and Slope have been at their highest values for >100 years. At the "other end" of the inflow path, the ICES Report on Ocean Climate for 2006 (ICES, in press) will show that temperatures along the Russian Kola Section of the Barents Sea (33°30'E) have equally never been greater in >100 years. Shorter records en route and beyond, on the Norwegian arrays off Svinoy (Skagseth *et al.*, in press), on the moored array monitoring the Fram Strait (Schauer *et al.*, in press) and on Polyakov's Nansen and Amundsen Basins Observational System (NABOS) moorings at the Slope of the Laptev Sea (Polyakov, 2005; 2007) have all remarked the passage of this warmth; Holliday *et al.* (2007) have described its continuity along the boundary. It forms part of the rationale for Overpeck's statement (2005) that "a summer ice-free Arctic Ocean within a century is a real possibility, a state not witnessed for at least a million years".

Why? What is driving extreme change through the system? Satellite-based observations seem to provide a plausible explanation: during the whole TOPEX-POSEIDON era (since 1992) as the Labrador Sea water warmed (Yashayaev *et al.*, in press), altimeter records reveal a slow rise in sea-surface height at the centre of the Atlantic subpolar gyre, suggesting a steady weakening of the gyre circulation (Hakkinen and Rhines, 2004, and in press). This weakening is accompanied by a westward retraction of the gyre boundary, which appears to have operated as a kind of "switchgear" mechanism to control the temperature and salinity of inflow to the Nordic seas (Hatun *et al.*, 2005). By that mechanism, when the gyre was strong and spread east (early 1990s), the inflows recruited colder, fresher water direct from the subpolar gyre but when the gyre weakened and shifted west (as in the 2000s), the inflows to Nordic seas were able to tap warmer and saltier water from the subtropical gyre, explaining the recent warmth and saltiness of inflow of Atlantic waters into the Norwegian

Sea. Thus, although the local and the short-term have certainly played their part west of Norway—the speed of the Atlantic Current is locally storm-forced (Skagseth *et al.*, in press)—the ultimate source of the observed changes in the Arctic Ocean appears to lie in a whole system of interactions of the polar and subpolar basins. Near and remote, short-term as well as long-term controls have been involved in providing the Polar Basin with a steady supply of increasingly warmer water through sub-Arctic seas.

We have only just begun to glimpse evidence of this "system" in our observations. But model results also seem to vindicate the view that it is the whole full-latitude system of exchange between the Arctic and Atlantic Ocean—not just spot "examples" of it—that has to be addressed simultaneously if we are to understand the full subtlety of the role of our northern seas in climate. As Jungclaus *et al.* (2005) conclude from their experiments using the Hamburg models ECHAM5 and MPI-OM, while "the strength of the [Atlantic] overturning circulation is related to the convective activity in the deep-water formation regions, most notably the Labrador Sea, ... the variability is sustained by an interplay between the storage and release of freshwater from the central Arctic and circulation changes in the Nordic seas that are caused by variations in the Atlantic heat and salt transport".

The iAOS 'vertical stack' of observations in the Arctic Ocean—from satellites to seabed

Direct observations of the sea ice and its controls within the Arctic Ocean are a fundamental component of iAOS and its component programmes. Recently, as Figure 7 demonstrates, we have seen strong indications of radical changes in the extent and thickness of Arctic sea ice (e.g. Comiso, 2002; Rothrock *et al.*, 2003; Serreze, 2003) but the processes

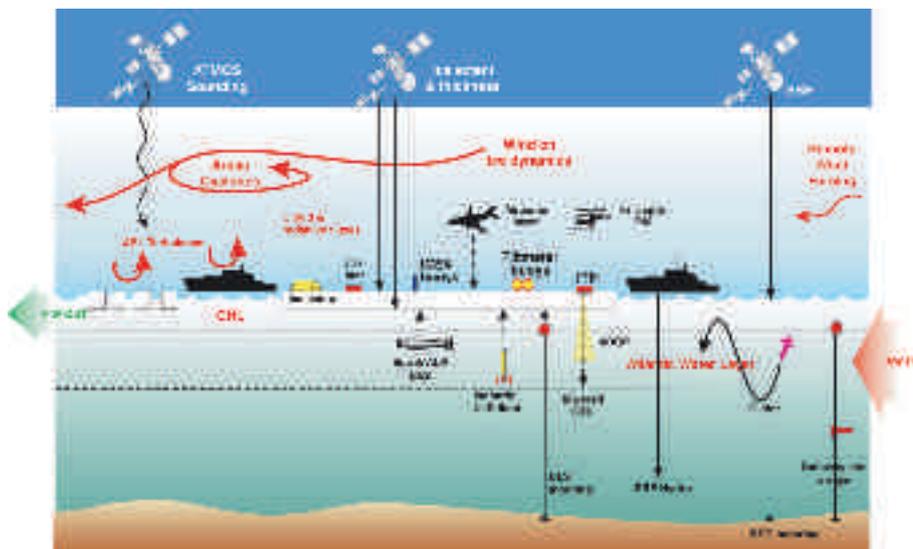


Figure 8 — Schematic of the vertical stack of observations from satellites to seabed thought necessary to inform an iAOOS study focused on the present state and future fate of the Arctic perennial sea-ice (for further details, see Dickson, 2006).

driving these changes are far from clear. In the Arctic Ocean itself, under the iAOOS initiative, soundings of the atmosphere, sea ice, ocean surface, and terrestrial snowcover involving satellites, surface ships, manned ice camps, autonomous ice-tethered platforms (ITPs) and IABP/ICEX buoys (Figure 8) will together provide a new and coordinated way of studying the state and fate of the Arctic ice and its role in European and global climate.

The “atmospheric” objectives of the DAMOCLES Project will enable us to better detect Arctic cyclones and to quantify their contribution to the transport of heat and moisture; to understand and model boundary-layer processes and turbulent fluxes in the atmospheric boundary layer over the Arctic Ocean; to understand and model the formation and life cycle of Arctic clouds, the radiative transfers through the Arctic atmosphere and their interaction with the snow/ice surface albedo. Satellite laser and radar altimetry will continue to provide estimates of ice thickness from direct measurements of freeboard (Laxon *et al.*, 2003). Above the ice, airborne laser and helicopter electromagnetic sensors will provide accurate local calibration and validation for the satellite-derived ice-freeboard

measurements. Across the ice surface, a network of a dozen or so tiltmeter buoys developed by Wadhams and co-workers, will measure the power spectrum of flexural-gravity waves propagating through the ice to provide their own new and independent measures of ice thickness, with on-board processing and transmission of spectra or raw data by low-orbit satellite (Iridium). Beneath the ice, autonomous underwater vehicles and

floats operating accurately at constant pressure will carry upward-looking sonar to further validate satellite estimates of ice-thickness, while a small scatter of bottom pressure gauges moored across the Arctic deep basins (Figure 8) will provide the necessary ground truth to derive estimates of the Arctic Ocean circulation from remotely sensed measurements of sea-surface height.

Though all these systems are new, all exist or are in immediate prospect, and by their use, for the first time, direct measurements or validated estimates of the circulation, stratification and ice-volume of the Arctic Ocean will be possible with monthly-to-seasonal resolution.

Towards implementation

In April 2007, the IPY began. At that point, we moved beyond the initial planning stage to the phase of piecing together the techniques and collaborations that would convert a “potential” iAOOS structure into an actual and funded programme. Deploying such novel studies on a pan-Arctic scale is an exciting challenge (Figure 9). Two examples,

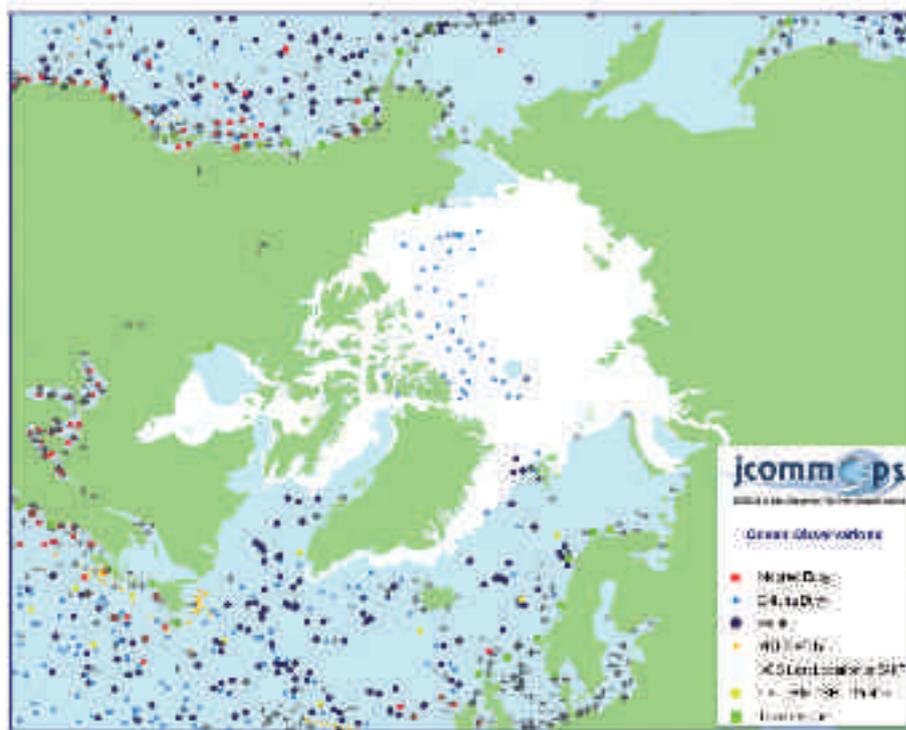


Figure 9 — Existing near-real-time data availability in the Arctic and sub-Arctic on 23 July 2007

currently getting underway, will make the point.

Under the EC-DAMOCLES component of iAOOS, an extensive integrated scheme of floats and gliders (Figure 10) will make subsurface profiles throughout the upper water column of the Arctic Ocean (emphasis on the upper 800 m but with excursions to 2 km depth), thus exploring and describing both the variable cold halocline layer (see Figure 8) and the variable Atlantic-derived sublayer, communicating their data to satellites and receiving measurement-control and navigation information via a net of ice-tethered platforms. Since various ITP designs have been proposed (by US-SEARCH, NOAA, and Woods Hole Oceanographic Institution, as well as by EC-DAMOCLES), their operations, deployment, communications and data systems will themselves require coordination. Some ITPs will deploy profiling CTDs through the upper water column and monitor the vertical structure of ocean currents using acoustic Doppler current profilers, while fulfilling their conventional role of collecting meteorological data at the ice surface.

As a second example, Figure 11 illustrates the recently arranged and effective collaboration between the UK-NERC flagship programme ASBO, Igor Polyakov's NABOS study (IARC Fairbanks), Andrey Proshutinsky's Beaufort Gyre Exploration Project (WHOI), and Ursula Schauer's SPACE programme (Synoptic Pan-Arctic Climate and Environment; Alfred-Wegener-Institut für Polar- und Meeresforschung (AWI), Bremerhaven), amongst others listed in the key.

Through this collaboration, these projects tackle the essential task of quantifying the ice and freshwater content of the Arctic Ocean. The panels to the right of Figure 11 show maps of elevation using the radar altimeter of Envisat (to 81.5°N) and the laser system of ICESat (to 86°N); since the laser measures to the top of

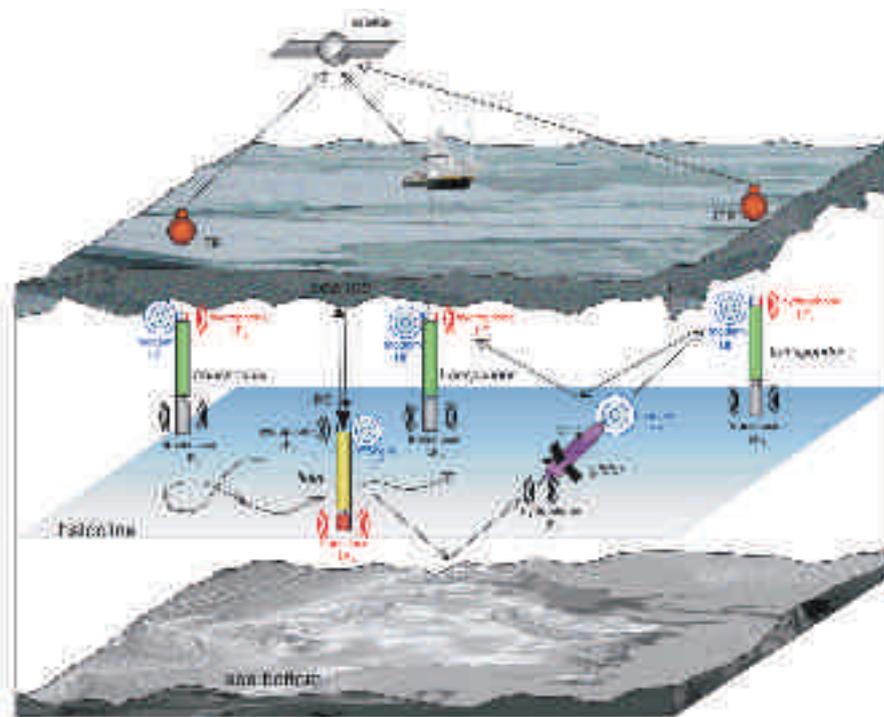


Figure 10 — The ocean-observing scheme for the Arctic Ocean currently being implemented by the DAMOCLES Integrated Project of EC-FP6. An extensive system of floats and gliders will explore the upper ocean, communicating their data to satellites and receiving measurement-control and navigation information via a net of ice-tethered platforms.

the snow and the radar to the top of the ice, their difference should yield snow-depth as well as ice-thickness. The US-UK trans-Arctic section on the Russian heavy icebreaker *Yamal* (main map) contributes the necessary link

between the east Siberian margin and the Eurasian margin (the AWI SPACE project) needed to close off the Arctic into the “boxes” needed to make conservative flux calculations for the whole Arctic Ocean. The panels to the

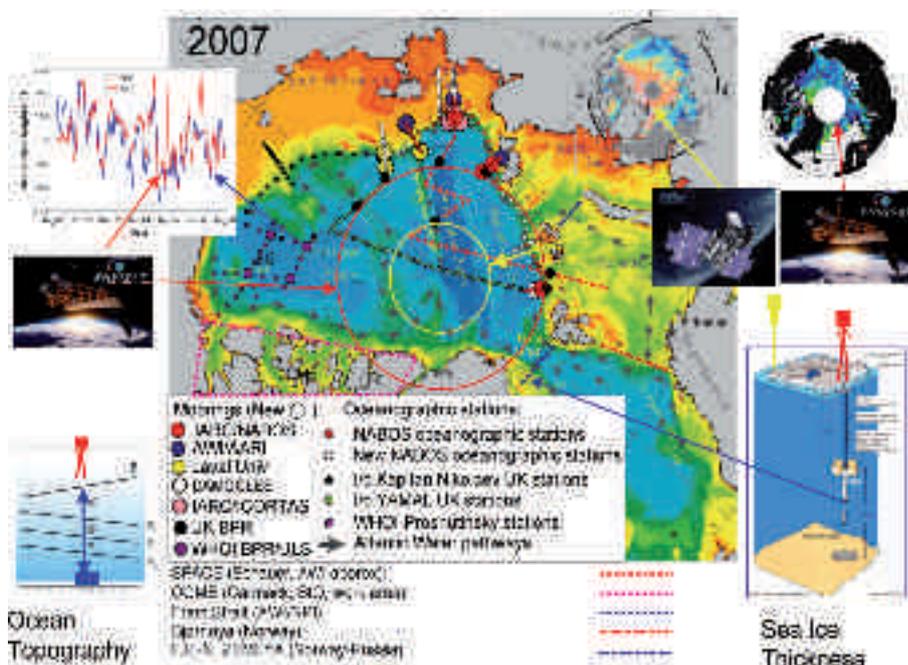


Figure 11 — Plans for iAOOS collaborative oceanography across the Arctic Ocean in summer 2007

left-hand side of this figure convey the exciting news (Seymour Laxon, Andy Ridout and Andrey Proshutinsky; personal communication) that a first comparison of sea-surface height inferred from bottom pressure recorder data in the Beaufort Sea and as measured by the Envisat radar altimeter shows that retrievals of ocean dynamic topography at the centimetre level (and hence measures of the Arctic Ocean circulation) are now possible, even in the presence of ice.

Space does not permit a fuller description of the novel systems that will be deployed across the northern seas in IPY and there are many. But these two examples indicate the major scientific gains to be derived when the available resources of manpower, equipment and shiptime are focused for a while on the problem of the northern seas and their changes, as they could only be for an International Polar Year, and as they will be in iAOS.

Planning for the legacy

A workshop was held in Hobart, Australia, on 15 July 2006, under the sponsorship of SCAR, the Partnership for Observation of the Global Ocean (POGO) and the Census of Antarctic Marine Life (CAML), to explore interest in developing a SOOS as part of the legacy of IPY. Participants agreed that a SOOS was highly desirable and formed a planning committee to take this forward. A workshop to draft an outline plan for a SOOS will be held in Bremen, Germany, 1-3 October 2007. The outline plan will be widely circulated for consultation before being refined at a workshop in St Petersburg, Russian Federation, in July 2008 (in association with the 30th meeting of SCAR) and published during the latter part of 2008. The document will advise on the science plan for a SOOS. It will be up to individual nations with Southern Ocean interests and to organizations such as IOC and WMO, to decide how best to put the plan into effect.

At the same time, nations have made substantial strides towards creating an Arctic Observing System (Lyons *et al.*, 2006), with contributions from existing GOOS regional alliances, such as EuroGOOS, international groups such as the International Arctic Science Committee and Arctic Ocean Sciences Board and, of course, national agencies in interested Member States. At its 24th Assembly in 2007, IOC passed a resolution entitled Programme of Action for GOOS, including a decision to “develop plans and commitments to build and sustain ocean observation networks in the polar regions as a legacy of International Polar Year activities”. It will surely be the new results and surprises that emerge from such a concentrated observing effort across both polar seas that will provide the primary stimulus for putting that resolution into effect.

Conclusions

The polar oceans are grossly undersampled. GOOS and GCOS will never be fully functioning unless we find a means to sample the polar oceans routinely and cost-effectively, with an appropriate level of coverage to capture the main oceanographic and marine meteorological processes taking place there and contributing to climate variability. The polar oceans are also the parts of the oceans which are changing fastest in response to global warming. It is imperative that we monitor this rapid change now as it is likely to be the harbinger of change elsewhere and can alert us to the possibilities. Given that the Intergovernmental Panel on Climate Change has taken a very conservative line in suggesting the amount of sea-level change over the next 100 years and the fact that ice melt triggered by ocean warming may lead to much more rapid and extreme change (up to 5 m; Hansen, 2007) in that same period, it behoves us to pay much closer attention to the behaviour of the polar oceans.

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