Understanding Earth's Polar Challenges: International Polar Year 2007–2008

SUMMARY BY THE IPY JOINT COMMITTEE

World Meteorological Organization
Weather • Climate • Water

ICSU
International Council for Science

PART TWO

IPY Science Program

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Introduction

Ian Allison and Jerónimo López-Martínez

As an internationally coordinated research effort, science was at the core of the International Polar Year (IPY) 2007–2008. In this section, the IPY scientific projects undertaken in major fields and disciplines are summarized, and some of the preliminary results are presented. The scientific results of IPY are still evolving and, as was also the case for previous international polar years, will continue to do so for years after this report is published. The chapters included here were primarily written from late 2009 to early 2010, only a few months after the conclusion of the field campaigns. In some cases, data and samples are not yet analyzed and interpretation and publication of the results is ongoing. In many cases, synthesis of results from different IPY projects will contribute additional outcomes. Hence, this section must be considered only as an early and preliminary summary of IPY scientific outcomes.

The IPY science program was closely linked with other key IPY components, particularly with observational and data-management efforts. IPY projects exploited both existing and newly established observing systems. In many cases, new observing systems have been promoted and developed in connection with IPY scientific projects. Hence, some of the chapters included here in *Part 2* refer directly to observational efforts discussed in *Part 3* and vice versa. In this section, however, the focus is on the scientific problems addressed and on the preliminary results rather than on the observational systems. Throughout IPY planning and implementation, data management was always considered an essential component of each project (*Chapter 3.11*).

The IPY scientific projects also provided fundamental support for other IPY objectives. They were key to attracting and developing a new generation of polar researchers and for engaging the interest of students, polar residents, and the general public. In addition, all endorsed IPY science projects were required to include an integral component of education, outreach and communication.

IPY aimed to establish a scientific program that addressed the six research themes defined by the IPY Planning Group in consultation with the international polar community and relevant organizations (Rapley et al., 2004; *Chapter 5.1*). These were: Status, Change, Global Linkages, New Frontiers, Vantage Point and Human Dimension of the polar regions. Science projects and research teams were expected to be interdisciplinary and to address relevant questions and issues lying beyond individual disciplines.

Considerable effort was given to assembling an IPY science program that addressed these objectives and built on the enthusiastic contribution of a flood of proposals from the community and the great diversity of scientific fields that these encompassed. This process, undertaken in several steps, involved assessing, distilling and combining the 490 initial "ideas" submitted to the ICSU Planning Group by mid 2004 (*Chapter 1.3*), the more than 1100 'expressions of intent' submitted to the Joint Committee by mid 2005 and the 337 full proposals for science projects and data management submitted by February 2006 (*Chapter 1.5*). The IPO and the JC members reviewed and assessed the EoIs and full proposals against the stated IPY objectives. They strived to avoid overlap, to increase interdisciplinarity, to fill identified gaps and to integrate smaller proposals within multidisciplinary, internationally coordinated projects. The final outcome of this process resulted in 170 IPY endorsed scientific research projects, plus one integrating data management project: these formed the core IPY science (*Chapter 1.5*). This IPY science program was documented as it developed in two publications compiled by the Joint Committee (Allison et al., 2007, 2009). IPY 2007–2008 also included an additional 57 EO&C projects. Information available to the IPO at the conclusion of the IPY field period indicated that 170 of the 228 total projects received some support and were able to go ahead.

This section (*Part 2*) consists of 11 chapters, organized by broad disciplinary field. Each chapter summarizes scientific activities in both polar regions, except for the ocean science chapters (*2.2* and *2.3*) and the ice sheet chapters (*2.4* and *2.5*) which treat the Arctic and Antarctic research during IPY separately.

Chapter 2.1 covers research related to the polar atmosphere. It includes reference to 16 projects that are grouped under two main topics: i) physics of the troposphere and stratosphere, and climate change, and ii) tropospheric chemistry, air pollution and climate impacts. *Chapter 2.2* on the Arctic Ocean focuses on the present and future state of northern seas and their role in climate. It describes some of the main advances that were made in research of Arctic and subarctic seas during IPY, and shows how the integrated Arctic Ocean Observing System (iAOOS) served as a coordinating framework for northern oceanographic projects during IPY. This chapter reports on important achievements during IPY that build on existing knowledge of: i) the changing inputs to the Arctic Ocean from subarctic seas; ii) the changing oceanography of the Arctic Ocean itself; and iii) the changing outputs from the Arctic to subarctic seas. IPY research in the Southern Ocean is covered in *Chapter 2.3*. It summarizes preliminary results on the role of the Southern Ocean in the Earth system resulting from multidisciplinary IPY projects in the Southern Ocean carried out by scientists from more than 25 countries. Activities here are grouped into sections on: i) ocean circulation and climate; ii) biogeochemistry; iii) marine biology, ecology and biodiversity; and iv) Antarctic sea ice. Much of the research covered in this chapter is coordinated with similar activities in the Arctic (*Chapter 2.2*) providing a bipolar perspective.

New measurements during IPY led to important advances in knowledge of the Antarctic and Arctic ice sheets, and these are described in *Chapter 2.4* and *Chapter 2.5* respectively. IPY projects investigated ice shelves and the interaction between the ice sheets and the ocean; the subglacial domain; surface and subglacial measurements, including satellite, geological and geophysical observations; and field and numerical modeling studies of climate and glacial history. Advances in the study of subglacial aquatic environments during IPY are summarized in *Chapter 2.6*. During IPY 2007–2008, subglacial lakes and water movement beneath the ice was recognized as a common feature of ice sheets, with potential influence on ice sheet movement and possibly on past and future climate change.

Chapter 2.7 covers regional, bipolar and multidisciplinary permafrost research. Activities during IPY focused on assessment of the thermal state of permafrost and the thickness of the active layer; on the quantification of carbon pools in permafrost and their potential future remobilization; on quantification of erosion and release of sediment along permafrost coasts; and on periglacial process and landform quantification.

Chapter 2.8 deals with IPY projects studying Earth structure and geodynamics in polar regions. It includes research into the geodynamic, tectonic and sedimentary processes that drive the topographic formation and the location of the ocean basins and corridors between emergent land masses. These corridors, which determine ocean current paths, have changed over time, with consequences to global climate. New geodynamic observations in several regions during and just prior to IPY, using seismic, magnetic, gravity and ice-penetrating radar techniques, together with satellite imagery and geological observations, contributed to this research. Research into geodynamic processes at the base of polar ice sheets are also covered in this chapter. This chapter shows how the network of polar Earth and geodynamics observatories has been significantly improved during IPY.

The research carried out during IPY on terrestrial ecology is covered in *Chapter 2.9*. Parts of the Arctic and the Antarctic Peninsula are warming twice as fast as elsewhere on Earth and many impacts already affect biodiversity and ecosystem processes, some of which have global consequences. Therefore, IPY 2007–2008 took place in a very opportune time to document changes in polar terrestrial ecosystems and their impacts on the atmospheric, hydrological and nutrient cycles as well as on the human communities that occupy and use those ecosystems. Altogether, 30 international projects on polar terrestrial biology and ecology were implemented during IPY, and activity has been intense throughout the Arctic and in the Antarctic. Many IPY projects were multidisciplinary ventures and a common denominator for the research was climate change impacts across the polar regions.

IPY 2007–2008 was the first polar year to include social science and humanities, and to involve active leadership from polar residents, particularly indigenous people, in research projects. *Chapter 2.10* covers IPY activities of the 35 endorsed research projects in social science (anthropology, archaeology, economics, linguistics, political science) and the humanities (history, literature, arts). *Chapter 2.11* is about human health and medical research in the northern polar regions and it also includes a substantial social component. It provides an overview of the history, which informed health research activities during IPY 2007–2008, and highlight the IPY activities, which were undertaken within a circumpolar health context. This chapter points out the disparities in human health that currently exist across different Arctic nations and regions.

Although results from many IPY science projects are still being analyzed and interpreted, this chapter, and the recent publications and web pages referenced in it, provide a much-needed early snapshot of the results of the IPY science program by major fields and disciplines. Another attempt as assessing the IPY science outcomes across six cross-disciplinary themes that were pivotal to the IPY 2007–2008 design is offered in *Chapter 5.1*.

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2.1 Polar Atmosphere

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Introduction

While meteorology was the major focus of the first IPY (1882–1883), in the IPY 2007–2008 only 17 from the 170 officially endorsed scientific projects were assigned to the domain of "atmosphere". This does not mean, however, that the role of atmospheric research in polar sciences is not as high as it used to be. The modern atmospheric science has become inherently multi-disciplinary and there is a very significant "atmospheric dimension" in IPY projects carried out in all IPY domains such as ice, ocean, land, people and others. Many of the critically important changes in the Earth system are occurring in the atmosphere ,including the buildup of greenhouse gases with corresponding increase of temperatures, evolving statistical structure of precipitation and stratospheric ozone depletion - to name just a few.

The 17 IPY projects assigned to the domain of "Atmosphere" are listed in Table 2.1-1.

We present here an overview of the preliminary results of polar atmosphere studies obtained in the course of implementation of some the above projects. They are grouped into two main topics: (1) physics of the atmosphere, climate change and processes in the stratosphere and (2) tropospheric chemistry, air pollution and climate impacts.

Project No	Abbreviation	Main topic of the project
19	NobleMet	Pollution Trends
28	CARE/ASR	Climate of the Arctic
32	POLARCAT	Climate, Chemistry and Aerosols
41	Concordiasi	Antarctic Plateau Science
76	ATMOPOL	Pollution Monitoring Network
99	ORACLE-03	Ozone Layer and UV Radiation
121	THORPEX-IPY	Polar Weather Forecasts
140	HIAA	Hydrological Impacts of Aerosols
171	POLAR-AOD-IPY	Aerosol Distribution Network
175	COPOL	Polar Region Contaminants
180	AC	Atmospheric Circulation and Climate
196	IASOA	Arctic Atmosphere Observing System
217	SPARC_IPY	Stratosphere = Troposphere Links
267	COMPAS	Comprehensive Meteorological Dataset of Active IPY Antarctic Measurement Phase for Scientific and Applied Studies
327	INCATPA	Pollution Transport to the Arctic
357	SCSCS	Climate System of Spitsbergen
443	RadTrace	Tracers of Climate Change

Table 2.1-1. IPY projects for polar atmosphere studies.

Atmospheric physics, climate and stratospheric processes

International Arctic Systems for Observing the Atmosphere **(IASOA no. 196)** aimed to enhance Arctic atmospheric research through intensive collaboration during the IPY and beyond. It includes the stations Abisko, Sweden; Alert and Eureka, Canada; Barrow, U.S.A.; Cherskii and Tiksi, Russia; Ny-Ålesund, Norway; Pallas and Sodankylä, Finland; and Summit, Greenland. Measurement and building upgrades took place at the stations Tiksi, Eureka, Summit and Barrow observatories (*Chapter 3.4*).

A new observatory building recently completed in Tiksi is available for installation of instruments (Fig. 2.1-1). A second Clean Air Facility (CAF) that is suitable for aerosol, chemistry, pollutant, greenhouse gases, fluxes and radiation measurements was completed in 2008. Instruments for continuous measurement of ozone and black carbon, and flasks for carbon cycle gas measurements for the new Tiksi station were obtained. Establishment of the Tiksi observatory is a significant step in the creation of an international circumpolar network of stations for monitoring of Arctic climate change. During the IPY period many Russian meteorological stations were substantially reconstructed. Twenty-three meteorological polar stations were upgraded. At several stations, upper-air and geophysical launches of radiosondes and meteorological rockets were restarted. Monitoring of cosmic rays in the Arctic atmosphere was also carried out. Fluxes of charged particles observed in the atmosphere from the ground up to altitudes of 30-35 km provide evidence of unusually profound and long-lasting minimum of the solar activity during the IPY period.

At the Eureka site many instruments including a flux tower, several CIMELs for the Aeronet Network and a Baseline Surface Radiation Network (BSRN) station were installed in summer 2007. With IPY funding, the level of technical support at the site has been increased to provide more reliable data collection and transmission.

The Summit, Greenland observatory has recently released a strategic plan highlighting climate sensitive year-round observations, innovative research platforms and operational plans to increase the use

Fig. 2.1-1. The new building of Tiksi Observatory.
(Photo: Alexander Makshtas; Makshtas, 2007)

renewable energy and maintain the pristine platform. Summit also has a new multi-channel gas chromotograph/mass spectrometer (GC/MS) for continuous measurement of trace halocarbon and CFC gas concentrations. All NOAA instruments were moved from the science trench to a new atmospheric watch observatory building.

The Barrow observatory has two new systems for measurements of aerosol size and chemistry composition, as well as persistent organic pollutants (POPs). The meteorological measurements and data system has been completely upgraded.

Current IASOA activities include the development of a web site (www.iasoa.org) that will serve as the "go-to" site for atmospheric Arctic researchers to obtain information about the member observatories. Information posted for each station includes a general overview of the observatory, a listing of available measurements and principal investigators, links to data bases and station contacts. These pages will help Arctic researchers find the data they need to complete their research. The development of these observatory webpages and the "observatories-at-a-glance" page has allowed us to identify gaps in atmospheric measurements in the Arctic (detailed information on this project is also given in *Chapter 3.4*).

Climate System of Spitsbergen (SCSCS no. 357): Intercomparison and analysis of radiation data obtained by Russian and Norwegian standard radiation sensors at Barentsburg and Ny-Alesund research stations

Joint analysis of historical and current data of radiation observations obtained in different countries indicates a need for comparing readings of instruments. This is especially true for the Russian and Norwegian stations on Svalbard (Spitsbergen). From the beginning of regular Russian radiation measurements on Svalbard (Barentsburg settlement), the observation program has used standard Russian sensors (Yanishevsky-Savinov pyranometers M-80 or M-115M). All radiation measurements carried out on the research stations of other countries involved in polar research (Norway, Germany, Italy, U.K., U.S.A., China, Republic of Korea and France) are compactly located in the Norwegian settlement Ny-Alesund (Kings Bay) and combined into one common network in the framework of the international "Kongsfjorden International Research Base" (Fig. 2.1-2).

The incoming global, diffuse and reflective radiations are recorded separately. As a rule, the aforementioned countries use universal common measurement

Fig. 2.1-2. *Yanishevsky-Savinov* (right) and *Kipp and Zonen* (left) pyranometers used in intercomparisons carried out at the Russian station Barentsburg (Svalbard) in April 2008.

(Photo: Boris Ivanov; Ivanov et al., 2008).

instruments on the basis of "Kipp & Zonen" sensors from The Netherlands (CMP6, CMP11 and CMP21). It seems to be both advisable and necessary to include the Russian observations conducted in Barentsburg into this network. Intercalibration studies in the framework of this program with the use of Russian and Norwegian instruments were carried at the Barentsburg research station in April 2007 and Ny-Alesund ("Sverdrup" research station of The Norwegian Polar Institute) in April 2008. The joint measurements by pyranometers M115M and CM11 have allowed us to obtain representative data for a combined analysis, reveal discrepancies between the Russian and Dutch sensors and take into account these corrections in the analysis of historical and current data aimed at comparative studies of radiation climate of this region. For comparative climatic studies, the data of the Russian station in Barentsburg and the Norwegian stations in Ny-Alesund were used as the reference and most representative and long-term stations. These studies granted mutual access to national data sources for the both partners thereby providing the data for their joint analysis. This project is a continuation and development of the Russian science program "Research of a meteorological regime and climatic changes on Svalbard", carried out by the AARI in the framework of the IPY and NPI projects "Arctic Climatic Diversity" (ARCDIV).

The conformity between diverse sensors (M115M and "Kipp & Zonen") is quite satisfactory as is apparent from Fig. 2.1-3. The discrepancies of average values are 6.3 ±5.6 W/m^2 for all observations. They were maximal at noon, reaching ~36 W/m^2. Nevertheless, in total, these discrepancies do not exceed absolute inaccuracy of measurements (for example, 8% for M115M).

Contribution of the POLAR-AOD (no. 171)

The principal aim of this project was to establish a bipolar network of sites, where multi-wavelength sun-photometers have been used to take regular measurements of aerosol optical depth (AOD) and optical properties of aerosols. Integrated regular measurements of aerosol physical and radiative properties at a number of polar stations were planned in order to (i) evaluate the seasonal background concentrations inferred from AOD measurements, (ii) define the spectral characteristics and patterns of the radiative processes induced by both natural and anthropogenic aerosols, and (iii) ameliorate the knowledge of physical, chemical and radiative properties of polar aerosols, and of their horizontal and vertical distributions and temporal variability, for better evaluating the role of polar aerosols in the

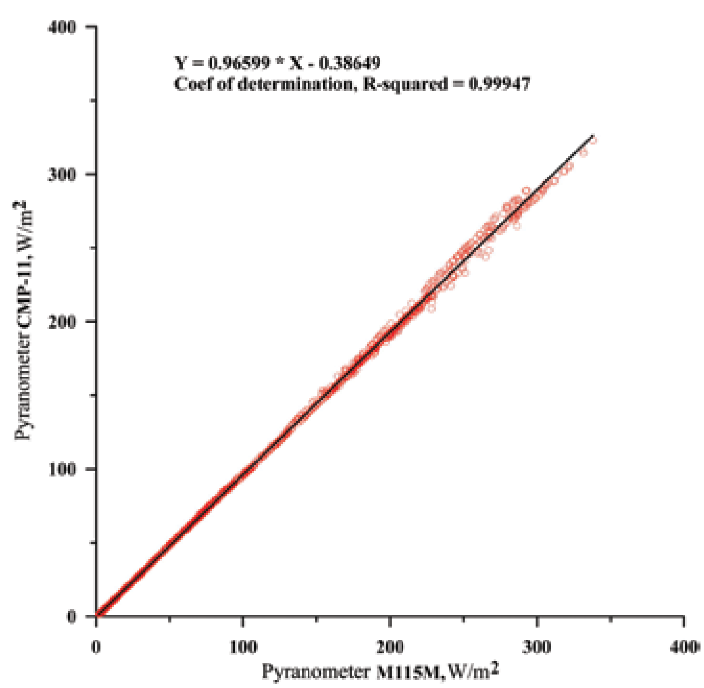


Fig. 2.1-3. Relationship between measurements by *Yanishevsky-Savinov* (M115M) and *Kipp and Zonen* (CMP11) pyranometers.
(Ivanov et al., 2008)

climate system.

Measurements at Arctic and Antarctic stations have been carried out during IPY with the logistic and financial support of established national programs, while archiving, data management, intercalibration and coordination of other activities have mainly been developed by the leading groups (Italy, Germany, U.S.A.) in cooperation with the other partners (43 research groups from 24 countries). During IPY, field data were recorded at 15 stations in the Arctic (Alert, Eureka, and Resolute Bay, in Canada; ALOMAR in Northern Norway; Barrow in Alaska; Hornsund in Poland; and Ny-Ålesund (five stations of Norway, Germany, Italy, Japan and China) in Svalbard, Norway, Pallas and Sodankylä in Northern Finland, Summit in Greenland and Tiksi in Siberia, Russia), and 23 stations in Antarctica (Aboa/Finland, Belgrano II/Argentina, Casey/Australia, Davis/Australia, Dome Fuji/Japan, Dome Concordia/Italy and France, Halley/U.K., Kohnen/Germany, Machu Picchu/Peru, Mastri/India, Marambio/Argentina, McMurdo/U.S.A., Mirny/Russia, Mario Zucchelli/Italy, Neumayer/Germany, Novolazarevskaya/Russia, Palmer/U.S.A., Princess Elisabeth/Belgium, South Pole/U.S.A., Syowa/Japan, Troll/Norway, Vechernaya Hill/Belarus and Zhongshan/China). All of these field data are still in the process of being archived and analyzed by the participating institutes.

The activities developed by the various partners primarily included: (1) management of long-term climate monitoring programs and/or performance of routine sun-photometric measurements over multiannual periods (groups from Italy, Germany, U.S.A., Canada, Japan, Russia, Norway, Switzerland and Finland); (2) implementation of sun-photometric observations and monitoring programs in the Antarctic and/or Arctic, over recent years (groups from Spain, Poland, Norway, France, Argentina, Australia, India, Belgium and Belarus); (3) development of programs to carry out *in situ* measurements of aerosol radiative parameters, chemical composition of particulate matter, and particle morphology and concentration (groups from U.S.A., United Kingdom, Sweden, Finland, Norway, Holland, Greece, Switzerland and China); and (4) improvement of radiative transfer models to simulate Rayleigh scattering (Tomasi et al., in press), gaseous absorption and aerosol extinction in the polar atmosphere (groups from Italy, U.S.A., Canada, Germany, Japan, Russia and Bulgaria).

Because sun-photometer measurement activities were performed by the various groups using different instruments, the POLAR-AOD project promoted two international intercalibration workshops with the purpose of attaining more homogeneous evaluations of AOD at the various visible and near-infrared wavelengths in the Arctic and Antarctic. The first workshop was held at the Japanese Rabben station (78° 56′ N, 11° 52′ E, 40 m a.m.s.l.) near the Ny Ålesund Airport, from 25 March to 5 April 2006 about one year before the official start date of the IPY (in February 2006), with the participation of ten research groups from nine countries (Canada, Finland, Germany, Italy, Japan, Norway, Poland, Spain and U.S.A.) using sun-photometers of different design already employed at a number of Arctic and Antarctic. The second workshop was held a few months before the end of the IPY field phase at the Izaña Meteorological Observatory at Tenerife, Spain (28° 19′ N, 16° 30′ W, 2368 m a.m.s.l.) from 5 to 20 October, 2008 with the participation of 13 research groups from ten countries (Canada, Finland, France, Germany, Italy, Japan, Norway, Poland, Spain and U.S.A.) and the participation of instruments employed in the AERONET and SKYNET networks.

Results obtained by the POLAR-AOD project are as follows:

1. The characterization of the radiative properties of Arctic aerosols made by plotting the daily mean values of Ångström (1964) exponent α versus the corresponding values of AOD (500 nm).
2. Large variations in AOD were often observed at the Arctic sites, passing from the background atmospheric loadings of aerosols (AOD $<$ 0.04) in summer to the period of higher frequency of Arctic haze episodes (often with AOD $>$ 0.30), as shown in Fig. 2.1-4.
3. Such enhanced turbidity characteristics of the Arctic atmosphere are not only due to the emission of anthropogenic pollutants from North America, Europe and Asia, but also to biomass burning, agricultural activities, dust plumes from Asian deserts and (in late spring and summer) smoke plumes from fires burning millions of hectares of boreal forest each year in North America and Siberia. The Arctic haze extinction levels were very high in the 1980s and early 1990s, mainly due to

anthropogenic pollutants, and were observed to decrease in the following years with the reduction of SO_2 emissions in North America and Europe. Nevertheless, simultaneous with the increasing patterns of AOD as shown in Fig. 2.1-4, both light scattering and light absorption (mostly due to black carbon) are now increasing (Sharma et al., 2006) along with the changes in atmospheric transport induced by the significant shifts recently observed in the atmospheric circulation. This implies that the deposition of black carbon particles and other light-absorbing aerosols, such as soot matter and dust, is increasing and is, therefore, expected to cause a lowering of the ice- and snow-surface albedo, leading to a positive and highly efficient radiative forcing and the most important positive feedback mechanisms in the climate system (melting of snow/ice → exposition of darker surfaces → decrease in the surface albedo → repetition of subsequent cycles).

4. The characterization of Antarctic aerosols, performed by plotting the daily mean values of α versus AOD (500 nm), has offered great evidence of the strong differences between coastal aerosol polydispersions (with predominant contents of sea-salt particles, and yielding AOD values ranging mainly from more than 0.02 to 0.10) and the High Plateau aerosols (with prevailing contents of non-sea-salt sulfates and methanesulphonate aerosols particles, presenting AOD values usually lower than 0.02). No relevant contents of black carbon were found in either coastal or Antarctic Plateau aerosol polydispersions, transported from mid-latitude regions and originated from biomass burning and tropical forest fires. In fact, the concentration of this highly-absorbing component was evaluated to assume values usually no higher than a few $ng \cdot m^{-3}$ at both coastal and internal high-altitude sites.

(5) The analysis of long-term variations of AOD (500 nm) in Antarctica over the last 30 years clearly indicate that solar radiation extinction produced by columnar Antarctic aerosols was quite stable, due to the long distance of Antarctica from the other continental sources of particulate matter.

A series of long-term spectral and photometric measurements of the solar radiation over the Atlantic Ocean and in the Antarctic was also performed by Russian researchers during the IPY period on board a research vessel to investigate the spatial distribution

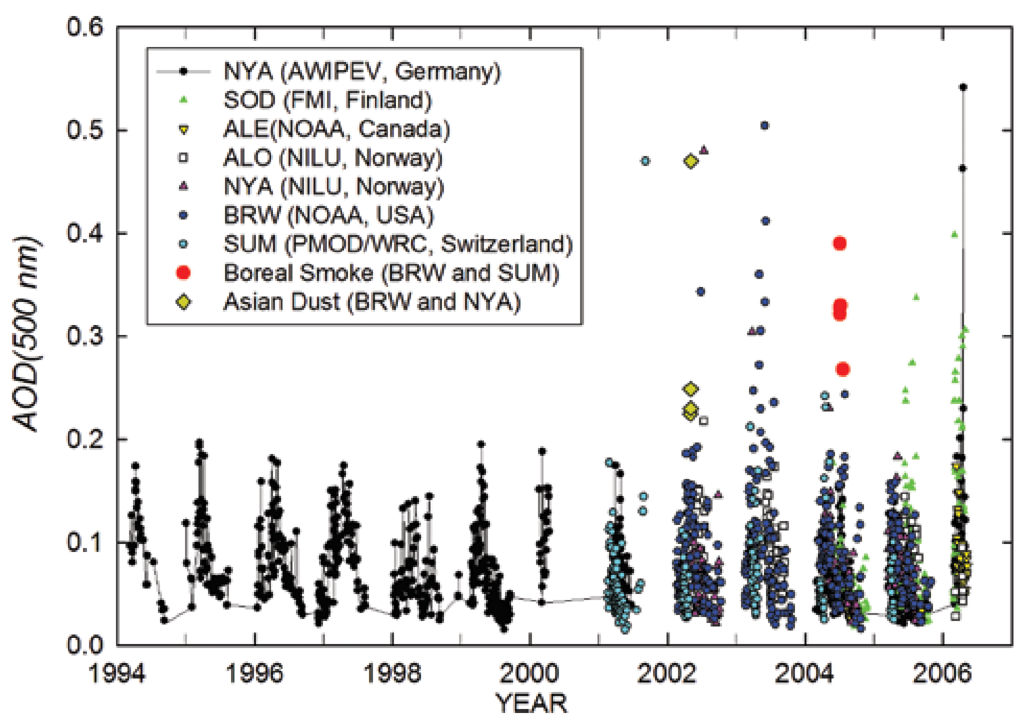


Fig. 2.1-4. Time-patterns of the daily mean values of aerosol optical depth AOD at the 550 nm wavelength, measured from 1994 to 2006 at seven Arctic stations. The strong aerosol extinction data observed in 1992 and 1993 and due to the Pinatubo eruption are excluded. Clearly seen is the sequence of gradually more marked aerosol extinction peaks due to the occurrence of an increasing annual number of Arctic haze episodes observed most frequently from December to April. Yellow diamonds refer to an Asian dust transport episode observed at Barrow in April 2002, and red circles to extinction by smoke aerosol clouds generated by forest fires in Alaska and Northern Canada in summer 2004 and subsequently transported over Greenland and Svalbard within a few weeks.
(Tomasi et al., 2007, Fig. 3)

of the aerosol component in the atmosphere over the Atlantic from 60° N to the Antarctic coast (Kotlyakov et al., 2010). A variable, called a spectral aerosol optical thickness (AOT) of the atmosphere, is used to characterize attenuation of the solar radiation by the aerosol particles within the whole air column. Magnitudes of the aerosol attenuation of the solar radiation measured in the Antarctic were the lowest values on the Earth, and they did not exceed limits of their natural variability. This is again the evidence of the fact that still to the present time the Antarctic atmosphere is not polluted by any aerosol of the anthropogenic origin.

ORACLE-O3 (no. 99)

LOLITA-PSC and MATCH-PSC campaigns

As part of the ORACLE-O3 ("Ozone layer and UV RAdiation in a changing CLimate Evaluated during IPY") global project, LOLITA-PSC ("Lagrangian Observations with Lidar Investigations and Trajectories in Antarctica, of PSC") is devoted to Polar Stratospheric Clouds (PSC) studies. Understanding the formation and evolution of PSC particles is an important issue to quantify the impact of climate changes on their frequency of formation and, further, on chlorine activation and subsequent ozone depletion. Statistical studies on PSC and temperature over the Dumont D'Urville in Antarctica have been updated (David et al., 2009) and a study based on the "Match" method, developed initially for ozonesondes, has been applied, for the first time, to lidar observations of PSC acquired during campaigns. These campaigns took place in Antarctica during winters 2006, 2007 and 2008, involving the three PSC lidar deployed in Antarctica, at Dumont d'Urville (66.67°S, 140.01°E), Davis (68.00°S, 78.50°E) and McMurdo (77.86°S, 166.48°E) and CALIPSO space-borne lidar observations. Observations were performed at each lidar station when the weather conditions permitted. Ten-days forward trajectories calculations from any station are performed each time a PSC is detected at the station. We consider a match when a trajectory issued from a station passes less than 200 km of another lidar station during a PSC observation period and when potential vorticity variations remain less than 40% along the trajectory. From the ground-based lidars, the evolution of scattering ratio can be drawn along the trajectories, completed with the CALIPSO values selected with a maximum time difference of 2.5 minutes and a maximum time distance of 200 km from the trajectories. As expected, a clear correlation appears between high scattering ratio values and the coldest temperatures, close or below the ice formation temperature [see Fig. 2.1-5, pers. comm. Nadège Montoux, LATMOS (Laboratoire atmosphères, Milieux Observations Spatiales), DNRS, France].

The impact of the model for trajectory and of the initialisation fields on the match determination was explored (Montoux et al., 2009 and publication in preparation). For cold temperatures, of interest for PSC formation, the pressure and altitude discrepancies are not significant. Time difference could occasionally impact, but do not seem to affect greatly, the lidar scattering ratios extracted. Yet, when close to PSC temperature thresholds, the temperature differences are a key issue and more realistic values for nitric acid and water vapour mixing ratios are needed to determine these thresholds (using, for instance, the Microwave Limb Sounder onboard the AURA satellite). The current step of the analysis is the modelling of PSC formation along the trajectories using the Danish Meteorological Institute microphysical box model (Larsen et al., 2000). The model includes microphysical Mie and T-Matrix modules, together with optical modules, and is able to simulate the size dis-

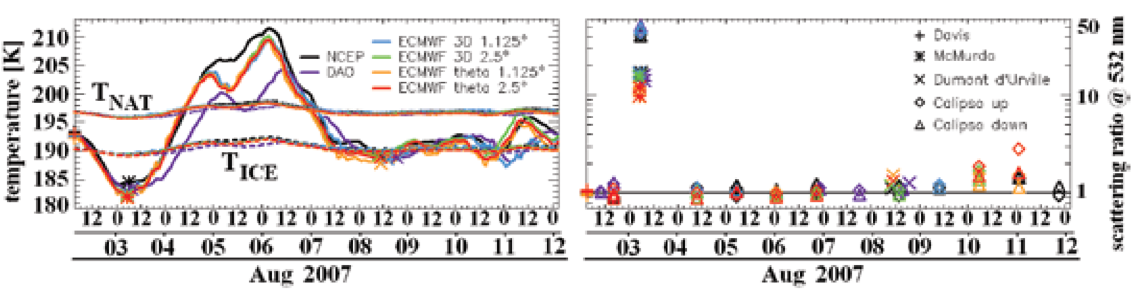


Fig. 2.1-5. Evolution of the temperature (left) and of the lidar scattering ratio at 532 nm (right) along different trajectories (color code) started from Davis station at 0300 UTC 2 August 2007 to 0300 UTC 12 August 2007.
(Courtesy: Nadège Montoux)

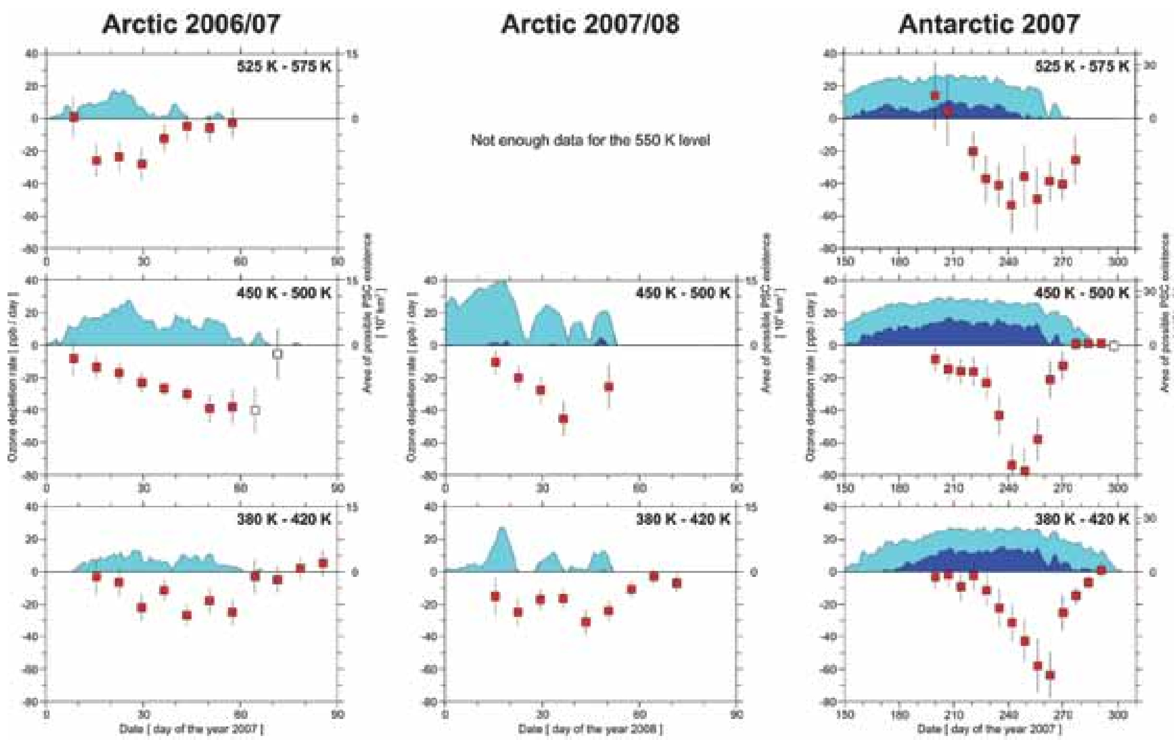


Fig. 2.1-6. Ozone loss rates (parts per billion by volume per day (ppb/day)) for three polar winters from Match campaigns. Three panels are shown for each winter, and each relates to a different atmospheric layer with a range of potential temperatures: top to bottom 525-575 K (approximate height 23 km), 450-500 K (19 km), 380-420 K (15 km). All data points (red and open square symbols) show temporal means spanning +/-10 days. The shaded portion of each panel shows the estimated areal coverage (in millions of square kilometres) of Polar Stratospheric Clouds of type I (light blue) and type II (dark blue). The loss rates in the two Arctic winters were moderate compared to earlier winters. Nevertheless, in 2007/08 the ozone loss occurred over a much wider vertical range than usual, leading to relatively greater ozone losses. The ozone loss rates in the Antarctic follow in general those of the first Antarctic Match campaign in 2003 reaching 60 to 80 ppb/day in the 450-500 K layer during September. Zero ozone losses at the end of the time period are not due to deactivated chlorine but due to already completely destroyed ozone.
(Graph: Peter von der Gathen, Alfred Wegener Institute, Potsdam)

tribution of PSC parameters and their optical properties at lidar wavelength.

Ozonesonde Match campaigns

In order to measure stratospheric ozone loss rates, three ozonesonde Match campaigns were performed – two in the Arctic and one in the Antarctic – during IPY. They followed one Antarctic and 12 Arctic campaigns in the past two decades (e.g. Rex et al., 2002). Primary results are shown in Fig. 2.1-6. In addition, the Arctic data fit well into a linear relation between winter integrated ozone loss and a winter mean temperature index (mean volume of possible PSC existence, V_{PSC}) as described in Rex et al., (2006). The whole data set is used to test our understanding of polar ozone losses in models. Past results showed more ozone losses than the models were able to explain. In consequence, the photolysis rate of the Cl-OO-Cl dimer is currently under discussion.

Arctic System Reanalysis (CARE/ASR no. 28): Synthesis Through Data Assimilation

The project "Arctic System Reanalysis" under the international Climate of the Arctic and its Role for Europe (CARE)/Arctic System Reanalysis activity is funded by the U.S. National Science Foundation to produce a high resolution re-analysis of the Arctic climate for the years 2000-2010. The project supports the interdisciplinary U.S. Study of Environmental Arctic Change (SEARCH) program to understand the nature and the future evolution of the Arctic system. The Arctic System Reanalysis (ASR) is a multi-institutional, interdisciplinary collaboration that provides a description of the region's atmosphere/sea-ice/land system by assimilating a diverse suite of observations into a regional model. Such a re-analysis may be considered an optimal blend of measurements and modelling. The project builds upon lessons learned from past re-analyses by optimizing both model physical parameterizations and methods of data assimilation for Arctic conditions. It represents a synthesis tool for assessing and monitoring variability and change in the Arctic system.

The domain considered extends well beyond the boundaries of the Arctic Ocean to include about one third of the Northern Hemisphere, so that all of the river basins that drain into the Arctic Ocean are included (see the inner grid in Fig. 2.1-7). The ASR output will include gridded fields of temperature, radiation, winds and numerous other variables at high spatial (10 km) and temporal (3 h) resolution, enabling detailed reconstructions of the Arctic system's state. A 30-km horizontal resolution prototype (June 2007 to September 2008) has been produced for distribution to the scientific community by March 2010. The prototype period includes the unprecedented (in the observational record) sea ice minima during late summer 2007 and 2008 as well as several Arctic field programs, including those for the IPY.

IPY funding from the U.S. National Science Foundation's Office of Polar Programs provides the backbone of support for advanced development, production and dissemination stages of the ASR. Start-up funding was supplied by the U.S. National Oceanic and Atmospheric Administration. Project administration requires close cooperation between the main participating institutions, facilitated by project meetings at least twice a year. The lead institution is the Polar Meteorology Group (PMG) of Byrd Polar Research Center at The Ohio State University. Other key partners are the Mesoscale and Microscale Meteorology Division (MMM) and the Research Applications Laboratory (RAL) of the National Center for Atmospheric Research (NCAR), the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado-Boulder and the Department of Atmospheric Sciences of the University of Illinois.

Extensive tests of the ASR's components are required before the high-resolution production phase is conducted. To represent the physical processes, the primary ASR tool is the polar-optimized version of the Weather Research and Forecasting (WRF) model (http://polarmet.osu.edu/PolarMet/pwrf.html, a regional coupled atmosphere-land model. The PMG has developed and extensively tested "Polar WRF" for the three main Arctic environments: ice sheets, ocean/sea ice and land. The stable boundary layer, mixed-phase clouds and surface energy balance were particularly emphasized. Arctic enhancements developed for this project are being channeled through NCAR for release to the scientific community. For example, the

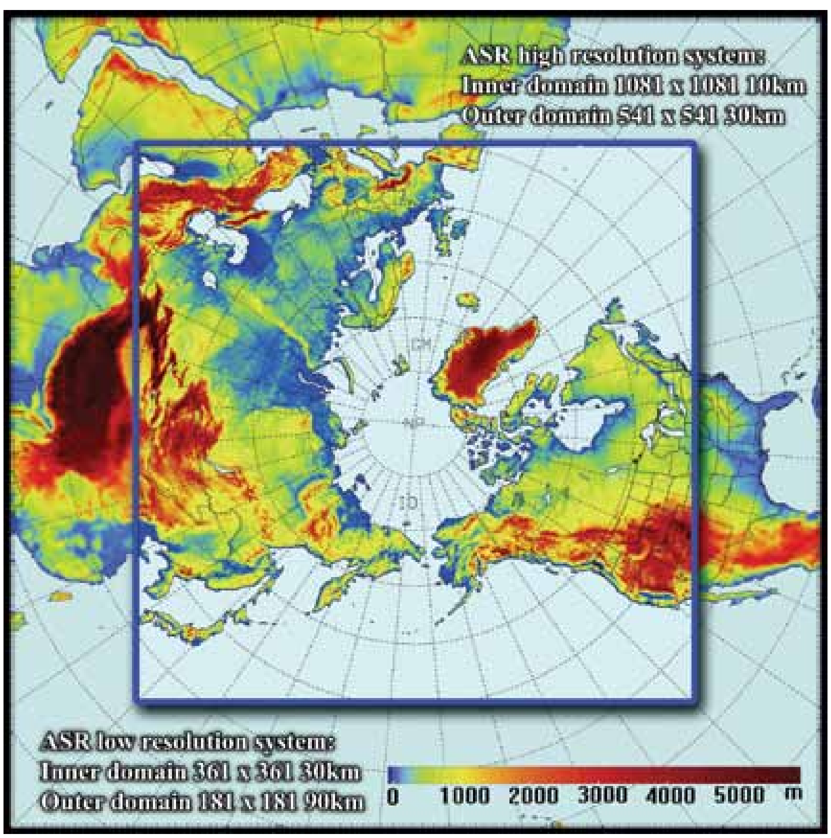


Fig. 2.1-7. Spatial coverage of the Arctic System Reanalysis includes 541×541 outer domain with 30-km horizontal resolution and 1081×1081 inner domain with 10-km horizontal resolution. The outer grid provides smooth boundary conditions for the inner grid. Grids are polar stereographic projections centered at the North Pole. Terrain height is shown by color scale. The low-resolution system summarized at the lower left is being used for the test assimilation spanning June 2007-September 2008.
(Bromwich et al., 2010)

fractional sea ice capability developed by the PMG is a standard WRF option beginning with version 3.1. The specified sea ice representation in the ASR is being enhanced by ice thickness distributions derived from remote sensing observations. Specified variable snow thickness over sea ice is also being represented.

Preparations for the ASR at RAL comprise improving the representation of Arctic land surface processes by the Noah Land Surface Model (LSM) that is coupled to WRF. In particular, key goals include improving the representation of spring snow-melt and the soil temperature profile. Detailed improvements to Noah include addition of an organic layer, deeper soil depths and a zero-flux bottom boundary condition. To best represent the land surface in the ASR, high quality fields will be obtained through High-Resolution Land Data Assimilation, driven by satellite data and run with the Noah LSM that interacts periodically with WRF.

A key challenge is fully assimilating the available Arctic observational data. The NCAR MMM has contributed considerable resources to enhance assimilation of in situ and remote sensing data in the polar regions, thus optimizing the advanced three-dimensional-variational (3D-Var) data assimilation capabilities of WRF-Var. In assembling the varied data that are to be processed by WRF-Var, Jack Woollen of the National Centers for Environmental Prediction (NCEP) has provided access to operational data streams and valuable advice on their usage. While conventional weather reports and satellite measurements make their way into the operational Binary Universal Format Representation (BUFR) database, other important Arctic data do not. These include the Greenland ice sheet automatic weather station reports, data from automated weather stations at northern Alaskan field sites, Multi-angle Imaging SpectroRadiometer (MISR) cloud-tracked winds supplied by the University of Illinois, Arctic snow water equivalent measurements supplied by CIRES and most of the IPY field measurements. The ASR eagerly solicits additional Arctic datasets from the community for assimilation into ASR or for testing its output. Completion of the ASR for 2000-2010 is scheduled for autumn 2011, and will be distributed to the community by the NOAA Earth System Research Laboratory (formerly CDC) and by NCAR.

World Weather Research Programme-THORPEX IPY cluster (no. 121)

From a weather forecasting perspective, the Arctic poses particular challenges for mainly two reasons: the observational data are sparse and the weather phenomena responsible for severe weather, such as polar lows, Arctic fronts and orographic influences on airflow, are inadequately represented in operational numerical weather prediction (NWP) models. The IPY-THORPEX cluster, comprising an international cooperation between ten individual IPY projects from nine countries, was set up to address these challenges. It has the following main objectives:

i) Explore the use of satellite data and optimised observations to improve high impact weather forecasts (from Polar THORPEX Regional Campaigns (TReCs) and/or provide additional observations in real time to the WMO Global Telecommunication System).
ii) Better understand physical/dynamical processes in polar regions.
iii) Achieve a better understanding of small scale weather phenomena.
iv) Utilise improved forecasts to the benefit of society, the economy and the environment.
v) Utilise the THORPEX Interactive Grand Global Ensemble (TIGGE) of weather forecasts for polar prediction.

A flavour of results from some of the projects is given below.

Focus of the **Greenland flow Distortion Experiment** (Renfrew et al., 2008) was upon Greenland tip jets, air-sea interactions, barrier winds and mesoscale cyclones with results that could be classified into all objectives above. The field campaign took place in February 2007. It provided a number of observational first looks at the strong winds and intense mesoscale weather systems that occur around the coastal seas of Greenland and Iceland. A number of detailed studies focusing on the structure, dynamics and associated air–sea interactions of the weather systems were performed, for example, with respect to the reverse tip jet, polar lows, lee cyclones and barrier winds (Fig. 2.1-8).

Aircraft and dropsonde data were used to assess the quality of a number of satellite products (e.g. QuikSCAT winds) and meteorological analyses. The

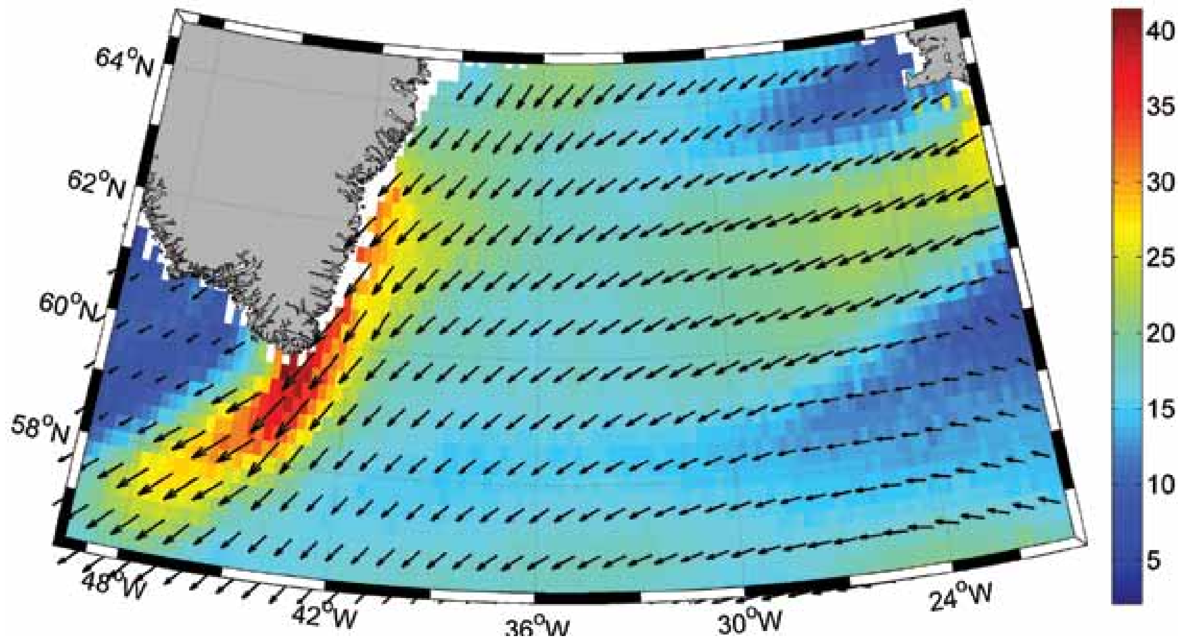


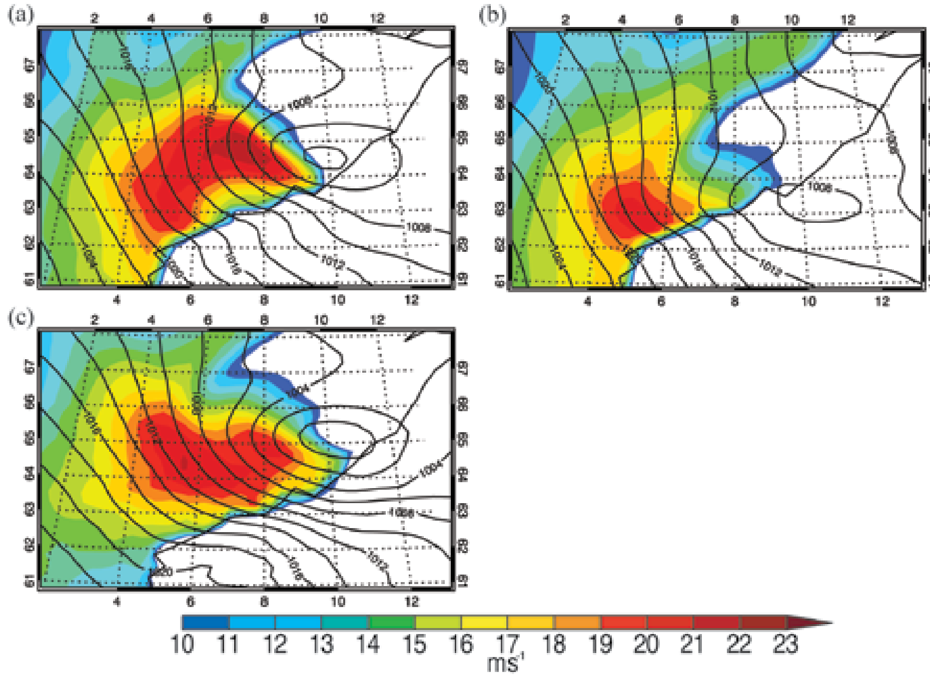
Fig. 2.1-8. Example of an easterly tip jet showing QuikSCAT-derived 10-m winds for the morning of 21 February 2007 (the satellite passes are from 0718 and 0900 UTC). The colours show wind speed (m s–1). The vectors are shown every third pixel (i.e. every 0.75°) (Renfrew et al., 2008).

impact of the targeted observations was assessed by Irvine et al., (2009), who found that the impact of the sondes was mixed. Only two out of the five cases showed clear forecast improvement; the maximum forecast improvement seen over the verifying region was the reduction of approximately 5% of the forecast error 24 hours into the forecast. In one of these cases, the improvement propagates into the verification region with a developing polar low. The impact of targeted sonde observations on the 1-3 day forecasts for northern Europe was evaluated using the U.K. Met Office four-dimensional variational data assimilation scheme and a 24 km grid length limited-area version of the Unified Model (MetUM). Targeted sonde data was assimilated operationally into the MetUM.

A study that focused particularly on local communities (objective "iv" above) was Storm Studies of the Artic (STAR, Hanesiak et al., 2010). It was not an international IPY project, but cooperated closely with projects participating in the IPY-THORPEX cluster. It included enhanced observations in the eastern Canadian Arctic and studied gap flow, air-sea interactions, orographic precipitation and interaction of cyclones with topography etc. With 14 research flights from Baffin Island, surface- and satellite-based instruments, STAR aimed to improve understanding and prediction of severe Arctic storms and their hazards. One of the more important tasks included developing a conceptual model of storms and associated phenomena in the region. Another important task was to evaluate operational and model forecasts of events to examine where improvements need to be made and under what circumstances.

The Norwegian IPY-THORPEX project (Kristjansson et al., submitted) sought to improve weather forecasts of phenomena typical for the high latitudes through a combined modelling and observational effort (mainly objectives i, ii and iii). The crux of the observational effort was a 3-week international field campaign out of Northern Norway in early 2008, combining airborne and surface-based observations. The main platform of the field campaign was the DLR (German Aerospace Center) Falcon research aircraft, equipped with LIDAR systems for profiling of aerosols, humidity and wind, in addition to *in situ* measurements and dropsondes. A total of 11 missions were flown, providing unique observations of polar lows, an Arctic front and orographic low-level jets near Spitsbergen, the coast of Northern Norway and the east coast of Greenland. Two major polar low developments over the Norwegian Sea were captured during the campaign. One of them (3-4 March 2008) was reasonably well predicted by operational models, while in the other case (16-17 March 2008) the operational models had

Fig. 2.1-9. Sea-level pressure (black contours) and 10 m wind speed exceeding 10 m/s (coloured shading) for 18 UTC 4 March 2008, for 24-hour forecasts from 18 UTC 3 March 2008 containing (a) routine and targeted observations, (b) only routine observations and (c) ECMWF analysis.
(Kristjansson et al., submitted)



huge errors both in strength and position. In the former case, targeting observations by the aircraft in sensitive areas led to improvements in predicted track and intensity of the polar low. Fig. 2.1-9 shows that the forecast containing targeted observations from 18 UTC 4 March 2008 improves the polar low position and strength, although the region of strong winds extends too far south compared to the analysis. Further work is underway to confirm the impact of the targeted sondes on the forecast and the reasons for this impact.

Thorpex Arctic Weather and Environmental Prediction Initiative (TAWEPI) is a science and research project partly funded by the Government of Canada Program of the International Polar Year. The primary objective of TAWEPI is to improve the Environment Canada's NWP capacity over the Arctic during the IPY observational period and beyond. TAWEPI's research activities started in April 2007. A research version of the regional GEM model, covering the Arctic basin and surroundings is being used to study the representation of radiative and cloud processes in weather forecasts. A multi-layer snow model coupled to sea-ice and blowing-snow parameterizations, describing processes over the various types of surfaces of the Arctic environment, was tested and evaluated. A methodology to validate model forecasts of cloud and radiation using satellite hyperspectral radiances was developed. Climatology of the sensitivity of the Arctic weather to disturbances originated elsewhere was generated and archived for the IPY period of 2007–2008. A state-of-the-science sea-ice model is being adjusted to improve the sea-ice representation in the Arctic (Ayrton Zadra, Environment Canada, pers. comm., see www.ec.gc.ca/envirozine).

The IPY-THORPEX cluster projects have demonstrated that improvements in NWP for polar regions are possible and have increased our understanding of how to improve models and how to use data from the Arctic; they also deepen our understanding of the physical processes involved. In particular they have acquired data for improving physical parameterization in NWP models (-clouds, microphysics, surface fluxes); improved assimilation techniques for high latitudes with emphasis on satellite data; increased our understanding on the effect of the use of ensemble simulations for high latitudes; increased our understanding of the effect of targeting in high latitudes; increased our understanding of high-latitude dynamics and high-impact weather phenomena; demonstrated the effect of new instruments; and demonstrated the effect of increased Arctic and Antarctic observations for local and extratropical NWP forecasting.

***Concordiasi project over Antarctica* (no. 41)**

Antarctica is operationally and climatologically data sparse due to highly limited surface observing facilities in the high southern latitudes. Satellite measurements have the potential to fill these data gaps, but they present their own unique challenges and difficulties. This is true, in particular, of the data provided by hyperspectral infra-red sounders such as IASI (Infrared Atmospheric Sounding Interferometer). These challenges must be overcome and errors need to be reduced to produce accurate reanalyses for climate studies that are based primarily on observed conditions.

Within the framework of IPY, the Concordiasi project (Rabier et al., 2010, www.cnrm.meteo.fr/concordiasi/) makes innovative observations of the atmosphere above Antarctica in order to:

- enhance the accuracy of weather prediction and climate records in Antarctica through the assimilation of *in situ* and satellite data, and
- improve our understanding of microphysical and dynamical processes controlling the ozone content of the polar air masses by quasi-Lagrangian observations of ozone and particle content and improved characterization of the polar vortex dynamics.

A major Concordiasi component is a field experiment during the Austral springs of 2008, 2009 and 2010 (Fig. 2.1-10). The field activities in 2010 are based on a constellation of up to 18 long duration stratospheric balloons deployed from the McMurdo station. Six of these balloons will carry GPS receivers and *in situ* instruments measuring temperature, pressure, ozone and particles. Twelve of the balloons are capable of releasing dropsondes on demand for measuring atmospheric parameters. In 2008 and 2009, radiosounding measurements were collected at various sites, including the Concordia station.

The atmospheric temperature profiles over the Antarctic plateau exhibit a very strong inversion at the surface, with surface temperatures colder by up to 20K than the lower troposphere, which is difficult both to model and observe. During the Concordiasi field campaign, special measurements were obtained measuring the atmospheric profiles together with surface parameters, synchronised with the track of the European MetOp platform with the hyperspectral IASI sensor onboard. They were then compared to IASI measurements and to the outputs of the meteorological model of Meteo-France, especially adjusted for this area (Bouchard et al., 2010). The available *in situ* obser-

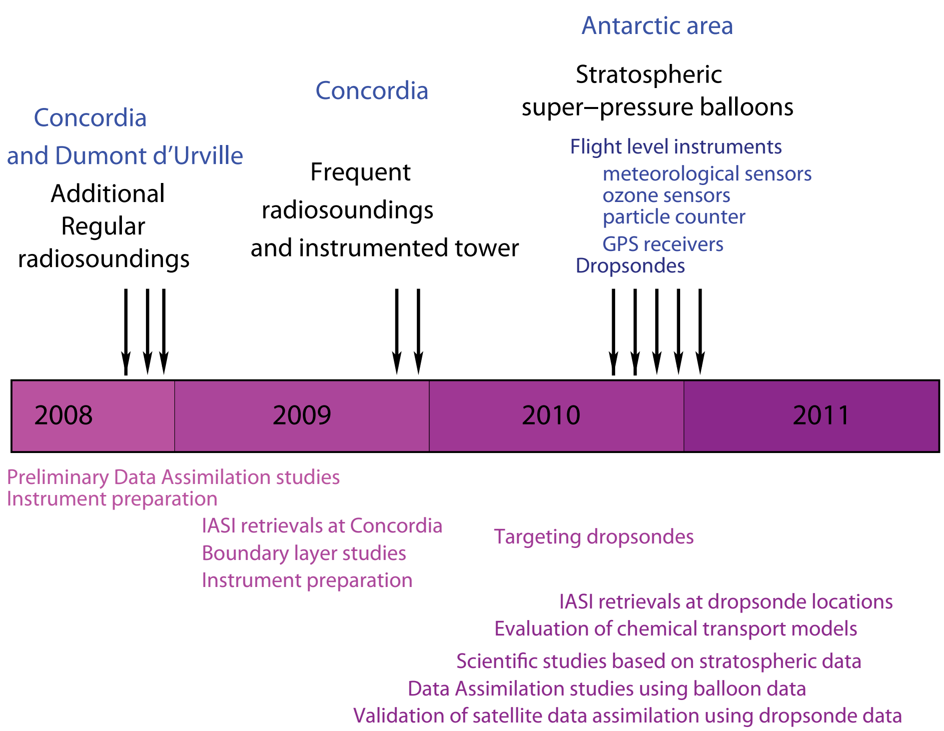


Fig. 2.1-10. The Concordiasi project timeline.
(Rabier et al., 2010)

vations obtained at Concordia were also compared to the results of IASI data retrievals. It was found that the problem of correct estimation of the surface temperature was the main limiting factor in the quality of IASI retrievals. A good prior estimation of skin temperature can be obtained using the radiative transfer equation together with IASI observations in a window channel. Results are presented in Fig. 2.1-11. In this figure, the skin temperature retrieved from a IASI window channel (blue line) is closer to the radiosounding surface temperature (black line) than the model skin temperature (red line) in terms of magnitude and time evolution. Based on this estimation of the skin temperature, retrievals have been performed over the same 44 cases during Austral spring 2008, with an improved analysis of the temperature profile above Concordia compared to a retrieval using the model surface temperature. In parallel, innovative approaches have improved the use of microwave observations from the AMSU (Advanced Microwave Sounding Units) instruments by better description of the surface emissivity, which is highly variable in space and time (Guedj et al., 2010). These studies have highlighted the potential of satellite observations to contribute to a monitoring of weather and climate over the polar areas, once particular attention has been paid to surface parameters.

Structure and Evolution of the Polar Stratosphere and Mesosphere and Links to the Troposphere during IPY **(SPARC-IPY, no. 217)** was to document the dynamics, chemistry and microphysical processes within the polar vortices during IPY, with a focus on the stratosphere-troposphere and stratosphere-mesosphere coupling. One of the key outcomes was a collection of analysis products from several operational centres and several research centres, which was archived at the SPARC Data Center. The analysis products covered the period of IPY (March 2007 to March 2009) and represented the best available self-consistent approximations to the state of the atmosphere during this period (McFarlane et al., 2009; Farahani et al., 2009; Klecociuk et al., 2009).

A major goal of the SPARC-IPY program was to document as completely as possible the dynamics and chemistry of the polar middle atmosphere during the IPY period. It was anticipated that achieving a unique synthesis of data on the polar middle atmosphere would require analysis of available research and operational satellite data, as well as ground-based and aircraft data. This would clearly include data from new measurement systems, as well as from enhanced measurement programs with established systems. The intent of SPARC-IPY, in cooperation with

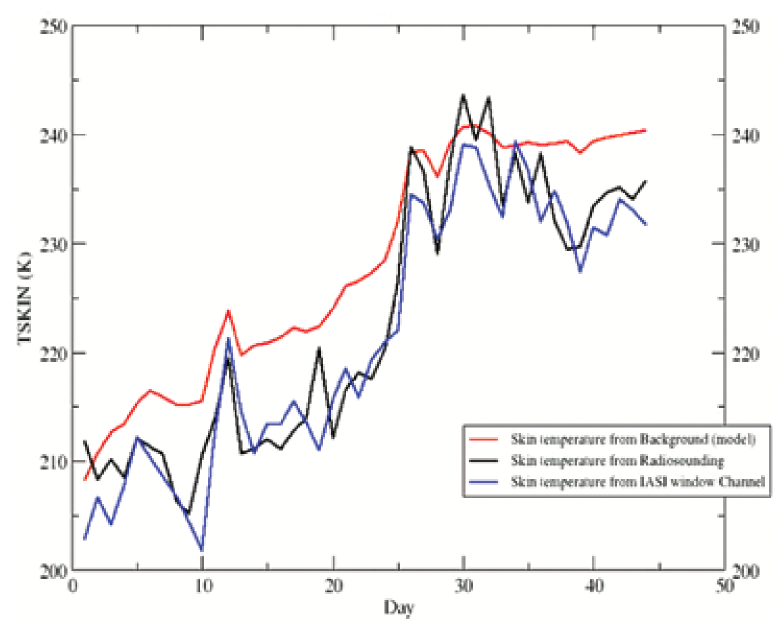


Fig. 2.1-11. Skin temperature (K) at Concordia in austral spring 2008 (44 daily cases at 0000 UTC from October to 29 November 2008) from model (red line), radiosounding (black line) and IASI window channel (blue line).
(Graph: courtesy Aurelie Bouchard and Florence Rabier)

related and linked IPY activities, was to facilitate such data acquisition, archiving and analysis activities. In addition to collecting the results of new measurement programs, SPARC-IPY also collected and archived objective analysis products from major centers during the IPY period. This activity was undertaken and coordinated within the SPARC-DA activity (Polavarapu et al., 2007). SPARC-IPY has also encouraged work on data assimilation and inter-comparison of the assimilated data sets.

Tropospheric chemistry: air pollution and climate impacts

Several IPY projects investigated the chemical composition of the Arctic troposphere. They studied a large range of different topics, such as the geographical and vertical distribution of pollutants in the Arctic, their sources, concentration trends on various time scales, the physical and chemical processes determining their concentration levels, and the climate impacts of aerosols and trace gases. Arctic ice cores also provide records of contaminant levels that are relevant not only for the Arctic itself, but also for the extra-polar regions where detailed historical records are more difficult to obtain.

The motivation for all of these projects arises either from the health and ecological impacts of contaminants or from the climate impacts of aerosols and short-lived trace gases. Arctic air pollutants are emitted mainly by sources in the middle latitudes and are carried northward by the winds in the troposphere. Some contaminants, such as POPs, can partition between different environmental media but the atmosphere generally provides the fastest transport pathway into the Arctic. Of particular concern is that even though Arctic sources are small, POPs can reach their highest concentration levels in the Arctic via a mechanism known as cold condensation whereby POPs (Persistent Organic Pollutants) are "extracted" from the atmosphere preferentially in the polar regions. POPs and heavy metals can furthermore bioaccumulate and biomagnify through food chains and thus pose significant health risks to humans and wildlife in the Arctic.

"Classical" pollutants, such as sulfate, can also reach surprisingly high atmospheric concentrations in the Arctic in winter and early spring, given that their local sources are relatively small. Nevertheless, in winter there is relatively efficient transport into the Arctic from high-latitude regions in Eurasia where strong pollution sources are located. The high static stability and dryness of the arctic troposphere in winter render removal processes such as dry and wet deposition inefficient and chemical degradation is also reduced by low temperatures and light intensity. This leads to long pollutant lifetimes and explains the high arctic pollution loads. Aerosol concentrations can reach such high levels that visible haze layers can form, which have become known as Arctic Haze. In the past, the main interest was in the acidifying properties and the high pollution loads of Arctic Haze. More recently, however, interest into the climate impact of the haze has grown. Aerosols affect the radiation transmission in the atmosphere and, because of the highly reflective surface in the Arctic, even small amounts of light absorbing material such as black carbon ("soot") can lead to a warming of the atmosphere. If light-absorbing aerosols are deposited on snow or ice, they can also reduce the surface albedo. Sufficiently large aerosols can also hinder the transmission of long-wave radiation and aerosols can also affect the properties of arctic clouds.

Metal pollution in Canadian High Arctic: Pollution trend reconstruction of noble metals **(IPY no. 19)** project provides a reconstruction of the historical concentrations of heavy metals (lead, cadmium, mercury) and sulfate through snow, firn and ice core measurements. Based on background data back to 4,000 BP, it was found, for instance, that lead (Pb) contamination in the High Arctic has started much earlier than the Industrial Revolution. The first outstanding Pb peak found in Devon Ice Cap was at ~3,100 years ago, which corresponds to the Iberian Peninsula mining and smelting. The second peak was much broader (lasting a longer time) and located from the Roman Period to the Middle Ages. Starting 700 years ago, the lead/scandium (Pb/Sc) ratio exceeded the background value and has not returned to natural values since. In the 1840s, many years before Pb additives were used in gasoline, approximately 80% of the Pb deposition on the Devon Ice Cap was already from anthropogenic sources. Even in the 1920s, still pre-dating the use of leaded gasoline additives, about 90% of Pb deposition was anthropogenic. Clearly, the use of leaded gasoline is only the most recent chapter in a very long history of atmospheric Pb contamination. Since the 1970s, Pb enrichments in snow and firn from Devon Island have gone into decline in response to the gradual elimination of leaded gasoline. Nevertheless, using the natural, background Pb/Sc ratio and Pb isotope data, it is found that at least 90% of the Pb in the High Arctic is still from anthropogenic sources.

***INterContinental Atmospheric Transport of Anthropogenic Pollutants to the Arctic* (INCATPA, no. 327** www.ec.gc.ca/api-ipy/default.asp?lang=En&n=8EBD7558-1) studied the risks associated with the emissions of POPs and mercury (Hg) in the Pacific region for the contaminant loads in the Arctic. Before IPY, air monitoring of POPs and Hg was performed mainly at Alert, Canada and Ny Ålesund, Norway in the 1990s under AMAP. Hg has also been continuously measured in air at Whistler, B.C. and Amderma, Russia under Environment Canada and Roshydromet for AMAP, respectively. During IPY, air measurements of POPs and/or Hg started at Little Fox Lake, Yukon, Canada; Valkarkai, Russia; Barrow, Dillingham and Fairbanks, Alaska, U.S.A.; Waliguan, Mt. Changbai, Wudalianchi and Xuancheng, China; and Ba Vi, Vietnam. At most stations, these measurements will continue until spring 2010. Soil and air samples were collected along the Chilkoot Trail, Yukon/Alaska, in summer 2007, at different elevations. The purpose is to investigate the atmospheric deposition of POPs and emerging chemicals on mountain ranges in the Kluane National Park, Yukon, Canada. Combined with the air concentration data collected at Little Fox Lake, this work will provide insight on the roles that mountains and forests play in intercepting POPs carried by trans-Pacific air masses. Another project, *Atmospheric Monitoring Network for Anthropogenic Pollution in Polar Regions* (ATMOPOL, no. 76), delivered the first annual data set on POPs in antarctic air. It also studied the influence of climate change on atmospheric distribution patterns of POPs and the identification of new emerging contaminants in arctic environments.

INCATPA models simulating the transport and fate of POPs showed that long-range atmospheric transport (LRAT) of POPs from sources in warm latitudes to the Arctic occurs primarily at the mid-troposphere. Cold condensation is also likely to occur at the mid-troposphere over a source region in warm low latitudes. The temperature dependent vapour pressures and atmospheric degradation rates of POPs exhibit similarities between the lower atmosphere over the Arctic and the mid-troposphere over a tropical region. Convection over warm latitudes transports the chemicals to a higher altitude where some of them may condense/partition to particles or to the aqueous phase and they become more persistent at the lower temperatures. Strong winds at the mid-troposphere then convey the condensed chemicals also to the Arctic where they can be brought down to the surface by large-scale descending motion and wet deposition. These studies provide a new interpretation on the cold condensation (Arctic trapping) effect and revealed major atmospheric pathways of POPs to the Arctic.

***POLar study using Aircraft, Remote sensing, surface measurements and modelling of Climate, chemistry, Aerosols and Transport* (POLARCAT, no. 32** www.polarcat.no) brought one of the largest atmospheric measurement campaigns ever conducted in the Arctic. Eight research aircraft from the United States, France, Germany, Russia, as well as research groups from many other countries, flew research missions in nearly all parts of the Arctic and sub-Arctic during spring 2007, spring 2008 and summer 2008. The campaigns were coordinated (Fig. 2.1-12) such that comparisons between the different parts of the Arctic can be made. The aircraft missions were complemented by a ship cruise in spring 2008, a railway campaign in Siberia in summer 2008 and measurement campaigns at several Arctic stations (e.g. Summit, Ny Ålesund). They were also supplemented with extensive use of satellite remote sensing products and a large range of different models. Detailed measurements of the gas-phase and particulate-phase chemical composition of the Arctic atmosphere, the optical properties of aerosols, the properties of clouds, etc. were made. In the result, the *POLARCAT* data set will provide a unique reference for future changes of the Arctic atmosphere.

While the data sets are still being processed and analyzed, several research highlights were already published in a POLARCAT special issue in Atmospheric

Fig. 2.1-12. The NASA DC8 research aircraft viewed from the DLR Falcon research aircraft during an intercomparison flight over Greenland as part of POLARCAT in summer 2008 (Photo: Hans Schlager, DLR).

Chemistry and Physics (www.atmos-chem-phys.net/special_issue182.html) and elsewhere. A substantial finding was the large influence of both agricultural and forest fires on the aerosol load of the Arctic atmosphere. Already in spring 2008, fires in Kazakhstan and Russia were a major source of Arctic aerosols, even over Alaska. In summer, extensive influence of burning was obvious, too, especially at higher levels in the Arctic atmosphere.

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2.2 Arctic Ocean

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Introduction

The integrated Arctic Ocean Observing System (iAOOS), originally conceived and sponsored by the Arctic Ocean Science Board (AOSB), was one of the proposals endorsed by the Joint Committee for International Polar Year. It was designed to optimize the cohesion and coverage of Arctic Ocean science during the IPY. As such, iAOOS is not a funded programme in its own right, but is rather a pan-Arctic framework designed to achieve optimal coordination of funded projects during IPY. It has a science plan (Dickson, 2006) based on the more than 1150 Expressions of Interest received by the IPY program office. Reflecting these proposals, its main concerns are with change in the Arctic, including all aspects of the role of the Northern Seas in climate, and it draws its primary focus on the present state and future fate of the Arctic Ocean perennial sea-ice. Because of its all encompassing aim and design, iAOOS is a suitable framework to use when presenting the oceanographic activities undertaken within IPY.

During the development of iAOOS, it became clear to the AOSB and to the investigators involved, that the scope of iAOOS could not be restricted to the Arctic Ocean. We know from major studies, such as the Arctic-Subarctic Ocean Flux Study, that the two-way oceanic exchanges that connect the Arctic and Atlantic oceans through subarctic seas are of fundamental importance to climate; that change may certainly be imposed on the Arctic Ocean from subarctic seas, including a changing poleward ocean heat flux that is central to determining the present state and future fate of the perennial sea-ice. The signal of Arctic change is expected to have a its major climatic impact by reaching south through subarctic seas, either side of Greenland, to modulate the Atlantic thermohaline conveyor. This report on the achievements during IPY is therefore arranged along three major themes or pathways: a) the changing inputs to the Arctic Ocean from the subarctic seas; b) the changing oceanography of the Arctic Ocean itself; and c) the changing outputs from the Arctic to the subarctic seas.

Observing the inputs to the Arctic Ocean

Fig 2.2-1 (Melling's compilation from Dickson, 2009) describes the distribution of all 173 current meter moorings and arrays deployed across the Arctic-subarctic domain during 2008 whether or not they were primarily intended for the support of IPY and its component programs. It is a considerable achievement. Though coverage continues to be thinly spread in places, this mooring network represents a slight increase on the first year of IPY (156) and was a healthy advance on the situation of earlier years, conforming well with the integrated Arctic Ocean Observing Plan (Dickson, 2006). All the main choke-points of ocean exchange between Arctic and subarctic seas are covered, historical time-series moorings have been continued and long-standing 'gaps' at climatically-important sites are now properly instrumented. In some key locations (offshore branch of the Norwegian Atlantic Current, Fram Strait, etc), the conventional coverage is now augmented by the use of gliders. Four of these gateway arrays may be picked out for special mention.

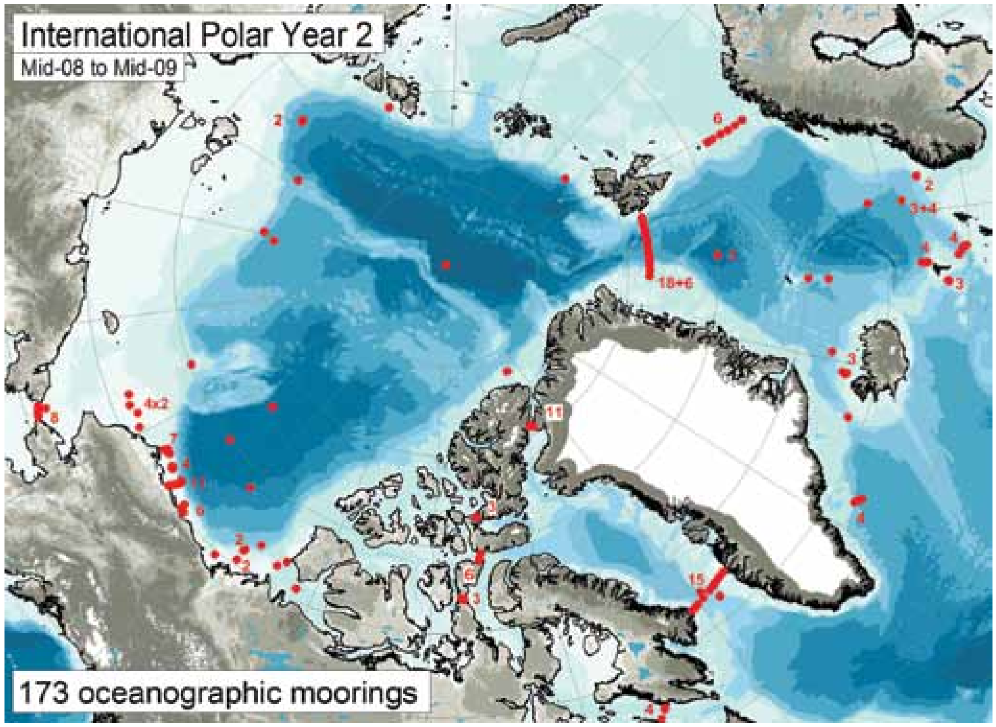

Fig. 2.2-1. Distribution of all 173 current meter moorings and arrays across the iAOOS domain in 2008. Compilation by Humfrey Melling, IOS Canada. Small numerals in red refer to the number of moorings in an array, where these are too numerous to distinguish individually.
(Map: Dickson and Fahrbach, 2010)

The development of the Svinøy section. A conspicuous highlight of IPY was the first concerted attack on the 'other half' of the northward ocean heat flux west of Norway. Briefly, although the 12-year time-series of transport had by then been recovered from the inshore branch of the Norwegian Atlantic Current against the Norwegian Slope, giving some sense of its local and remote forcing, the offshore branch, passing north through the Norwegian Sea as a free jet, had remained unmeasured. In an attack on this critical but difficult measurement, satellite altimetry, hydrography and conventional current meter moorings were combined to calculate the volume, heat and salt transports of both NAC branches between 1993 and 2007 (Mork and Skagseth, 2009). In the eastern branch these results agree well with previous estimates (Orvik et al., 2001), but in the western branch they differ substantially from SeaGlider based estimates reported in Mauritzen et al., (2009). During IPY, iAOOS-Norway continued its aim of "developing the Svinøy Section into a complete, sustainable, simple and robust upstream reference system for monitoring Atlantic inflow towards the Arctic Ocean moved during CTD and current IPY", adding conventional moorings, profiling instruments (MMP CTD/RCM) and SeaGlider transects. Apart from capturing the successive waves of warmth that have passed through towards the Arctic in recent years, this key array continues to highlight the independence between the flow field and temperature field, with the flow field dominating annual variability and with temperature variations dominating on longer timescales.

Table 2.2-1. Estimates of volume, heat and freshwater transports for the two branches of the Norwegian Atlantic Current west of Svinøy.

Inflow branch	Volume transport (Sv)	Heat transport (TW), Tref=0oC	Freshwater transport (mSv) Sref=34.93	Reference
Eastern	4.2 3.7	133 157	 -45	Orvik et al., (2001). Mork and Skagseth (2009)
Western	3.5 1.4 6.5	 39	 -13	Orvik et al., (2001). Mork and Skagseth (2009) Mauritzen et al., (2009)
Total	7.7 5.1	 179	 -58	Orvik et al., (2001). Mork and Skagseth (2009)

The instrumenting of Fram Strait. Fram Strait represents the principal entry-point for heat, salt and mass to the Arctic Ocean, so these quantities and their variability are of considerable importance to our understanding of arctic change. The overall objective for Fram Strait in IPY was to augment the conventional (ASOF) picket fence array of current meters with a range of new systems designed to improve the monitoring of volume, heat and freshwater transports, including the building, testing and use of an ocean acoustic tomography system across both the West Spitzbergen Current and the East Greenland Current, establishing and validating a high resolution (2 km) ice-ocean model, and combining ship-borne hydrography, acoustic thermometry, satellites, sub-surface moorings, gliders and coupled ice-ocean modelling through advanced assimilation techniques. Using three vessels, the field aims were largely accomplished through the use of seven main observing systems. A comparison of the main ocean fluxes carried to the Arctic by these two Atlantic inflow branches can be attempted below (Schauer et al., 2008; Schauer and Beszczynska-Möller, 2009).

Table 2.2-2. Volume- and heat transports through the Barents Sea Opening and Fram Strait 1) calculated for zero net volume transport, for details see Schauer and Beszczynska-Möller, 2009 2) mean for the whole observation period in Fram Strait 3) mean for the period of observations by the optimized, high-resolution moored array.

(Source: A. Beszczynska-Möller, AWI)

	Volume transport (Sv)	Heat transport (TW)
Barents Sea Opening	2	46
Fram Strait Atlantic water inflow[1]	6 (sd 1.5)	38 (sd 15)
Fram Strait total mean 1997-2008[2] mean 2002-2008[3]	2.6 southward (sd 4.2) 2.9 southward (sd 2.5)	-

New insights on the Bering Strait throughflow. The Bering Strait is the only Pacific gateway to the Arctic Ocean. The flow through the Strait, typically ~ 0.8 Sv in the annual mean, is an important source of heat, freshwater, nutrients and stratification for the Arctic Ocean and beyond. Mooring work in the Bering Strait region has been carried out almost continuously since autumn 1990 except for a 1-year gap in 1996-1997, but prior to IPY had employed only small numbers of moorings (maximum four), usually in the centre of the channels of the Strait, with an extra mooring in some years to measure the warm, fresh Alaskan Coastal Current (ACC), found seasonally in the eastern Strait. For the IPY, however, an expanded high-resolution array was deployed (Fig 2.2-2; Rebecca Woodgate, pers. comm.) consisting of eight moorings – three spanning the western (Russian) channel; four in the eastern (U.S.) channel; and one (A3) at a "climate" site located just north of the Strait in U.S. waters and hypothesized to provide a useful average of the total flow properties. This monitoring is integral to the RUSALCA (Russian-American Long-term Census of the Arctic) program (www.arctic.noaa.gov). All moorings measured lower layer temperature (T), salinity (S) and velocity. A novel aspect of the IPY deployment was that six of the moorings also carried upward-looking ADCPs to measure water velocity in 2m layers to the surface plus upper-level TS sensors, the latter in the form of the ISCAT sensor (a microcat in a trawl resistant housing, with inductive telemetry of data to a deeper logger). Two bottom pressure gauges and some bio-optics sensors are also included in the array (for full details see http://psc.apl.washington.edu/

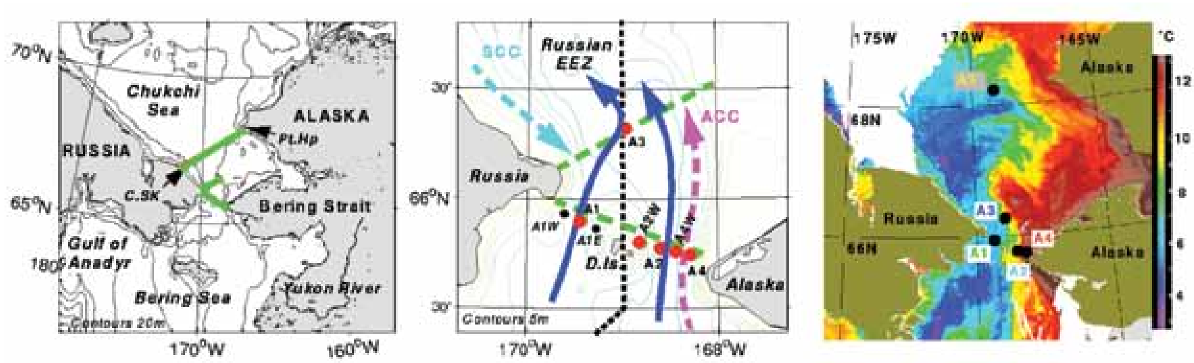

Fig. 2.2-2: Left: The Bering Strait, with preferred CTD lines (green). Middle: Detail of Bering Strait, with schematic flows, mooring locations (red and black dots) and CTD lines (green). The main northward flow passes through both channels (dark blue arrows). Topography diverts the western channel flow eastward near site A3. The warm, fresh Alaskan Coastal Current (ACC) (pink dotted arrow) is present seasonally in the east. The cold, fresh Siberian Coastal Current (SCC) (light blue dotted arrow) is present in some years seasonally in the west. All these currents reverse on time scales of days to weeks. Right: MODIS sea surface temperature image, courtesy of NASA, from August 2004, with historic mooring locations (A1, A2, A3, A3' and A4), occupied variously since 1990.

(Maps: Dickson and Fahrbach, 2010)

BeringStrait.html). The expansion of the array during IPY provided a number of important insights. First, the new sensor systems have provided the first year-round measurements of stratification in the Bering Strait region. Second, although instruments are still being calibrated, preliminary results suggest that the annual mean 2007 transport had strengthened to around 1Sv, comparable with the previous high northward flow of 2004, which had been related to a reduction in the southward winds. The increased flow, coupled with a very modest warming, suggests the Bering Strait heat flux in 2007 was also at a record-length high. Servicing of these moorings also took place during the fall and summer of 2008 and 2009 on board the *Akademik Lavrentiev* and the *Professor Khromov*.

Tracking the inflows downstream: the NABOS arrays across the circum-Arctic Boundary Current are our main source of information on the Atlantic inflow branches once they enter the Arctic Ocean and subduct to intermediate depths. The cruises of the RV *Viktor Buynitsky* in 2007 and of the *Kapitan Dranitsyn* in 2008 were the sixth and seventh in an annual series designed to service an increasingly international array of instruments set across the circum-Arctic boundary current (Fig. 2.2-3). The program has had major successes, notably the recovery of two-year-long datasets from at least two of the moorings (M4, M6; Fig. 2.2-3), which confirmed the presence of strong seasonal oscillations in the Atlantic Water, and the hydrographic cross-sections, which confirmed the continuation of warming along this boundary [based on a standard JOIS/C3O transect, Fiona McLaughlin and Eddy Carmack (pers. comm., 2009), later confirm the arrival of the latest warm pulse in the Atlantic-derived sublayer at the southern margins of the Canada basin in 2007]; one very long MMP record near Svernaya Zemlya showing bursts of very warm (2°C) Atlantic water up to 90m right through the halocline in 2008.

The losses of equipment and data in this difficult environment have also prompted certain changes in NABOS strategy for the future however, (i) a limited number of very well equipped moorings capable of surviving deployments of at least two year's duration now seem appropriate to form the frame of a climate-oriented observational network; (ii) no MMPs will be used for these moorings in future because, at this location and in this boundary current, they have shown low reliability; (iii) NABOS will deploy cluster-like groups of several (five or more moorings) each year, moving this cluster from one climatological mooring location to another so as to investigate the processes responsible for driving change at these sites. As the behaviour of the Atlantic Current branches in the Nansen Basin is still of considerable scientific interest, the continuation of the NABOS array in some form remains a priority.

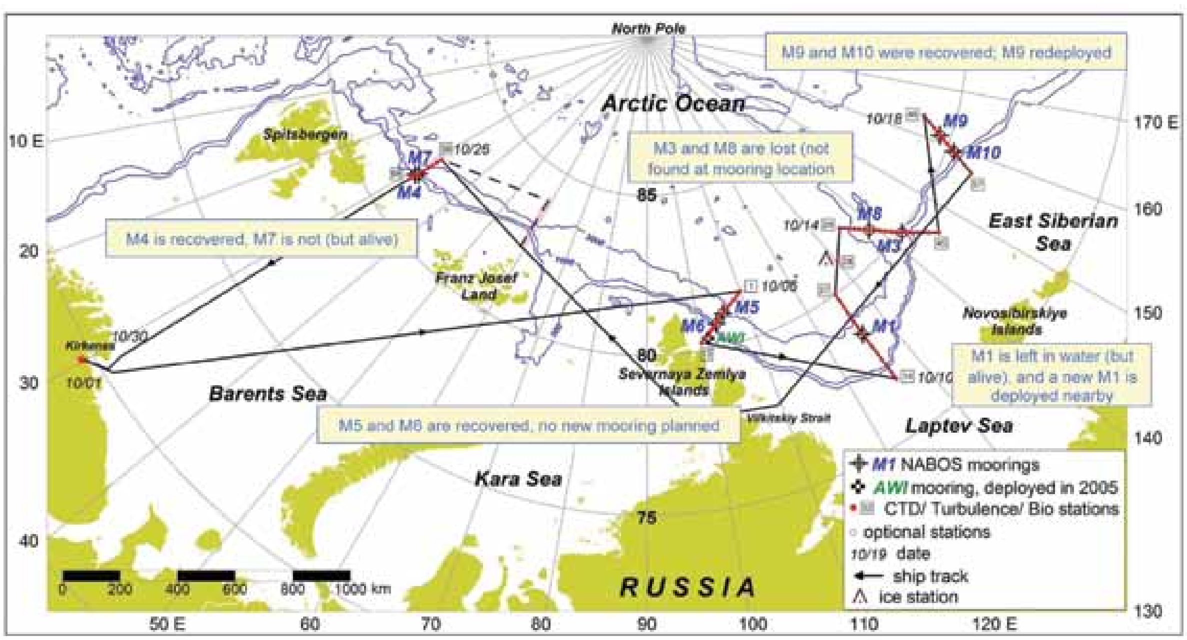

Fig. 2.2-3. Track of the NABOS Cruise aboard R/V *Kapitan Dranitsyn* showing mooring locations and affiliations in October 2008. (Source: Igor Polyakov, IARC, November 2008)

The spread of SeaGliders support of Arctic-subarctic exchanges. The SeaGlider (usually the UW version) has proved a versatile and effective means of solving long-standing observational problems of oceanic exchanges between Arctic and subarctic seas. Drawing these uses together into a single paragraph will underscore their versatility. On the Greenland-Scotland Ridge, Eriksen and Rhines employed three UW seagliders to map and measure the small, thin, dense water overflows that have eluded measurement by any more conventional means (see Dickson, 2008). In the case of iAOOS-for-Norway, as we have seen, the observational difficulty was to find some means of observing the offshore free jet of the Norwegian Atlantic Current where it passes north through the Svinøy Section, carrying half the northward heat flux through the Norwegian Sea; this was solved by the use of a UW SeaGlider from July 2008. In the case of the Fram Strait throughflow, the need was to resolve the filamented two-way flow through the Strait in a way that even a dense 'picket fence' of current meter moorings cannot do; AWI introduced glider surveys for this purpose in both 2007 and 2008 and intend, with Craig Lee's continued collaboration, to expand this effort westward to recover data from the ice-covered part of the Strait. In the case of Craig Lee's Davis Strait Monitoring effort, to be described below, the observational need was to measure the totality of ocean exchanges to the west of Greenland, in particular the freshwater flux passing south under the seasonal ice cover in the western part of the Strait. After first trials in December 2006, this was solved in 2009 by a SeaGlider operating autonomously (acoustic navigation, ice-sensing, independent decision-making) to avoid the surface and continue its westward transit after encountering the ice edge. Prospectively, acoustic gliders operating under the perennial ice of the Arctic deep basins will form the essential third component of the DAMOCLES system to monitor ice keel-depth, acting as the data link between upperward looking sonar (ULS) floats and their acoustic Ice Tethered Platforms (ITP). A first full deployment is intended in spring 2010 at the North Pole. In all five of these examples, a measurement of considerable importance to our understanding of the Arctic climate system had stalled until the unique capabilities of SeaGliders were introduced to help solve the observational problem. The new Deepglider development will add a further dimension. Deepgliders are expected to be able to survey oceanic variability autonomously over the entire water column on deployments and recoveries made on successive summers, making them well-suited to observing subpolar as well as subtropical and tropical seas. To give only one example, the development of Deepgliders capable of cruising the watercolumn of the subpolar gyre has been called for (Dickson et al., 2008) as a necessary aid to capturing the baroclinic adjustments that cause interannual changes in the transport of the dense water overflows from Nordic Seas. We note that the cost of fabrication is estimated to be less than half again that of SeaGliders, while the cost of operation will be perhaps half that of their upper ocean relatives (Charlie Erikson, pers. comm., January 2009). Testing of the first full ocean depth Deepglider took place in mid-2009.

Observing the Arctic Ocean and Circum-arctic shelves.

We need little reminding that barely a decade ago, the Arctic Ocean was a data desert. If we did, Fig. 2.2-4 would be all that was needed to remind us. That situation has now changed. In addition to the expanded ship-based CTD coverage achieved during IPY (described in Dickson, 2008; 2009), the rapid elaboration and expansion of the ice-top observatory brought a range of new autonomous systems to bear on the Arctic Ocean and its ice cover that hardly existed before the Millennium. In particular, the spectacular expansion of CTD coverage throughout the Arctic deep basins is principally the result of the WHOI Ice Tethered Profiler and JAMSTEC Polar Ocean Profiler Systems. In consequence – and probably for the first time – it is now impractical for a summary such as this to provide a complete accounting of what was achieved, voyage by voyage or instrument by instrument, during IPY. Instead, we attempt to provide a flavour of that achievement by describing an inconsistent selection of voyages, instruments and ideas whose novelty, difficulty, effort, complexity, climatic importance or collaborative nature fulfilled one aspect or another of what IPY set out to do. In paring down our description to a few voyages, it is important that we don't discard all of the detail: one suspects that it will be the multi-layered and often internationally-provided complexity of the field

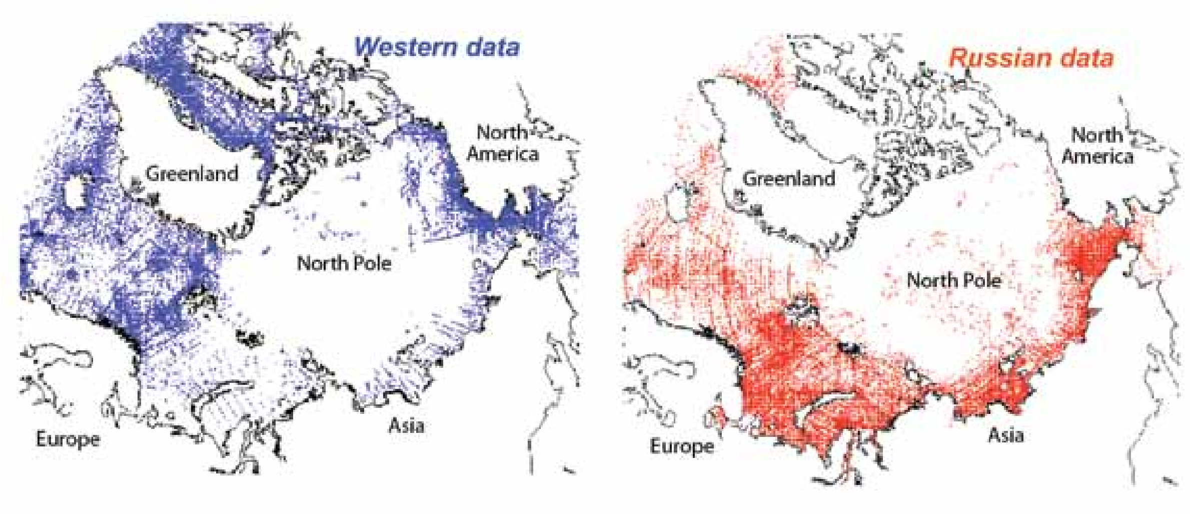

Fig. 2.2-4. Distribution of the oceanographic stations over the Arctic Ocean for the summer period according to the findings of the Environmental Working Group (EWG, 1997).

programme that will generate the new insights that IPY set out to provide.

Instrumenting the Western Arctic: the 2008 voyage of F/S Polarstern ARK-XXIII/3 (ECDAMOCLES). This cruise, from 12 August to 17 October 2008, was designed as a contribution to the Synoptic Pan-Arctic Climate and Environment Study (SPACE), designed by Ursula Schauer (AWI) for IPY, but with input from a range of multinational programs including, principally, EC-DAMOCLES. The cruise was remarkable for its geographic scope (from the NW to the NE Passage), for the international breadth of its collaborations and for the range of novel instrumentation that it deployed across this climatically-active sector of the western Arctic. These novel systems included the first two deployments of the Polar Area Weather System (PAWS; Metocean; Burghard Brümmer, UHH) designed to collect air temperature, ice temperature, barometric pressure, relative humidity, wind speed and direction, and position, with one-year life; two WHOI Ice-tethered Platforms (ITP; John Toole and Richard Krishfield, WHOI); five Surface Velocity Profilers (SVP; Meteo France; Pierre Blouch, EUROMETNET Brest) providing ice-top position, temperature and pressure; two Polar Ocean Profiler buoys (POPS, JAMSTEC, Takashi Kikuchi); ice-tethered systems providing profiles of water temperature, salinity and pressure to 1000 m; and a single Ice-tethered Acoustic Current Profiler (ITAC; Optimare + RDI 75 kHz Long Ranger ADCP; Jean-Claude Gascard of DAMOCLES) – essentially an ice-tethered ADCP providing profiles of ocean current velocity to 500m every two hrs – employing Kikuchi's system of 2 GPS units placed some 100m apart to obtain not only position, but also the orientation of the ice floe in areas of weak horizontal field strength.

Revolutionizing the hydrographic record of the Arctic Deep Basins: the contribution of Ice tethered Profiler systems. Of the many new systems that have revolutionized the Arctic Ocean data set in recent years, a principal success has been the rapid expansion of CTD coverage throughout the Arctic deep basins, provided largely by the autonomous use of ice-tethered profiler systems. The two main types are the WHOI ITP system (Krishfield et al., 2008) and the JAMSTEC POPS (Inoue and Kikuchi, 2007; Kikuchi et al., 2007).

The rapid expansion of the ITP system since 2004, but principally during IPY, is documented in Table 2.2-3 (next page). It is now a fully-international effort with contributions from the EC-DAMOCLES and with IPY collaborations between WHOI and AWI, Arctic and Antarctic Research Institute (AARI, St Petersburg), French Polar Institute (IPEV), Shirshov Institute of Oceanography and the U.K. Arctic Synoptic Basin-wide Oceanography (ASBO) project. In 2008, in collaboration with Canadian, U.K., Russian and German colleagues, the WHOI team collectively deployed a dozen systems from the *Borneo* ice camp near the N. Pole (1), the *Louis St.Laurent* in the Canada Basin (five systems) and well upstream in the Transpolar Drift from the *Fedorov* (4) and *Polarstern* (2). Since April 2006, the Polar Ocean Profiler (POPS) has used a similar system with an inductive modem providing data transfer between ice platform and profiler. Trials confirm that POPS can measure temperature and salinity with conservative accuracies better than 0.01 C for temperature and 0.01 for salinity.

Table 2.2-3. Expansion of the WHOI ITP program between 2004 and 2008, from www.whoi.edu/itp.

	Completed missions	Active missions
2004	ITP 2	
2005	ITP 1, ITP 3	
2006	ITP 4, ITP 5	ITP 6
2007	ITP 7	ITP 8, ITP 9, ITP 10, ITP 11, ITP 12, ITP 13, ITP 14, ITP 15, ITP 16, ITP 17, ITP 18
2008		ITP 19, ITP 20, ITP 21, ITP 22, ITP 23, ITP 24, ITP 25, ITP 26, ITP 27, ITP 28, ITP 29, ITP 30

Altogether, the ITP array has now returned something in excess of 20,000 CTD profiles between ~7 and ~750 m depth since the first unit was deployed in 2004 (pers. comm., John Toole WHOI, October 2009), transforming the former data-desert into one of the most-densely-observed oceans on the planet. Though still a work in progress (part of the data-set remains to be calibrated), Fig. 2.2-5 by Ben Rabe, AWI Bremerhaven, illustrates the barely believable progress that has been made by combining the recent output of autonomous profiling systems with conventional ship-based CTD-hydrography (Rabe et al., in press). In fact, Fig. 2.2-5 illustrates three recent advances, all of them important to the success of IPY. First (it goes almost without saying), usefulness is linked to the extent and density of coverage; the pan-Arctic distribution of 'freshwater content' is an output of direct relevance to the role of the Arctic in climate that could only have been obtained by merging the full expanded sets of CTD profiles, from all sources. Second, our ability to merge these data sets stems from a quite new attitude to the accessibility and availability of data. Thus the ITP data are rapidly provided by the WHOI ITP Program via www.whoi.edu/itp; the POPS data are provided by EC-DAMOCLES and by JAMSTEC through the international ARGO programme. Data can be found at www.ipev.fr/damocles/ and ftp://ftp.ifremer.fr/ifremer/argo/dac/jma/4900904/. The ship-based CTD data are courtesy of AWI and were acquired during the RV *Polarstern* cruises ARK- XXII/2 (Aug/Sep 2007) and ARK-XXIII/3 (September - October 2008); these data can be found at www.pangea.de. Having merged the data, the third comment made in Fig. 2.2-5 concerns the general

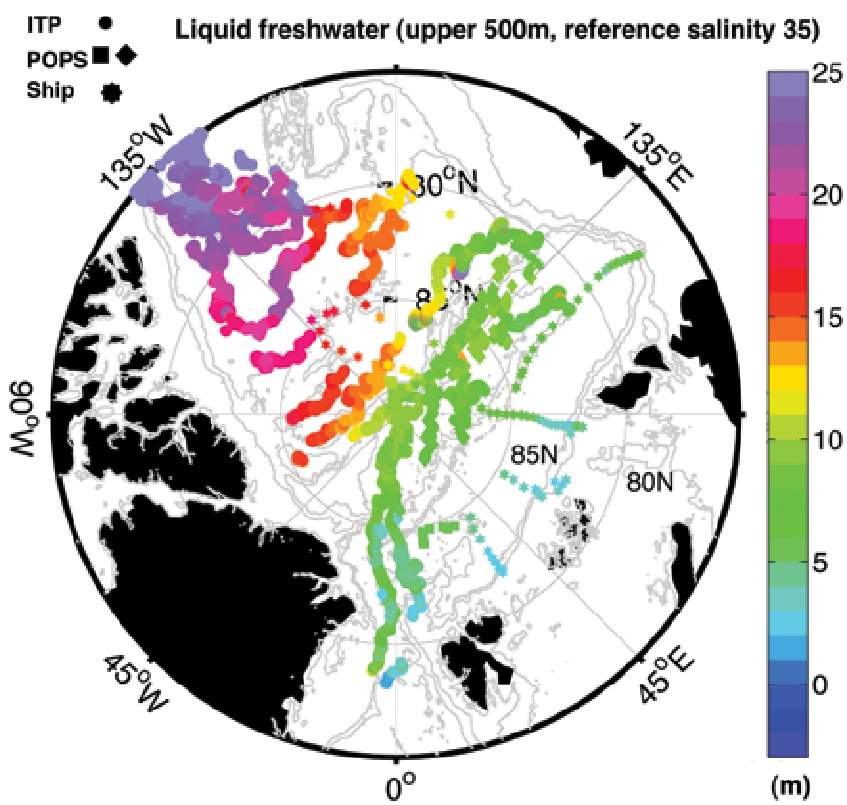

Fig. 2.2-5. The distribution of liquid freshwater content in the upper 500m of the Arctic Ocean from ITP (2006 to 2008), POPS (DAMOCLES and JAMSTEC/ARGO, 2006 to 2008) and *Polarstern* cruises ARK-XXII/2 (2007) and ARK-XXIII/3 (2008). The freshwater content is expressed in metres. This analysis, kindly provided by Ben Rabe AWI, is not yet finalised; the ITPs (no. 6 to 18) have been salinity-corrected using non-autonomous CTD observations but the POPS data have not yet been corrected in this way. The *Polarstern* CTD data have been fully post-processed and corrected using *in situ* salinity bottle samples and pre-/post-calibration of the sensors.
(Map: Dickson and Fahrbach, 2010)

quality of the data; though not yet fully calibrated, the component data sets merge without obvious inhomogeneities.

A broad range of problems in arctic oceanography have been addressed by this powerful new technique. *Inter alia,* its data-set has been used to: document space-time variability since AIDJEX (1975) and SCICEX (1997) in the major water masses of the Canada Basin; describe the double-diffusive thermohaline staircase that lies above the warm, salty Atlantic layer; measure the seasonal deepening of the surface mixed layer and its implications; explore the structure of mesoscale eddies (Timmerman et al., 2008); support a broad range of process studies; and facilitate the initialization and validation of numerical models. To achieve the prospect of having ITPs sweep through a large fraction of the Arctic over the next few years, the surface buoy of both systems has been redesigned to better survive thin ice and even open water and from 2009–2010, the WHOI system will operate with just a clonical float. NSF OPP has recently agreed to continue the ITP program for another five years.

Satellite remote sensing. Fig. 2.2-6, from (Morison et al., 2007 and pers. com.) will serve to introduce the subject of the use of satellite altimetry and time-variable gravity in improving our understanding of Arctic Ocean hydrography and circulation, showing something of what has been accomplished to date. GRACE Release 4 bottom pressure trends in the Arctic Ocean during 2005-08 describe a declining trend in bottom pressure throughout in the Beaufort Sea and eastern Canada Basin (green tones) due to the persistent freshening trend. In the central Arctic, a rising trend in 2005–2008 (red tones) is associated with the advance of salty Atlantic-derived water. A correspondence between measured steric and bottom pressure trends (not shown here) seems consistent with the idea that changes in bottom pressure at long time-scales are dominated by steric changes as opposed to sea surface height changes (Vinogradova et al., 2007). From radar altimetry, a real goal – already partly realised (Katharine Giles and Seymour Laxon, UCL-CPOM, pers comm.) – is to derive maps of sea surface height (SSH) for the Arctic Ocean even in the presence of ice.

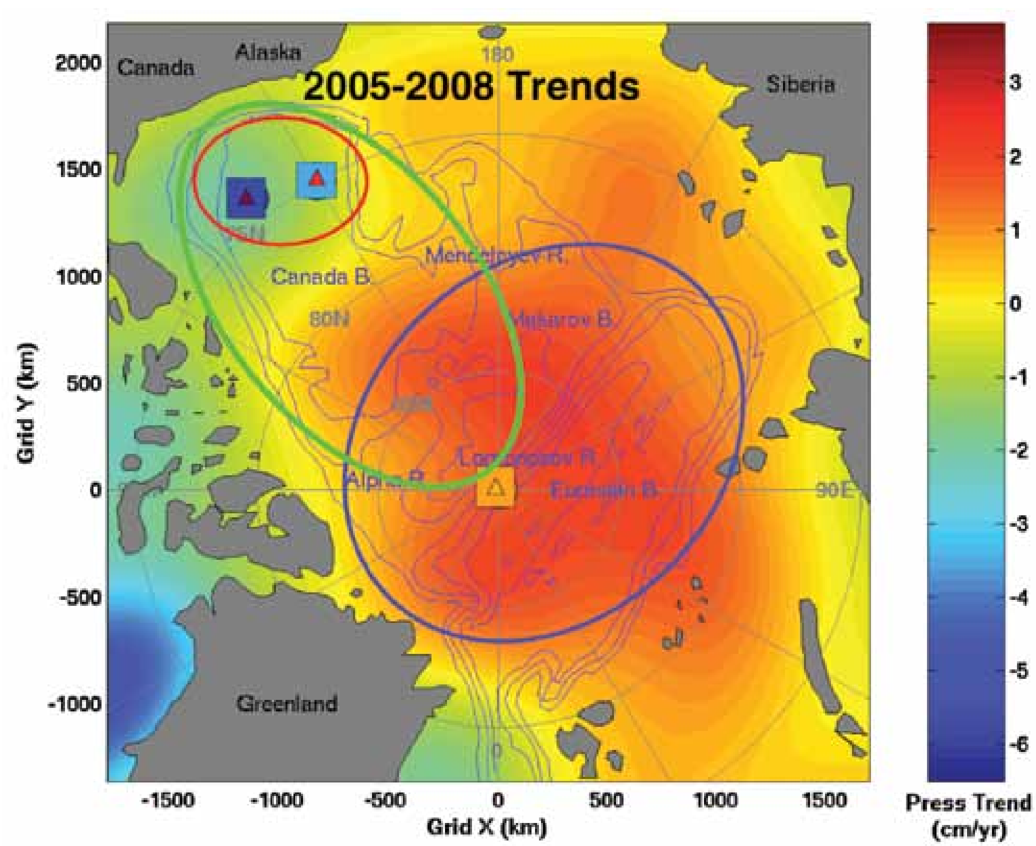

Fig. 2.2-6. GRACE Release 4 bottom pressure trends in the Arctic Ocean during 2005-2008, from (Morison et al., 2007 and pers. com.).

Towards a new autonomous sub-ice system for monitoring the keel depth of sea-ice; the collaboration between EC-DAMOCLES and the Chinese National Arctic Research Expedition (CHINARE) in 2008. Ice thickness is an important parameter. The 22 ice-prediction groups that participated in the SEARCH-for-DAMOCLES (S4D) Sea Ice Outlook exercise concluded that an improved measure of ice thickness in spring was the prime requirement for improved prediction of ice extent at the time of the late summer minimum. Supplementing remote sensing techniques, including the laser and radar altimetry on ICESAT and ENVISAT, and the use of ice-surface sensors (e.g. tiltmeter buoys), a new autonomous system based on the use of isobaric sub-ice floats fitted with upward-looking sonar has been developed by EC-DAMOCLES during IPY and is now on the point of completion. The ULS floats are designed to drift at a constant depth of 50m beneath the arctic ice for up to two years. The equally-new acoustic ice-tethered platforms (AITP; now 'amphibious' rather than ice-tethered) are designed to form the link between ULS floats and satellite transmission, with the EC-DAMOCLES plan calling for ten AITPs and eight ULS floats in total. The first deployment of two ULS floats and four AITP systems were deployed by Canadian twin-otter aircraft above the Alpha Ridge in April 2008, together with seven PAWS weather monitors (Broemmer, UHH) and three ice mass-balance buoys (IMBs; Richter-Menge et al., 2006). The remainder of the 2008 deployment, including four more AITPs, an extensive CTD grid and a complex ice camp of instruments was later set by the Chinese CHINARE 2008 Expedition aboard R/V Xue Long (11 July - 24 September, 2008). The full realization of data retrieval from ULS-floats will depend on the development of acoustic gliders as the third component of the system. DAMOCLES began the stepwise development of such an acoustic glider, starting in autumn 2008, followed by trials off Svalbard in spring 2009 and leading to a first planned deployment in spring 2010 at the North Pole. In the meantime, data retrieval will involve ships approaching ULS floats and forcing a download to an acoustic modem (Gascard, pers comm). Altogether, ten AITPs plus four ULS floats have been deployed to date fulfilling most of the DAMOCLES plan and the unequivocal requirement of the S4D Sea-ice Outlook exercise for data on sea-ice thickness commends the continued use of this technique into the IPY legacy phase. A further four ULS floats and four new 'hybrid' AITPs are being constructed; in addition to having a profiling hydrophone, the new AITPs will begin to contribute to the ITP dataset by carrying a CTD profiler for the first time.

The drift of the Russian Ice Island North Pole-35 and the Arktika-2008 expedition aboard R/V Akademik Fedorov. Since 1937–1938, the Russian Arctic and Antarctic Research Institute (AARI) has operated a total of 34 drift stations in the Arctic Ocean making this type of observational platform something of a Russian specialization. After a considerable search for a suitable floe, NP-35 was established on September 25, 2007 at 81°26'N 103°30'E by the *Akademik Fedorov* working in conjunction with the nuclear icebreaker *Russia* as part of the "Arktika 2007" expedition. For most of the following year, NP-35 was occupied by AARI as a contribution to IPY, contributing new results in polar oceanography, sea ice studies, processes of greenhouses gas exchange in presence of ice cover and polar meteorology.

During the first 7-month winter drift of NP35, the Russian team was joined by Jürgen Graeser from the Potsdam Research Unit in Germany and, during this phase, the investigations of the ocean upper layer, the characteristics of the sea ice, the snow cover and the energy balance above the ice surface were supplemented with further atmospheric data (temperature, moisture, wind and air pressure) collected by ascents of a tethered balloon up to a height of 400 metres as well as by balloon-borne sensor ascents up to an altitude of 30 kilometres. Both contributed rarely-obtained winter data with high temporal and spatial resolution to the improvement of global climate models. The exchanges of heat and moisture in the atmospheric boundary layer to an altitude of ~400 metres, now measured for the first time during the complete polar night, were of especial value. As the layer that determines the lower boundary conditions for all model calculations, a realistic representation of the planetary boundary layer in the Arctic is crucial for the construction of climate models; hitherto, temperature profiles from regional climate models have shown considerable deviation from those measured on the floe. The data set of NP 35 will also contribute significantly to the determination of how much of the ozone destruction in the Central Arctic is caused by human activities. In fall 2008, the Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet) conducted the "Arktika-2008" research expedition in the Arctic basin and the Arctic seas aboard *R/V Akademik Fedorov* of AARI. The expedition was the biggest in Russia in 2008, within the framework of IPY, and deployed a series of experiments into the processes responsible for the changes in the arctic climate system and the environment in ocean, sea ice and atmosphere. Apart from evacuating NP-35 at the end of its long drift, this expedition also established a new drifting research station NP-36.

The transpolar drift of the polar yacht Tara. On 3 September 2006, at a point north of the Laptev Sea, the polar schooner *Tara* embarked on its transpolar drift, embedded in the arctic ice-pack as *Fram* had been, drifting along a more-or-less parallel track, but twice as fast as expected. Scientists on board were responsible for running ten different research programmes under EC- DAMOCLES: collecting data related to sea ice, atmosphere and ocean, servicing a sophisticated web of autonomous buoys spread within a 500 km range around the ship, and with IAOOS-for-Norway contributing installations of radiometers and optical measurements. *Tara* passed out of the Arctic Ocean through 80N in December, was picked up by the ice off east Greenland and was finally released into the western Greenland Sea, 300 km north of Jan Mayen on 21 January 2008, some 500 days and 5000 km since her drift began. We have space in this brief summary to describe just two areas of *Tara's* work-program that have some ice-ocean connection and that already seem to be of lasting significance. 1)

In the context of arctic change, the albedo feedback process has been identified to play a key role for snow and sea ice melting. This process operates on different spatial scales, from snow metamorphosis involving snow grain changes, to processes where the dark surface of open water in leads absorbs more heat and contributes to enhanced melting of sea ice. Besides its importance for the surface energy and mass balance in the Arctic Ocean, the light budget above and below the sea ice is of crucial importance for the arctic marine ecosystem and for remote sensing calibration and validation. During her long drift across the Arctic Basin, a setup with three radiometers and a data logger was installed near *Tara* in April 2007; detailed optical measurements of spectral surface albedo and snow and ice transmissivity were made automatically and autonomously until September 2007. 2)

Melt ponds have a substantially lower surface albedo than other ice and snow surfaces, so the *Tara* program on the role of melt pond formation for the arctic sea ice and climate, including the improved detection of melt ponds (using a mast-mounted time-lapse camera) and their consideration in climate models, will also be of lasting significance.

First Iron Section through the Arctic Deep Basins. Dissolved iron is an essential trace nutrient for all living organisms and is often limiting for the plankton ecosystem in the world oceans. The low

Fig. 2.2-7a. Ultrapure all-titanium frame holding 24 teflon-coated water samplers of 12 Liters each, deployed with a Kevlar cable. Upon recovery the complete frame is placed inside an ultraclean room for subsampling. The frame never touches the steel ship and thus permits reliable sampling of ultralow concentrations of dissolved Fe in pristine ocean waters.

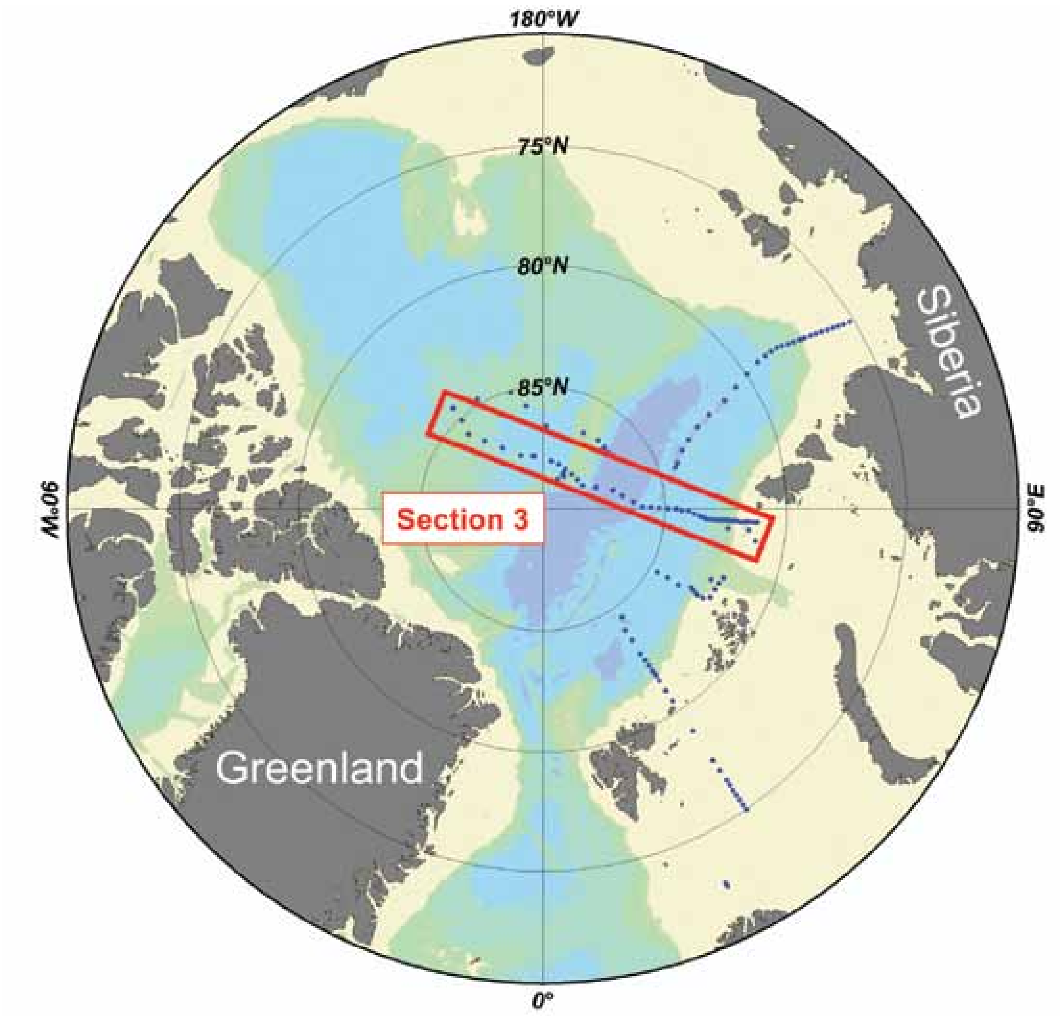

Fig. 2.2-7b. Sampling stations for dissolved iron in the Arctic Ocean.
(Map: Dickson and Fahrbach, 2010)

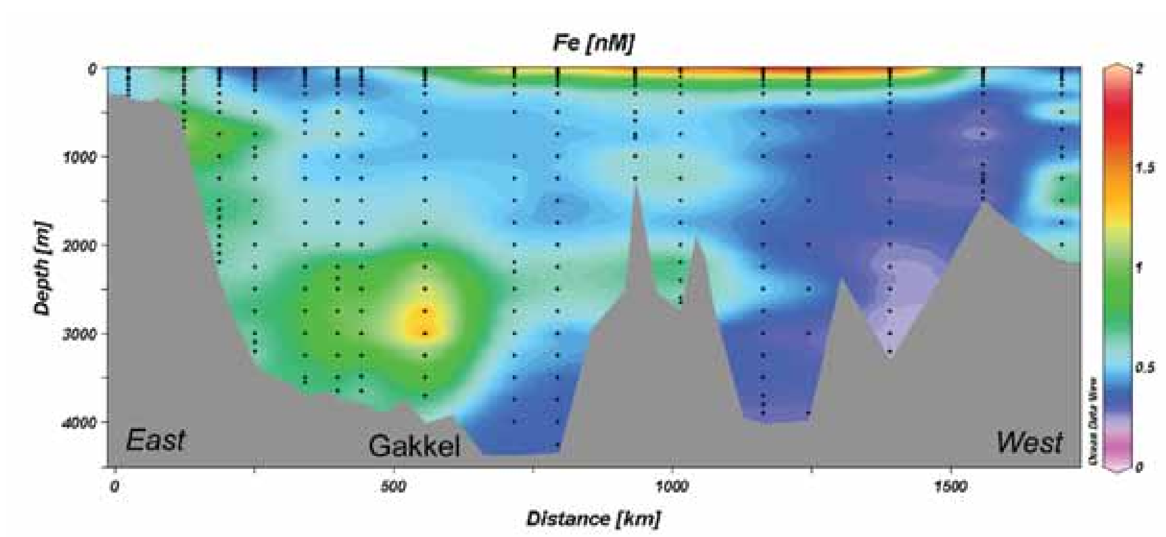

Fig. 2.2-7c. Vertical distribution of dissolved iron along Section 3 in the central Arctic Ocean. High values in surface waters are due to river input and sea-ice. The very large plume over Gakkel Ridge is due to hydrothermal vent supply.
(Graph: Dickson and Fahrbach, 2010)

concentration makes it difficult to quantify Fe in seawater. Samples were taken with a novel ultraclean CTD sampling system (Fig. 2.2-7a) deployed during the IPY-GEOTRACES program aboard R.V. *Polarstern* ARK-XXII/2 in July-October 2007. The results are the first ever comprehensive overview of the distribution of dissolved Fe in the deep basins and surface waters of the Arctic Ocean. Shipboard analyses by flow injection were calibrated with excellent agreement versus certified standard (SAFe) seawater (Johnson et al., 2007). Along the long trans-Arctic section 3 (Fig. 2.2-7b), the dissolved iron showed high (>2nM) concentrations in the upper 100m with a negative correlation ($R^2 = 0.80$) with salinity. This, together with corresponding manganese maxima (by Rob Middag, not shown) and low light transmission values, points to fluvial input and input via melting of sea-ice to be main contributors of iron to the surface waters. Hydrothermal activity above the Gakkel Ridge (Fig 2.2-7c) is a major input source of iron as confirmed by a very similar pronounced dissolved manganese maximum (by Rob Middag, not shown) and anomalies of potential temperature and particle abundance (less light transmission). Decreasingly, very low concentrations of iron with depth below 3000 m in the Amundsen and Makarov Basins are most likely due to net removal caused by a high scavenging regime and relatively little remineralization.

Exploring the biogeochemistry and geophysics of the entire Eurasian-Arctic continental shelf in IPY: the International Siberian Shelf Study 2008 (ISSS-08). The ISSS-08 study aboard *RV Yakob Smirnitski* involved 30 scientists from 12 organizations in Russia, Sweden, U.K. and U.S.A., including three from DAMOCLES responsible for physical oceanography. The motivation for ISSS-08 was to alleviate the scarcity of observational data on transport and processing of water, sediment and carbon on the East Siberian Arctic Shelves (ESAS). The ESAS, composed of Laptev, East Siberian and Russian part of Chukchi Sea, is the world's largest continental shelf and at the same time the most understudied part of the Arctic Ocean. It is characterized by tundra discharge through the Lena, Indigirka and Kolyma rivers, coastal erosion, methane seeps from subsea-permafrost reservoirs and shelf-feeding of the Arctic halocline. The region is of particular interest from the perspective of carbon-climate couplings as it has witnessed a 4°C springtime positive temperature anomaly for 2000-2005 compared with preceding decades.

The coplex program included the sampling of river-borne organic material, trace elements, methane, CO_2, freons and nutrients, with sampling from air, watercolumn and sediments. Additionally, a Russian group carried out a seismic program using towed equipment. Sampling was accomplished during a 50-day cruise in August – September 2008 using two vessels. The main vessel *R/V Yacob Smirnitskyi* travelled the entire length of the Siberian coast from Kirkenes, Norway to Herald Canyon, Chukchi Sea and back along the outer shelf. A second ship sampled the Lena River and the southeastern Laptev Sea. Significant at-sea findings included new methane seeps and bubble plume fields in both the Laptev and East Siberian Sea, several associated with geophysical gas-chimney structures. The cruise also studied the Pacific inflow through Herald Canyon and remnants of salty and cold bottom waters on the shelf break. A vigorous mixing zone was encountered just north of Herald Canyon between warm north-flowing Pacific Summer Water and cold winter water. Still planned are the analyses of collected air, seawater, eroding soil and sediment material including molecular and isotopic biomarker composition as well as trace element and isotope characterizations (GEOTRACES protocol) to elucidate provenance, remobilization of "old" terrestrial matter, the relative importance of river versus erosion sources, degradation of organic matter in seawater and sediments and variations in these processes with dynamic climate forcing.

Deploying Canada's 'climate antenna' through its Northern Seas: the 15,000 km annual transects of the Canada Three Oceans (C3O) Program. The three oceans that surround Canada are connected by waters that flow from the Pacific to the Arctic and then into the Atlantic; changes in the ice cover and ecosystems of the Arctic are tightly linked to the global climate system in general and to the bordering subarctic Pacific and Atlantic oceans in particular. C3O (Canada's Three Oceans, led by Eddy Carmack) links all of Canada's three oceans and investigates the interconnectedness of arctic and subarctic domains. During IPY, C3O joined under the iAOOS cluster with the ongoing JOIS (Joint Ice Ocean Studies, led by Fiona

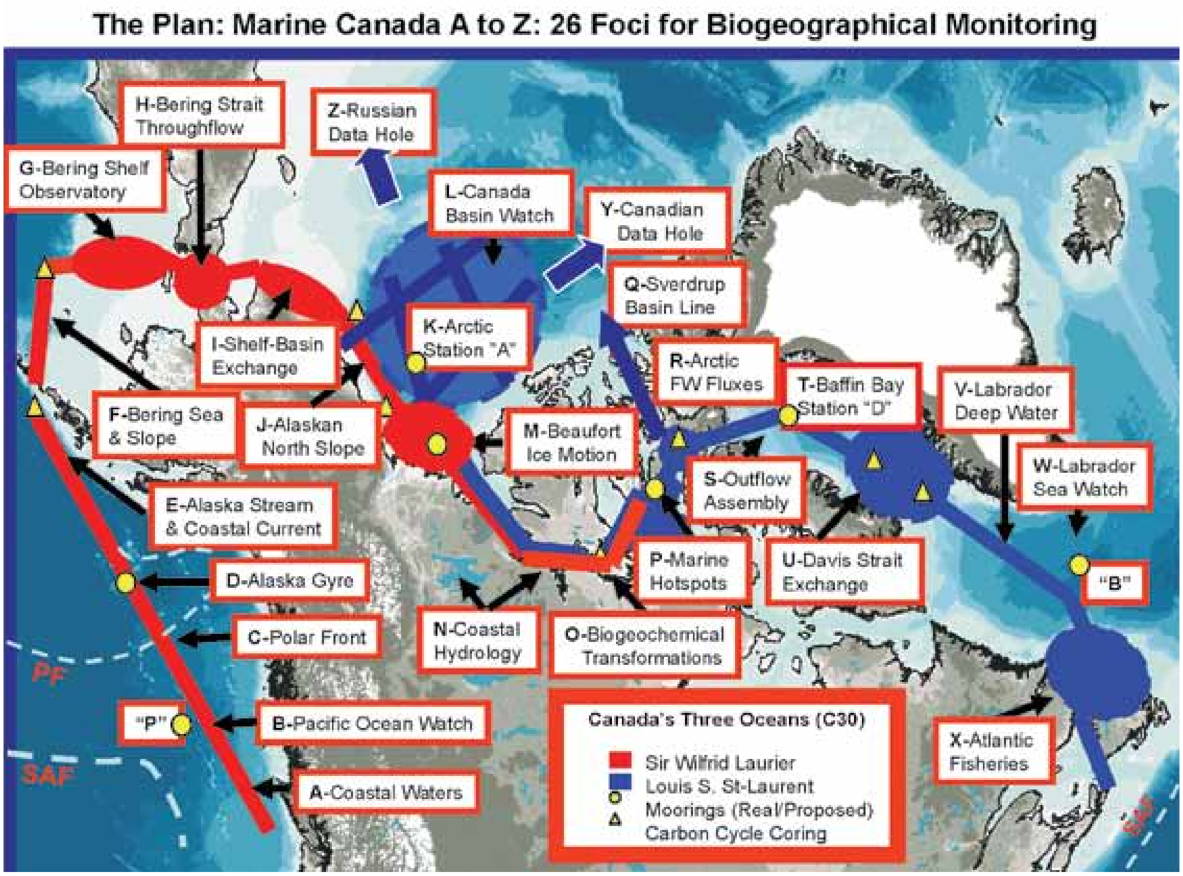

Fig. 2.2-8. The 26 sites and subjects that are presently monitored under the two-ship Canadian C3O program, designed to assess the progress of global change throughout Canada's three oceans.
(Source: Eddy Carmack, IOS)

McLaughlin) and the BGEP (Beaufort Gyre Exploration Project, led by Andrey Proshutinsky) to optimize use of available resources.

In 2007 and 2008, C3O used two science-capable icebreakers of the Canadian Coast Guard whose current mission tracks encircle Canada (Fig. 2.2-8) to obtain a snapshot of large-scale ocean and ecosystem properties and thus establish a scientific basis for sustained monitoring of Canada's subarctic and arctic seas in the wake of global warming. C3O collected fundamental data on temperature, salinity, nutrients, oxygen, the carbon system, virus, bacteria, phytoplankton, zooplankton, fish, benthos and whales, with the goal of establishing connections between the physical environment and the living nature. The following observations were made in the two-year period: 551 CTD/rosette stations; 324 underway CTD and expendable CTD stations; 148 zooplankton net hauls; 64 biological stations (viral abundance, DNA/RNA, primary production); and approximately 24,000 km of underway sampling. The ultimate goal of C3O is to establish a 'scientific fence' around Canada with observations that will allow both observers and modellers to gauge the progress and consequences of global change and thus provide policy makers and the Canadian public with information essential to governance, adaptation and resilience-building in the Canadian North. Regular repetition through to 2050 would reveal the expected redistributions of oceanic boundaries and biomes (Carmack and McLaughlin; 2001; Grebmeier et al.; 2006) and give scientists and policy makers access to the time-scales of change that have the greatest social relevance and impact. Nevertheless, the value of C3O will not rest entirely with its own findings. With 26 separate study sites covering a broad range of disciplines, the 'connectivity' of C3O with the results of other major IPY projects can be expected to be high. These expected yet unpredictable linkages between project results represent, in many ways, the unplanned 'profit' of IPY, developing a more thorough and a more complex understanding of the processes of arctic change than might be evident from any single project. One emerging example – from

Jackson et al., (in press) – will illustrate the point.

For more than a decade, we have known of the existence of a narrow temperature maximum just below the surface (~25m) of the Canada Basin in summer (Maykut and McPhee, 1995), Jackson et al., (in press) have recently combined CTD profiles from four of the Woods Hole ITPs (nos. 1, 6, 8 & 18; Table 2.2-3 above) with shipborne CTD data from IPY (C3O) and from earlier years (JOIS 1997; JWACS 2002-6) to reveal much of what is important about this seemingly-delicate, but in fact extensive and rather robust layer. The Near Surface Temperature Maximum (NSTM) that they describe is first formed in June-July when sufficient solar radiation enters the upper ocean through narrow leads and melt ponds to warm the near-surface waters. Ice melt from these warmed surface waters then accumulates to form a strengthening near-surface halocline, effectively capping-off the NSTM and trapping solar radiation in the ocean until late September when sea ice begins to form once again, allowing penetrative convection (from brine rejection) and air-ocean or ice-ocean stresses to deepen the surface mixed layer. This is not an unvarying process. As the ice has retracted from the western Arctic in what Overland et al., (2008) have called the "Arctic Warm Period" (2000-2007), Jackson et al., (in press) reveal that the temperature of the NSTM in the Canada Basin has increased north of 75ºN at a rate of 0.13ºC per year since 2004. Some of the interconnections between this result and others *within* the C3O project are already evident: the idea that the warming of the NSTM is closely linked to sea-ice melt receives strong support from the fact that the warmest NSTMs were found in the same region of the Canada Basin that Yamamoto-Kawai et al., (2009) have recently described; a threefold increase in the ice-melt component of the freshwater in the watercolumn between 2003 and 2007. But the *external* implications of these results have the potential to be even more significant. If the warmer NSTM persists later in the year, which is one scenario discussed by Jackson et al., (in press) *'heat from the NSTM might maintain thinner sea-ice through winter which would then melt sooner in spring'*. As they also point out, thinner sea-ice is likely to alter the effect of wind stress on sea ice, increasing ice drift and air sea coupling in the manner suggested by Shimada et al., (2006). Hence their conclusion that *'the dynamics of the NSTM should be considered when modelling climate change in the Arctic'*.

Observing the outputs from the Arctic Ocean

First long term measurements of the freshwater flux east of Greenland. De Steur et al., (2009) report the results of a decade of observations of the freshwater flux in the East Greenland Current at 78° 50'N. The special nature of this result lies in the considerable achievement of recovering 10 years of moorings from these difficult waters and in the usefulness of this result as a missing term in our understanding of the freshwater balance around Greenland. The main finding itself is rather less dramatic: over this decade of measurements, the annual mean liquid freshwater flux passing south through the western Fram Strait proved to be surprisingly constant at ~1150 km^3 y^{-1} (36 mSv). Though based on an earlier dataset, Dodd et al., (2009) have recently used a mix of tracers (hydrographic, oxygen isotope ratio and dissolved barium concentration) to determine the sources and fate of the freshwater carried in the East Greenland Current. Rabe et al., (2009) use hydrographic data and $\delta^{18}O$ values with modelling (NAOSIM) to distinguish changes in the various freshwater components and transports in the Fram Strait since the late 1990s, showing *inter alia,* that the high transport of meteoric water (precipitation and riverine sources) in the Fram Strait in 2005 is in agreement with the temporary storage of river water on the Siberian shelf in the mid-1990s, which reached the north of Greenland in 2003.

Ocean Currents of Arctic Canada; new insights on the Canadian Arctic Through-flow during IPY. The Canadian Arctic Through-flow (CAT) study is the culmination of ten years of effort within Canada and the international community to measure flows of freshwater, saltwater and ice through the Canadian Arctic Archipelago (CAA; see Kleim and Greenberg, 2003; Prinsenberg and Hamilton, 2005; Münchow et al., 2007; Falkner et al., 2008; Melling et al., 2008). Although first attempts date back to the early 1980s, the recent revival in activity was stimulated by the development of techniques for measuring the current direction near the geomagnetic pole and for observing the hazardous zone beneath drifting ice pack. The installations in Lancaster Sound and Cardigan Strait have been maintained since 1998. The installation in Nares Strait was discontinued after loss to icebergs of both moorings in Smith Sound during 1999. Nevertheless, four years later in 2003, a large array of sub-sea instruments was installed from *USCG Healy* across Kennedy Channel, much further north in Nares Strait where icebergs are less common. Most of these instruments were retrieved using *CCGS Henry Larsen* in 2006. The array for IPY was complete by late August 2007. In July 2007, two moorings were placed from *CCGS Louis S St-Laurent* in Bellot Strait, the narrowest and only unexplored choke point for CAT; one of these moorings carried a variety of sensors for biological parameters (chlorophyll, turbidity, dissolved gases, acoustic backscatter and marine vocalization). In early August 2007, moorings in western Lancaster Sound was recovered and replaced from *CCGS des Groseilliers*. By the end of that month, the array at the southern end of Kennedy Channel (Nares Strait) had been re-established from *CCGS Henry Larsen* and the long-standing installations in Cardigan Strait had been recovered and re-deployed. The high logistic cost of working in Nares Strait precluded the recovery and re-deployment of moorings in this remote area in 2008, but the full array was recovered in August 2009. With this recovery, one of the hardest observational tasks in oceanography was successfully accomplished. The 'point' of making these measurements remains; carrying the main freshwater flux between the Arctic Ocean and North Atlantic west of Greenland, the passageway-flows of the Canadian Arctic Archipelago carry significant inputs to the Atlantic MOC and are thus of importance to climate. The task now will be one of maintaining these difficult arrays over years to decades, but at lesser cost.

A major advance in monitoring ocean fluxes through Davis Strait; the first autonomous sub-ice glider profiles. The Davis Strait carries all of the exchanges of mass, heat and freshwater between the Arctic and the Northwest Atlantic west of Greenland and thus acts as a vital monitor of Arctic and subarctic change. Beginning in autumn 2004, Craig Lee (U. Washington) has devised a system of moorings and extended-endurance (9-12 months) autonomous gliders capable of monitoring oceanic exchanges across the full width of the Strait. The major milestone was achieved in December 2006 with the first successful operation of a glider beneath the ice-covered western Davis Strait; a single SeaGlider successfully navigated from the ice-free eastern Strait westward to 59°W, shifting to fully autonomous behaviour, avoiding the surface and continuing its westward transit after encountering the ice-edge. Significantly, all aspects of the ice-capable glider system functioned properly, including acoustic navigation, ice sensing and autonomous decision making. The entire section was conducted without human intervention, with the glider making its own decisions and surfacing to report its data after navigating back to the ice-free eastern side of Davis Strait. By returning observations to within a few meters of the ice-ocean interface and at roughly 5 km horizontal resolution, the technique successfully resolved the south-flowing, surface-trapped arctic outflow from CAA. Unfortunately, a hydraulic failure and faulty Iridium modems and Iridium/ GPS antennas caused the temporary suspension of under-ice SeaGlider operations for 2007–2008. Nevertheless, in 2009, operations resumed with a second major milestone: an autonomous glider, engineered for extended operation in ice-covered environments, completed a six-month mission sampling for a total of 51 days under the ice-cover of the western Davis Strait during which the glider traversed over 800 km while collecting profiles that extended to within a few meters of the ice-ocean interface.

Applying iAOOS: Linking environmental- and ecosystem-changes in Northern Seas

Much of the point of expanding the observing and modeling effort in northern seas during IPY has had to do with the ecosystem and its changes. Many of the projects that were funded for IPY had the ecosystem as their prime focus. Nevertheless, it is clear that after two years of effort, many of these studies will be at an early stage so it will take some care if we are to do these projects justice. Here, we adopt the approach of trying first to identify those aspects of environmental variability that are most likely to drive change through the ecosystem of northern seas, 'ecosystem: temperature' and 'ecosystem: ice' relations seem to be the most fundamental. We then describe some of the hypothetical linkages between the ecosystem and its environment that have been put forward in studies of longer duration than IPY. Finally, we seek out cases where these hypotheses are being tested, altered, developed or predicted in either our observations or models during IPY. Rather than attempt the task of describing the many dozens of IPY ecosystem projects, mostly at an early stage, these descriptions of IPY work take the form of regional essays focused on the Bering Sea', Jackie Grebmeier, the 'Canadian Arctic shelf', David Barber, and 'the Barents Sea', Jorgen Berge and Finlo Cottier. It is hoped that their large geographic spread and their varied content – a flaw lead/polynya study, an investigation of small scale ocean processes important to large scale expected change and, what might be termed, the more-traditional region-scale studies of ecosystem change – will provide a representative flavour of ecosystem science during the IPY.

Atlantic Sector

The warming of Northern Seas. The poleward spread of extreme warmth must form an important part of any description of the present state of arctic and subarctic seas. The temperature and salinity of the waters flowing into the Norwegian Sea along the Scottish shelf and Slope have recently been at their highest values for more than 100 years (Bill Turrell, FRS, pers. comm., 2006). At the 'other end' of the inflow path, the Report on Ocean Climate for 2006 by The International Council for Exploration of the Sea (ICES, 2007) shows that temperatures along the Russian Kola Section of the Barents Sea (33°30'E) have equally never been greater in more than 100 years. Holliday et al., (2007) have described the continuity of the spread of warmth along the boundary. Most recently, Polyakov et al., (2007 and pers. comm.) have documented the arrival of successive warm pulses at the Slope of the Laptev Sea (Polyakov, 2005), their continued eastward spread beyond the Novosibirskiye Islands (Polyakov et al., 2007) and the beginnings of their offshore spread along the Lomonosov Ridge, all neatly confirmed in simulations using the NAOSIM model (Karcher et al., 2007). A very similar warming has been recorded in the Bering Sea of the Pacific sector.

Northward shift of zooplankton assemblages in the NE Atlantic and Nordic Seas. There is an accumulating body of evidence to suggest that many marine ecosystems, both physically and biologically, are responding rapidly to changes in regional climate caused predominately by the warming of air and sea surface temperatures (SST) and to a lesser extent by the modification of precipitation regimes and wind patterns. The biological manifestations of rising SST have variously taken the form of biogeographical, phenological, physiological and species abundance changes. Since it is unexploited by man, the planktonic ecosystem is a valuable index of environmental change. From the 108 copepod taxa that it records, the Continuous Plankton Recorder (CPR) surveys have already identified that during the last 40 years there has been a northward movement of warmer water plankton by 10° latitude in the north-east Atlantic, a similar retreat of colder water plankton to the north and a large shift in phenology (seasonal timing) of plankton communities of up to six weeks. The precise mechanism is not known; SST has direct consequences on many physiological and reproductive attributes on marine life both directly and indirectly (e.g. by enhancing the seasonal stability of the water-column and hence nutrient availability). Equally, the consequences of such changes on the function and biodiversity of arctic ecosystems is at present unknown. Nevertheless, SAHFOS (Sir Alister Hardy Foundation for Ocean Science) has recently developed two new statistical tools, one to measure ecosystem stability and predict potential tipping points and the second to model the changes of niche that may develop under various forcing mechanisms. Using these tools, SAHFOS intends to develop its capability to predict the probable habitat of organisms, including commercially important fish species, in the north-east Atlantic and Arctic Oceans over the next century.

The CPR route network extends northwards. To cover the temporal and geographical shifts in the planktonic ecosystem, an agreement has been reached between SAHFOS and the Research Council of Norway to introduce regular CPR sampling along two routes – the old 'T' route to OS M and a new route from Tromsø to Svalbard. A next step under consideration by SAHFOS is a possible eastwards expansion into Russian waters where significant changes in marine production are anticipated both from natural and anthropogenic causes (Peter Burkhill, SAHFOS, pers. comm.).

Northward shift in the spawning location of the arcto-Norwegian cod stock along the Norwegian coast. Throughout the past century, though its time of spawning has remained relatively insensitive to temperature, it is now apparent from historical records (Sundby and Nakken, 2005) that the Arcto-Norwegian cod stock has made subtle adjustments to temperature in terms of its spawning location: a clear relative shift into the two northernmost spawning districts (Troms and Finnmark) and out of the southernmost district (Møre) during the earlier and recent warm episodes; and with a reverse southward shift during the cool periods prior to the 1930s, and in the 1960s and 1970s (Fig. 2.2-9). The recovery of the East Finnmark spawning areas after a 40-year absence (arrowed in Fig. 2.2-9) is, therefore, the expected response to the most recent waves of warming along the Norway coast. Other non-commercial fish species appear to have participated in the same poleward shift in distribution, one of the more conspicuous being the snake pipefish, which has rapidly spread from the North Sea to the Svalbard shelf and Barents Sea since 2003 (Harris et al., 2007).

Projected effects of climate change on the environment and ecosystem of the Barents Sea. The Barents Sea is not only an important high latitude nursery and feeding area for commercial fish stocks such as cod, capelin and herring; its ecosystem is divided by the presence of the Ocean Polar Front (OPF) into cold-Arctic and warm-Atlantic ecotypes making it potentially liable to a large space-time variability. Its 'environment: ecosystem' relations provide a valuable test of skill and a source of management advice in simulating the effects of climate change. Ellingsen et al., (2008) have conducted such a study, providing a modern account of the expected changes. Combining a hydrodynamic model (SINMOD) with an ecosystem model (Wassman et al., 2006), they compare a baseline scenario (1990-2004) based on realistic forcing and observational data with a 65-year climate change run (1995-2059) using atmospheric input from a hydrostatic regional climate model REMO that has been run for the ECHAM4/OPYC3 IPCC-SRES B2 scenario by the Max-Planck-Institut for Meteorology, Hamburg. Their main conclusions are first, that there will be no change in the decade-mean inflow to the Barents Sea over the next 50 years. Nevertheless, the temperature of the inflow will become substantially higher (increase of 1°C during the simulation period) so that the temperature of the Barents Sea will increase, the fraction of water in the Barents Sea warmer than 1°C will increase by 25% and the fraction occupied by the Arctic watermass will decrease. Second, the position of the Ocean Polar Front will move toward the north and east. Third, primary production in the Barents Sea will increase during the next 50 years, primarily in the eastern and northeastern Barents Sea (Fig. 2.2-10). Fourth and final, the zooplankton biomass of Atlantic species will increase by 20% in the eastern Barents Sea, but this will not be enough to offset the 50% decrease in the abundance of Arctic zooplankton species that will accompany the

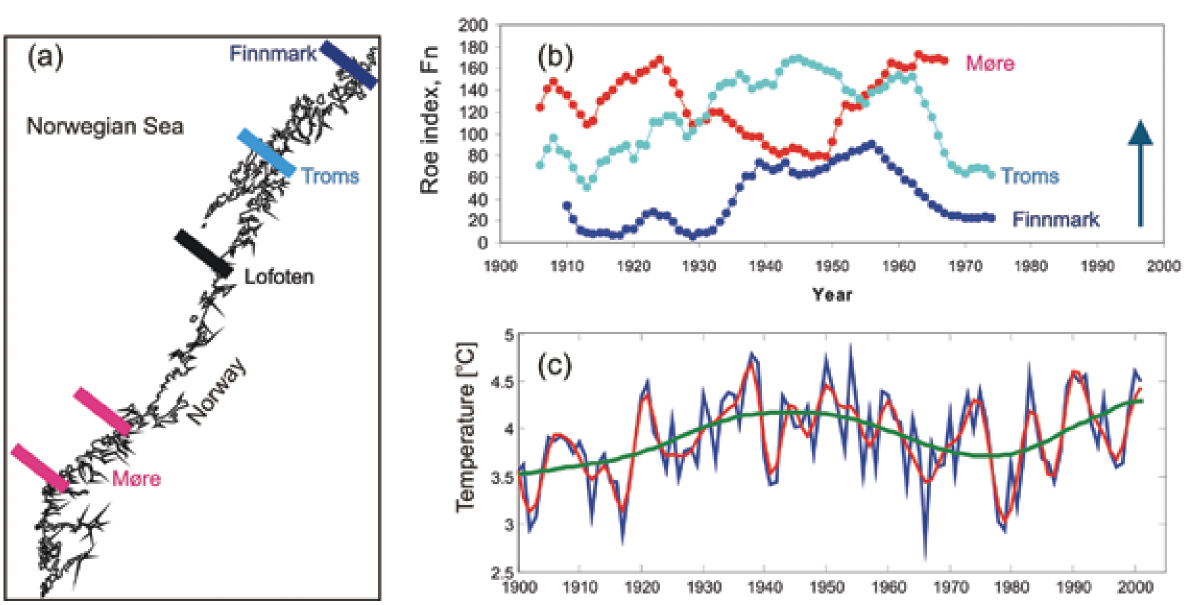

Fig. 2.2-9. Relative north-south shifts in the spawning location of the Arcto-Norwegian cod stock over past century in response to long-term changes in ocean temperature. Based on a roe index defined by Sundby and Nakken (2005), panels (a) and (b) show the relative shift in spawning activity from More in the south (red bars) to the Troms and Finmark spawning areas in the north (blue bars) during the warmer middle decades of the past century. The arrow to the right of panel (b) indicates the recovery of East Finmark spawning areas during the most recent wave of warming in 2004 and 2005 after 40 years of absence, while panel (c) shows the long-term changes in Barents Sea temperature along the Kola Section at 33°30'E.

decrease in the Arctic watermass (Fig. 2.2-10).

Even though the biophysical model predicted rather modest changes in the climate and plankton production of the Barents Sea (Ellingsen et al., 2008), these changes were nevertheless sufficient to produce responses in capelin abundance, spawning area and adult distribution.

New insights into temperature effects on the distribution of capelin of the Barents Sea. The capelin stock of the Barents Sea has long been recognized as a principal food fish for cod and, therefore, as a key component of the ecosystem on the Norwegian arctic shelf. The importance of temperature as a control on distribution of capelin has also long been recognized, in general terms, but the specifics of that relationship have now been examined in a study by Randi Ingvaldsen, IMR Bergen. She finds that when the temperature increases, the capelin spread northwards and the distribution-area increases. When the capelin stock is large, the feeding area is normally extended eastwards. Consequently, the largest distribution areas occur when the temperature is high and the stock is large at the same time.

Complementing this study, Huse and Ellingsen (2008) have modelled the likely consequences of global warming on capelin distribution and population dynamics. With input on physics and plankton from a biophysical ocean model, the entire life cycle of capelin including spawning of eggs, larval drift and adult movement is simulated. The model generates output on capelin migration/distribution and population dynamics; simulations are performed using both a present day climate and a future climate scenario. For the present climate, the spatial distributions resemble the typical spatial dynamics of capelin, with the Murman and North Norway coasts as the main spawning areas. Nevertheless, for the climate change simulation, the capelin is predicted to shift spawning eastwards and also utilize new spawning areas along Novaya Zemlya. There is also a shift in the adult distribution towards the north eastern part of the Barents Sea and earlier spawning associated with the warming. As the authors point out, it remains an open question whether capelin will take up spawning at Novaya Zemlya as predicted by the model, but there is some evidence that such easterly spawning has taken place in the past (see Gjøsæter, 1998).

The IPY in the NW Barents Sea. The Svalbard archipelago in the NW Barents Sea is the eastern gateway for Atlantic Water flowing into the Arctic. Consequently the oceanography of the region is characterized by the distinct water masses of Atlantic or Polar origin, contrasting strongly in their temperature and salinity. The sea ice conditions around the archipelago reflect these contrasts, with northern and eastern coasts having seasonal ice cover while the west coast is relatively ice-free. Such a range of conditions permits comparative studies of ecosystem function to be conducted and has enabled the investigation of the likely impact of warm, ice-free conditions on arctic ecosystems (Willis et al., 2006) and of how ecosystems might respond to changes in the seasonal timing of retreat of the ice-edge.

Two sites in the archipelago have proved ideal for such studies. Rijpfjorden, a fjord in Nordaustlandet that faces north to the Arctic Ocean, represents the Polar extreme while Kongsfjorden in NW Spitsbergen is a site that is dominated by warm Atlantic Water with water temperatures in excess of 6°C (Cottier et al., 2007). The ice-covered nature of Rijpfjorden and the relatively ice-free conditions in Kongsfjorden provide a natural setting to investigate the role ice plays in structuring arctic ecosystems. A key observational capability is the placement of moored instruments in each fjord, to provide background environmental data or as a means of studying the shelf processes. These moorings have been maintained by the Scottish Association for Marine Science (www.arcticmarine.org.uk) since 2002, with the logistical assistance of Norwegian institutes, particularly University Centre in Svalbard (www.unis.no).

The issue of ecosystem response to changes in sea ice conditions have been captured in a Norwegian IPY project called CLEOPATRA (Climate effects on planktonic food quality and trophic transfer in Arctic Marginal Ice Zones). CLEOPATRA was conducted in Rijpfjorden which can be considered as a mesocosm site representative of Arctic processes. The main objectives of the IPY CLEOPATRA project were to study:

(1) the timing, quantity and quality of ice algal and phytoplankton spring bloom;
(2) how variations in light and UV radiation affect algal food quality; and
(3) the importance of timing and available food

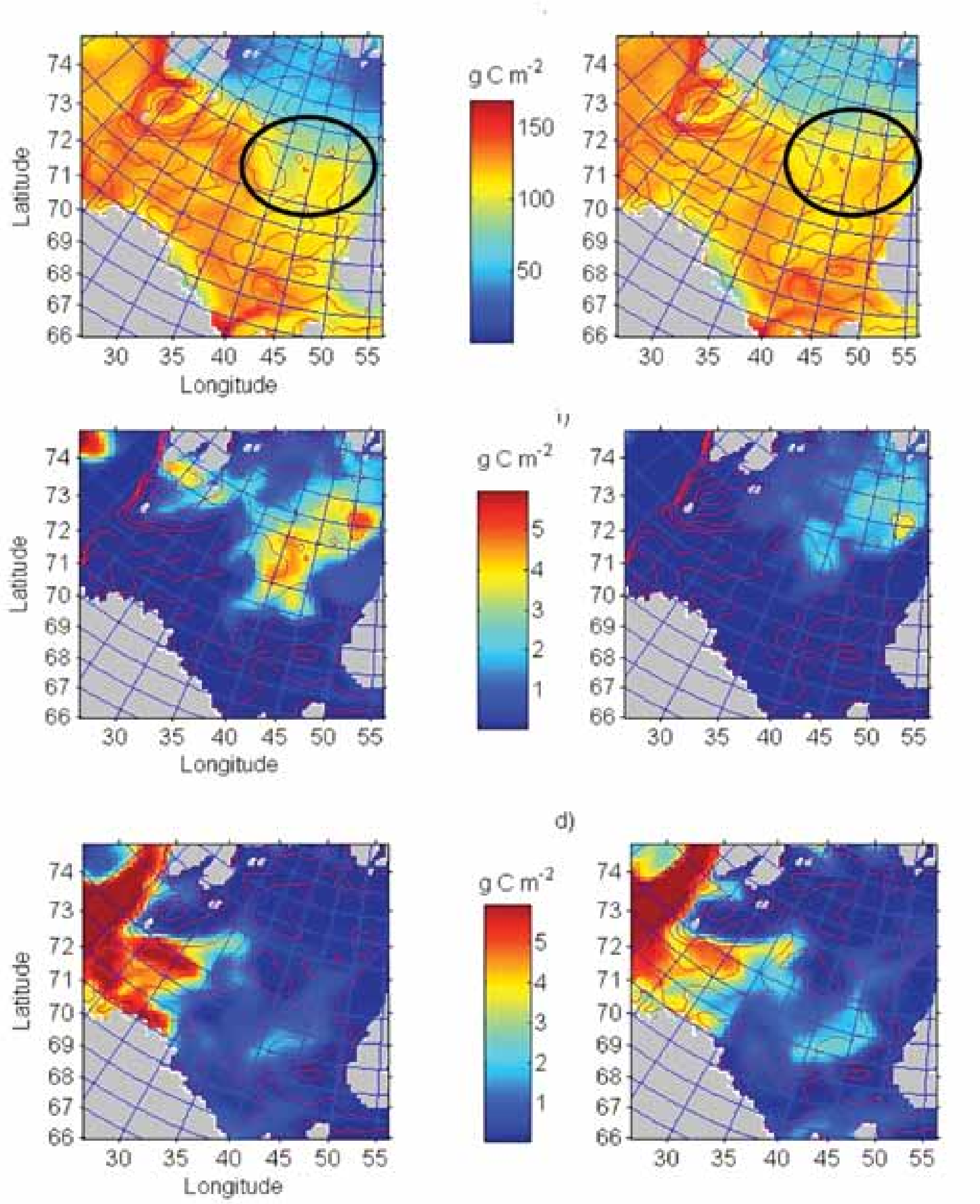

Fig. 2.2-10. Simulated changes in the primary and secondary production of the Barents Sea, between 1995-2004 (left hand panels) and 2045-2054 (right hand panels). Comparison of production between these dates suggests that annual primary production (top pair of panels) will increase by 10-15%, mainly due to a higher production in Arctic waters caused by a reduction in sea ice (more light). The lower panels suggest that the mean distribution of Arctic zooplankton (middle row) can be expected to decrease and of Atlantic zooplankton (bottom pair of panels) to increase in August between these dates as the Barents Sea warms and the OPF shifts towards the north and east.

(Ellingsen et al., 2008)

for reproduction, and growth of the dominant herbivorous zooplankton species in Arctic shelf seas: *Calanus glacialis.*

The CLEOPATRA hypotheses are centred on the Marginal Ice Zone (MIZ) as the key productive area of Arctic shelf seas. The ongoing warming of arctic regions will lead to a northward retreat of the MIZ and to an earlier opening of huge areas in spring. This may result in a temporal mismatch between the phytoplankton spring bloom and zooplankton reproduction (Melle and Skjoldal, 1998). Less ice will also reduce the ice algae production that may be an important food source for spawning zooplankton prior to the phytoplankton spring bloom. Quantity and quality of primary production in seasonally ice-covered seas is primarily regulated by light and nutrients. Excess light, however, is potentially detrimental for algae and can reduce algal food quality. A decrease in the relative amount of essential polyunsaturated fatty acids (PUFAs) in algae, due to excess light, may affect the reproductive success and growth of zooplankton (Leu et al., 2006) and thereby the transport of energy to higher trophic levels, such as fish, birds and mammals.

One of the key results of CLEOPATRA has been to demonstrate the critical importance of ice algae for high latitude ice covered ecosystems. In Rijpfjorden in 2007, ice algae was the only available food for grazers during the months from April to June. Ice broke up and left the fjord mid-July while a phytoplankton bloom developed in late-June to early-July. This phytoplankton bloom peaked two months after the ice algae bloom. The food quality of the ice algae and phytoplankton blooms was the same, but highest food quality, i.e. highest amount of polyunsaturated fatty acids (PUFAs), was early in the growth phase of each bloom. *Calanus glacialis* is the key grazer in ice covered shelf ecosystems and is a very important, energy rich food item for larger zooplankton, fish and sea birds. Observations from Rijpfjorden have shown that *C. glacialis* can time its reproduction to match both the ice algae and phytoplankton blooms. Ice algae fuelled high egg production in *C. glacialis,* allowing early reproduction so the offspring can then fully exploit the later-occurring phytoplankton bloom. By utilizing both ice algae and phytoplankton, *C. glacialis* extends its growth season substantially, which can explain the success of this species (up to 80% of the mesozooplankton biomass) in arctic shelf seas. Future climatic scenarios with less or no sea ice may have negative impacts on the population growth of *C. glacialis,* which may have severe impacts on higher trophic levels in arctic shelf seas.

A second main result of the project concerned the study of the impact of sea ice cover on zooplankton behaviour. One of the great unknowns of arctic ecosystems is the status of winter communities and the processes that are active. The classic paradigm of marine ecosystems holds that most biological processes will slow or cease during the polar night and one key process that is generally assumed to cease during winter is Diel Vertical Migration (DVM) of zooplankton, the biggest synchronized shift of biomass on the Planet. Using acoustic data collected from the moorings in Kongsfjorden and Rijpfjorden, it can be demonstrated that synchronized DVM of zooplankton continues throughout the Arctic winter, in both open water and under sea ice (Fig. 2.2-11; Berge et al., 2008). It is possible that the sensitivity of these organisms to light is so acute that even during the high arctic polar night, DVM is regulated by diel variations in illumination at intensities far below the threshold for human perception. The full winter data set shows that DVM is stronger in open waters compared to ice-covered waters, implying that the active vertical flux of carbon will become more effective if there is a continued retreat of the arctic winter sea-ice cover.

Pacific Sector

Northward shift in the ecosystem of the Bering Sea. Drawing together a large body of evidence, Grebmeier et al., (2006) have described a major ecosystem shift in the Northern Bering Sea since the late 1970s. A system characterized by extensive seasonal sea-ice cover, high water column and sediment carbon production, and a tight pelagic-benthic coupling of organic production gave way to a reduction in sea ice, an increase in air and ocean temperatures, an increase in pelagic fish and a geographic displacement of marine mammal populations coincident with a reduction of their benthic prey populations. A telling point of detail has been the reduction in sediment oxygen uptake south of St Lawrence Island between 1988 and 2004, from ~40 to about 12 mmol O_2 m^{-2} day^{-1} (Grebmeier

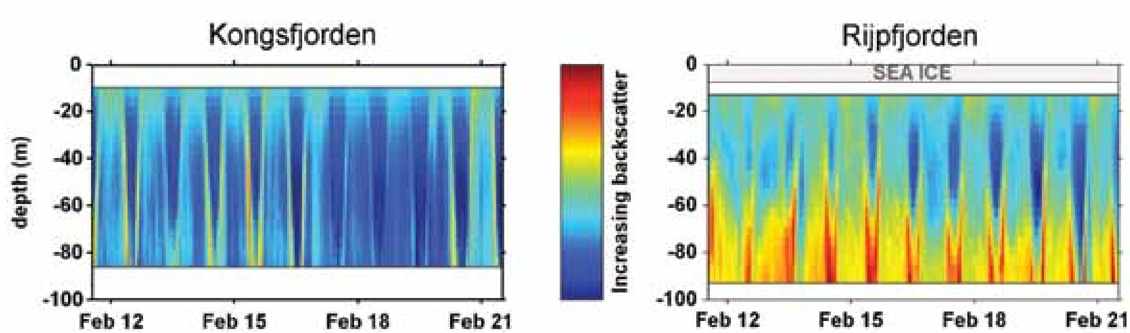

Fig. 2.2-11. The acoustic data from ADCPs (acoustic Doppler current profilers) provides a means of monitoring the backscatter levels (linked to biomass) through the water column. The banded pattern of backscatter is characteristic of DVM with biomass remaining deep at noon and ascending into the surface at night (Cottier et al., 2006).

et al., 2006), since this exemplifies the reduced carbon supply to the benthos.

The proximate cause of the change is a northwards retraction of the subsurface cold pool, formed as a result of ice formation in winter but persisting beneath warmer surface waters in summer, that normally extends near-freezing temperatures across the Bering Sea floor. As warming caused the cold pool to retract, the subarctic-Arctic boundary defined by its southern margin also retracted northwards, allowing a northward shift of the pelagic-dominated marine ecosystem that had previously been confined to the warmer waters of the southeastern Bering Sea.

In Fig. 2.2-12, which is unpublished, but based on the data in Mueter and Litzow (2008), Franz Mueter (UAF) quantifies this ecosystem shift by showing the rate of northward movement (km/25y) in the center of distribution of 45 species over 25 years (1982-2006). As Mueter points out, these rates are a community-level phenomenon and are similar to those recently reported for the North Sea (Perry et al., 2005) though we note that in the latter case, there was a parallel tendency for species to deepen as part of their response to warming (Dulvy et al., 2008). In agreement with other studies including Grebmeier et al., (2006), Mueter and Litzow conclude that the proximate cause of these distributional changes is changing bottom temperature and provide a figure of ~230 km for the northward retreat of the southern edge of the summer cold pool in the Bering Sea since the early 1980s (Fig. 2.2-12): *'other climate variables explained little of the residual variance not explained by bottom temperature, which supports the view that bottom temperature is the dominant climate parameter for determining demersal community composition in marginal ice seas'.*

Establishing a mechanism for the Influence of climatic regime-shifts on the ecosystem of the Bering Sea: new evidence for the Oscillating Control Hypothesis. Though it predates these studies, the Oscillating Control Hypothesis (OCH) of Hunt et al., (2002) is an attempt to rationalize these changes in terms of ecosystem function. Basically, the hypothesis predicts that pelagic ecosystem function in the southeastern Bering Sea will alternate between bottom-up control in cold regimes and top-down control in warm regimes. The timing of spring primary production is determined mainly by the timing of ice retreat. *Late* ice retreat (late March or later) leads to an *early*, ice-associated bloom in *cold* water, whereas *early* ice retreat before mid-March, leads to a *late* open-water bloom in May or June in *warm* water. Zooplankton populations are not closely coupled to the spring bloom, but are sensitive to water temperature.

In years when the (early) spring bloom occurs in cold water, low temperatures limit the production of zooplankton, the survival of larval/juvenile fish and thus (eventually) the recruitment of large piscivorous fish, such as walleye pollock. Continued for decades, this will lead to bottom-up limitation and a decreased biomass of piscivorous fish. Alternatively, in periods when the (late) bloom occurs in warm water, zooplankton populations should grow rapidly,

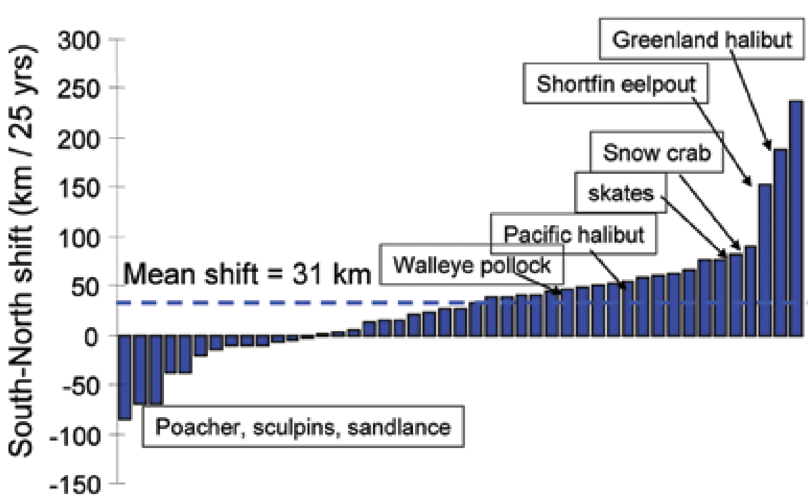

Fig. 2.2-12. The rate of the northward shift in the center of distribution of 45 species in the Bering Sea, 1982-2006. Unpublished, courtesy of Franz Mueter, UAF, pers comm.

providing plentiful prey for larval and juvenile fish and the abundant zooplankton will support strong recruitment of the predatory fish that control forage fish. Piscivorous marine birds and pinnipeds may achieve higher production of young and survive longer in cold regimes, when there is less competition from large piscivorous fish for coldwater forage fish, such as capelin *(Mallotus villosus)*. Piscivorous seabirds and pinnipeds may also be expected to have high productivity in periods of transition from cold regimes to warm regimes, when the young of large predatory species of fish are numerous enough to provide forage. The OCH predicts that the ability of large predatory fish populations to sustain fishing pressure will vary between warm and cold regimes. The OCH also underscores the relationship between the timing of ice retreat and water temperatures during the spring bloom and the 'direction' of coupling between zooplankton and forage fish. In essence, the early bloom in cold water tends to go to the seabed providing better survival of demersal species; the later bloom in warm conditions tends to favour pelagics (for details see Hunt et al., 2002). It is Hunt's point that an ecosystem approach to management of the Bering Sea and its fisheries is necessary if all of the ecosystem components valued by society are to thrive; since climatic regimes may fundamentally alter relationships within the ecosystem, there is a demonstrable need to develop an understanding of the causal relationships between climate, primary and secondary production, and the population dynamics of upper trophic-level organisms. The Oscillating Control Hypothesis is Hunt's attempt to supply it.

So, is it valid? Once again we are indebted to unpublished work by Franz Mueter. Based on the data series described in Mueter et al., (2007) the inverse correlation between the survival anomalies of yellowfin sole and walleye pollock does appear to offer support to Hunt's Oscillating Control Hypothesis, though as Mueter et al., point out, many details of this relationship remain to be explained and tested, including the time-varying roles of cannibalism, larval transport, ice cover and wind mixing.

The IPY in the Bering Sea: results from BEST, BSIERP, C3O, CHINARE and other IPY-relevant research in the northern Bering Sea. The longest biological time series data in the northern Bering Sea (NBS) are from sites south of St. Lawrence Island where significant changes have occurred in the benthic biomass and community structure over the last few decades. Bivalves dominate the benthic biomass in the region and are the key prey base for benthic-feeding spectacled eiders and walrus. Both the recent decline of overall infaunal biomass and the change in species dominance in this region are impacting the coincident decline in spectacled eider populations (Lovvorn et al., 2003; Grebmeier et al., 2006). The time-series studies indicate that chlorophyll biomass differs significantly during a similar timing of ice-melt, but under different oceanographic conditions. Repeat sampling shows that even within-season variation is large and blooms are highly localized both in the water column and underlying sediments, the latter a further indicator of food availability to benthic populations. Sediment oxygen uptake measurements, an indicator of carbon supply to the benthos, show a similar finding that fresh organic matter settles to the benthos quickly. Water mass and nutrient variation, wind mixing and late winter brine formation are potentially important variables that will also impact spring productivity in addition to the timing of ice retreat. The BEST/BSIERP study initiated during IPY (2008) includes late winter field sampling, along with retrospective studies, to evaluate benthic infaunal populations, sediments and oceanographic conditions in the context of walrus feeding sites, both historical and tagged. The study is evaluating a grid of benthic infaunal collections in the walrus feeding area at various spatial scales (<5-20 nautical miles) to evaluate variable prey patches and food quality as well as undertaking a videographic evaluation of epifauna. Within the collaborative program, both helicopter survey and on-ice tagging of walruses are employed to track the their location and feed areas to evaluate predator-prey patch dynamics.

As part of the C30 program in 2007 and 2008, stations were occupied in July in the NBS. Both the winter-produced cold pool and now subsurface chlorophyll maximum from the spring bloom are evident looking at the 1000 km point on the Dutch Harbor to Barrow, Alaska transect (Fig. 2.2-13). Repeat of our time series measurements of hydrography, water and sediment chlorophyll, carbon tracers and infaunal populations also occurred. Repeat measurements at our time-series stations for the BEST/BSIERP patch dynamics cruise allow us to evaluate seasonal aspects of this ecosystem. Benthic sampling in the NBS area on the CHINARE program also occurred during summer 2008 and the data from this collaborative IPY program will also add to the time-series study in this region.

Monitoring Change in the Chukchi Sea: RUSALCA. Unprecedented minima of the sea ice area have occurred in the Arctic Ocean during the International Polar Year. In surrounding seas there has been a northward shift of ice-dependent marine animals. NOAA proposed the Russian American long-term Census of the Arctic (RUSALCA) with its partners to carry out observations in this area to measure fluxes of water, heat, salt and nutrients through the Bering Strait, gather observations about physical change in the state of the ocean in the Bering and Chukchi Seas, and study impacts of physical change on marine ecosystems as a consequence of the loss of sea ice cover. In 2007, the first U.S. to Russia chain of moorings was completed with the partnership of the National Science Foundation. Greater coverage of this region took place with the RUSALCA missions in 2008 and 2009, including a team of participants from the Korean Polar Research Institute.

RUSALCA is organized so that the Pacific-Arctic Ocean ecosystem can be monitored for change every four years. Planned for summer 2008 but delayed until 2009, the RUSALCA mission hosted 50 scientists who worked as teams representing the following disciplines: ocean acidification, benthic processes, zooplankton biomass and processes, epibenthos, fish assessments, hydrography, nutrients and productivity, geology and geophysics, methane microbiology, and marine mammal observations. Due to the extreme reduction in sea-ice cover, the vessel was able to carry out observations on the Chukchi Plateau at a latitude of 77°N (more than 400 km north of the 2004 expedition).

Highlights of the 2009 expedition include the following: the Eastern Strait of the Bering Strait was fresher and cooler than in 2008; 134 CTD and Rosette stations were taken; and a high-speed hydrographic survey of the Herald Canyon (a notable canyon that transports Pacific water north into the Arctic Ocean) was undertaken. The results showed that the hydrographic conditions were greatly different from those observed during 2004. Water masses on the western side of Herald Canyon were warmer in 2009 and on the eastern side the summer water reached much further north than in 2004. In addition the Siberian Coastal current was discovered to extend more than 70 km offshore. It was not present during the 2004 expedition into this region.

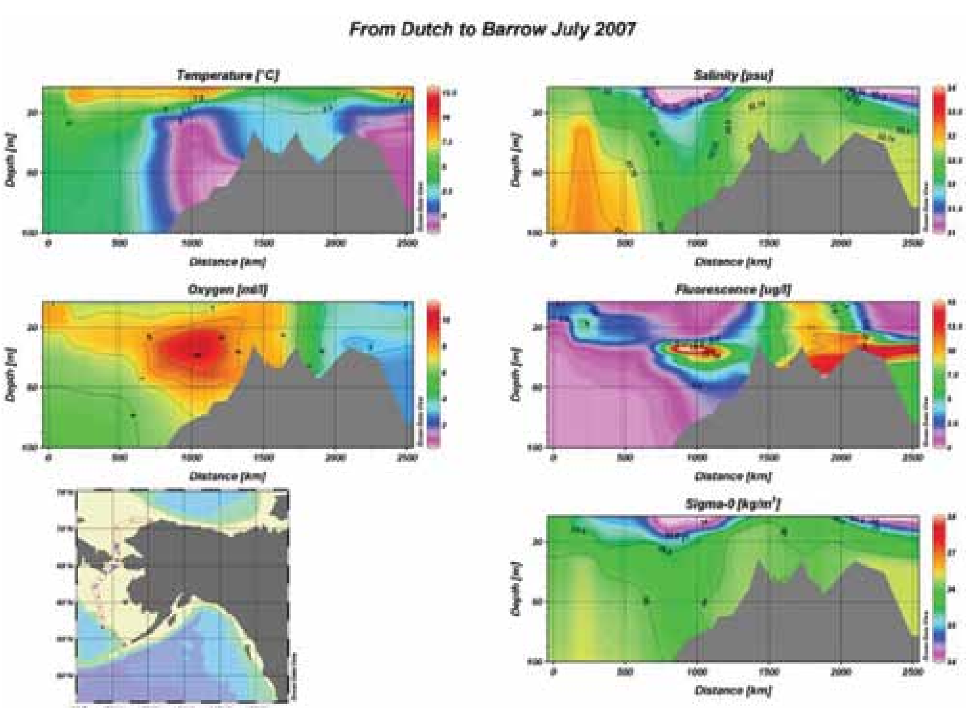

Fig. 2.2-13. Hydrographic data collected during the C3O program in transit from Dutch Harbor to Barrow, Alaska in July 2007.
(Image: Bon van Hardenberg)

Sampling of the field of pockmarks on the Chukchi Plateau by a team of geologists did not reveal any evidence of present-day flux of methane from the seafloor.

Ecosystem observations revealed that the pockmark area at around 600 m depth was the site of the lowest observed benthic biomass. (The highest was located at the head of Herald Canyon.) ROV operations show clearly that the benthic biomass is underestimated when determined by standard sampling techniques.

Fish were sampled from the water column and near the seafloor at 25 stations ranging from west of Wrangle Island (in the East Siberian Sea) and north to 77°30'N. This northerly sampling was the furthest north fish trawl ever deployed in the Pacific Sector of the Arctic. Several fish were sampled at a depth of about 550 m that had previously only been located in the Atlantic side of the Arctic. The question remains of how and when did these fish get to the Pacific Side of the Arctic.

Plankton sampling in the region clearly showed a reduction in the numbers of meroplankton and larvaciae in the waters of the Chukchi Sea than sampled in 2004. Strong across-Chukchi Shelf difference in the populations of plankton occurred in the northern domain and strong E-W gradients were detected in the southern part of the Chukchi Sea.

The RUSALCA mission in 2009 provided a rare opportunity for marine mammal scientists to search for marine mammals in the East Siberian Sea and further north. Seven species of marine mammals were observed. More than 100 gray whales were spotted over the benthic "hot spot" at 67.5°N and 169.5°W. Gray whales were also spotted north of Wrangel Island and these may be a northern range record. Walrus were observed to be concentrating (hauled out) on narrow slivers of ice in a nearly ice free sea.

Analyses of these observations will take place during 2010 and 2011 with the next biodiversity and change mission occurring in 2012.

The Arctic Ocean

Changes in the extent and concentration of sea-ice can be expected to exert dominant control on the ecosystem of the Arctic Ocean shelves and basins, operating on a range of space and time scales from the localized scale of small polynyas and the 'ice: nutrient' relations of the circumarctic shelf-break in summer to the complex impacts of a shrinking ice-cover on marine production.

The influence of tidal mixing on the distribution of small polynyas. Polynyas are an important component of both the physical and biological system in ice covered seas (Hannah et al., 2009; Smith and Barber, 2007) and are widely distributed across the Canadian Arctic Archipelago (Fig. 2.2-14). From the physical point of view, polynyas are areas of enhanced air-sea fluxes in winter relative to the neighbouring ice-covered regions; from the biological perspective, polynyas that reliably occur each year are thought to be of particular ecological significance, especially for marine mammals and seabirds (e.g. Stirling 1980).

Hannah et al., 2009 use a tidal model of the Canadian Arctic Archipelago to explore the idea that tidal currents make an important contribution to the formation and maintenance of many of these recurring polynyas. By mapping three parameters in particular – the strength of tidal currents, tidal mixing (h/U^3) and the vertical excursion associated with the tidal currents driving water up and down slope – they are able to show that the hot spots in these quantities do indeed correspond to the location of many of the small polynyas in the Archipelago. A known polynya was identified with every region that had $\lambda<3$ and vertical excursion > 10 m ($\lambda = \log10\ h/U^3$), including the polynyas at Hell Gate, Cardigan Strait and Dundas Island, and a tidal contribution was also indicated in the case of the polynyas at Fury and Hecla Strait, Lambert Channel, Committee Bay and the Karluk Brooman polynyas. Though the link between h/U3 and summer plankton productivity has not yet been demonstrated in the Archipelago, it is likely that the hot spots of h/U3 that correspond to polynyas have the potential to be biologically important year round.

What changes are anticipated as the Arctic ice-cover retracts from the circumarctic shelves? As Carmack and Chapman (2003) point out, the efficiency of shelf-basin exchange (SBE) in summer is strongly moderated by the location of the ice-edge in relation to local topography. Their model suggests that upwelling-favourable winds generate very little SBE so long as the ice-edge remains shoreward of the shelf-break but an abrupt onset of shelf-break upwelling takes place when the ice-edge retreats beyond that point. Thus if the shelf break is covered by ice, only shelf water circulates. Nevertheless, as the summer ice-cover continues to retract, it will expose more and more of the shelf-break for longer periods of time to upwelling-favourable winds. The depth to which upwelling extends will increase as the slope waters become ice-free and salty nutrient-rich water will be permitted to cross the whole shelf in a thin bottom boundary layer. To Carmack, Williams, McLaughlin and Chapman (pers. comm.) Fig. 2.2-15 illustrates the extraordinary sensitivity of shelf conditions to ice edge location; in effect the position of the summertime ice edge acts as a 'switch' for exchange between the shelf and the deep basin of the Arctic Ocean. If valid, the implication of this modelling exercise by Carmack et al., is that systems important to production on the circumarctic shelves are liable to change. At present, strong stratification due to ice melt and rivers acts to limit nutrient availability in the euphotic zone on the shelf and a chlorophyll maximum typically forms at the top of the halocline, characteristic of nutrient limitation. Increased upwelling at the shelf-break as the ice retracts will increase the nutrient flux to the shelf, where it is likely to relieve nutrient limitation and support enhanced primary production. Their second conclusion is also of interest; that some shelves, particularly the Beaufort and Chukchi shelves, will experience greater upwelling than others and that the increase in the on-shelf nitrate flux (i.e. the modelled onshore Ekman Transport multiplied by the maximum nitrate in the water column) will reflect this. They suggest a need to survey the present day conditions of the pan-Arctic shelf break and to plan their long-term monitoring.

Impact of a shrinking ice cover on the primary production of the Arctic Ocean: new estimates. By

Fig. 2.2-14. A map of known polynyas in the Canadian Arctic Archipelago.

(Adapted from a range of sources by Hannah et al., 2009) exposing an ever increasing fraction of the sea surface to solar radiation and increasing the habitat suitable for phytoplankton growth, we can well appreciate that the unprecedented loss of arctic sea-ice in recent years must have had some significant effect on marine primary production across the Arctic basins and shelves. Hitherto, however, we have had no clear idea of where and how much. In two recent papers (Pabi et al., 2008; Arrigo et al., 2008), a Stanford Group have now quantified that impact. By coupling satellite-derived sea ice, SST and chlorophyll to a primary production algorithm parameterized for Arctic waters, they find 1) that annual pan-Arctic primary production (419 ± 33 Tg C a-1 on average during 1998–2006) was roughly equally distributed between pelagic waters (less productive, but greater area) and waters located over the continental shelf (more productive, but smaller area); 2) that annual primary production in the Arctic has increased yearly by an average of 27.5 Tg C yr^{-1} since 2003 and by 35 Tg C yr^{-1} between 2006 and 2007; and 3) that 30% of this increase is attributable to decreased minimum summer ice extent and 70% to a longer phytoplankton growing season. Arrigo et al., (*op cit*) suggest that if these trends continue, the additional loss of ice during Arctic spring 'could boost productivity >3-fold above 1998–2002 levels, potentially altering marine ecosystem structure and the degree of pelagic-benthic coupling. Changes in carbon export could in turn modify benthic denitrification on the vast continental shelves'.

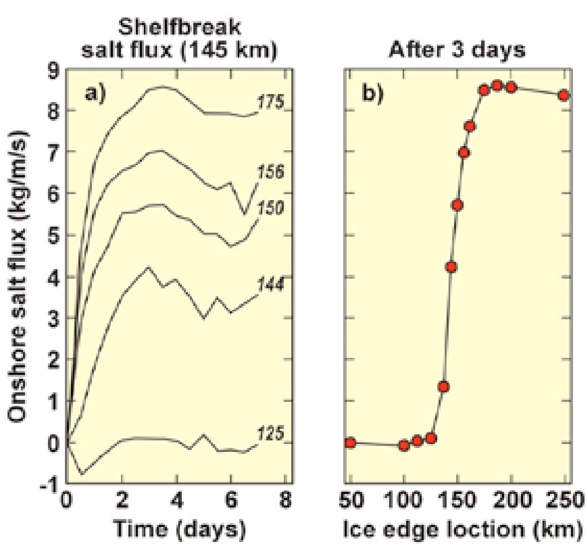

Fig. 2.2-15 The position of the ice edge relative to the circum-Arctic shelf-break acts as a sensitive 'switch' for the onshore flux of salt (Carmack et al., pers. comm.).

IPY on the Canadian Arctic shelf: the Circumpolar Flaw Lead System Study. The Circumpolar Flaw Lead (CFL) system study was a Canadian-led multidisciplinary initiative for IPY with over 350 participants from 12 countries. The CFL is a perennial characteristic of the Arctic, that forms when the central pack ice (which is mobile) moves away from coastal fast ice, opening a flaw lead which occurs throughout the winter season. The flaw lead is circumpolar in nature, with recurrent and interconnected polynyas occurring in the Norwegian, Icelandic, North American and Siberian sectors of the Arctic. Due to a reduced ice cover, these regions are exceedingly sensitive to physical forcings from both the atmosphere and ocean and provide a unique laboratory from which we can gain insights into the changing polar marine ecosystem. This study examines the importance of climate processes in the changing nature of a flaw lead system in the northern Hemisphere and the effect these changes will have on the marine ecosystem, contaminant transport, carbon flux and greenhouse gases. The CFL study was 293 days in duration and involved the overwintering of the *CCGS Amundsen* icebreaker in the Cape Bathurst flaw lead throughout the winter of 2007–2008. This represented the first time an icebreaker had overwintered an entire winter in the Arctic while remaining mobile in a flaw lead.

The CFL field season commenced in fall 2007. Between 18 October and 27 November 2007, 74 unique open-water sites were sampled (Fig. 2.2-16a) and multiple moorings were collected and redeployed throughout the Amundsen Gulf region. On November 28 2007, the ship entered its 'drift mode', during which the ship parked in a piece of ice that was large, thick and homogeneous enough for setting up equipment and collecting samples, until conditions or ice movement necessitated a move to another location. A total of 44 drift stations averaging 3 ± 4 days (max. 22 days) were sampled between 28 November 2007 and 31 May 2008, generally located on the northern side of the Amundsen Gulf to the south of Banks Island (Fig. 2.2-16b). Though the initial project plan had called for the establishment of a semi-permanent ice camp on the ice bridge that typically forms between Banks Island and Cape Perry, this ice bridge never in fact formed. During the melt season of May and June, several fast ice sites were sampled to follow the ice melt from a thick winter ice cover through to complete break-up, concluding with open water stations. The majority of these sites were located on the south side of the Amundsen Gulf at the entrance of two shallow coastal bays (Franklin Bay and Darnley Bay) where a SCUBA diving program aided sample collection (Fig. 2.2-16b). Fast ice was also sampled in the Prince of Wales Straight and near the north end of Banks Island; a total of 17 fast ice stations were sampled averaging 1.3 days (max. 9) in duration. Distributed open-water sampling fully resumed at the end of June 2008. Between this time and 7 August 2008 (the end of the field season), a total of 96 unique sites were sampled (Fig. 2.2-16a), many of which were long-term sampling sites also used by the ArcticNet and CASES projects. In July, a series of moorings were again collected and redeployed. In 2008, transects were sampled across the Amundsen Gulf, along the Amundsen Gulf, up the west side of Banks Island, across McClure Strait, as well as several transects from open water into fast ice or mobile pack ice. A total of 295 people spent time aboard, including 102 research scientists, 113 graduate students and post-docs, 55 technicians and research associates, and 76 for outreach.

The diversity of physical and biological sampling conducted around *CCGS Amundsen* is illustrated in Fig. 2.2-17. This included CTD-rosette, zooplankton nets, meteorological sensors, box coring equipment and a remotely operated vehicle (ROV), as well as various kinds of moorings that were deployed throughout the project. Specialized features were the moonpool within the ship allowing deployment of equipment in winter conditions, the specialized labs including a Portable Lab for Mercury Speciation (PILMS) with a class-100 clean room allowing for trace metal analysis, and a range of sampling vehicles including snowmobiles, ATV, half-track and helicopter. Due to its size and complexity, the delivery of new science from the CFL project can be expected to take up to 3 years. Here, we have space for just two early examples of these novel results, one physical and one biological.

Eddies in the Amundsen Gulf. Mesoscale eddies in the Arctic Ocean transport salt and heat and are considered critical for the ventilation of its cold halocline layer (Muench et al., 2000; see also Timmermans et al., 2008; Spall et al., 2008). They are also a source of nutrients and zooplankton for the Canada Basin (Llinas et al., 2008), and could play the same role for the less productive regions of the Amundsen Gulf. Three eddies have been observed in the Amundsen Gulf, one at the CASES winter station in Franklin Bay in December 2003 and two more – in January 2008 and March 2008 – while the *CCGS Amundsen* was in drift mode in the CFL program. What make these observations important is the suite of concurrent meteorological, biological and chemical observations that the CFL Study provided. The March 2008 eddy, for example, was a subsurface feature with a core centered at 90 m. The ship-mounted ADCP captures the structure of the eddy showing a reversal of the northward flow at its center. The *Amundsen* eddies were generated by shallow brine convection at freezing time. As the surface water of the lead freezes, brine is rejected in the surface layer; this then sinks and settles at mid-depth because of the strong local stratification. The Amundsen data set is thought to be the first complete set of

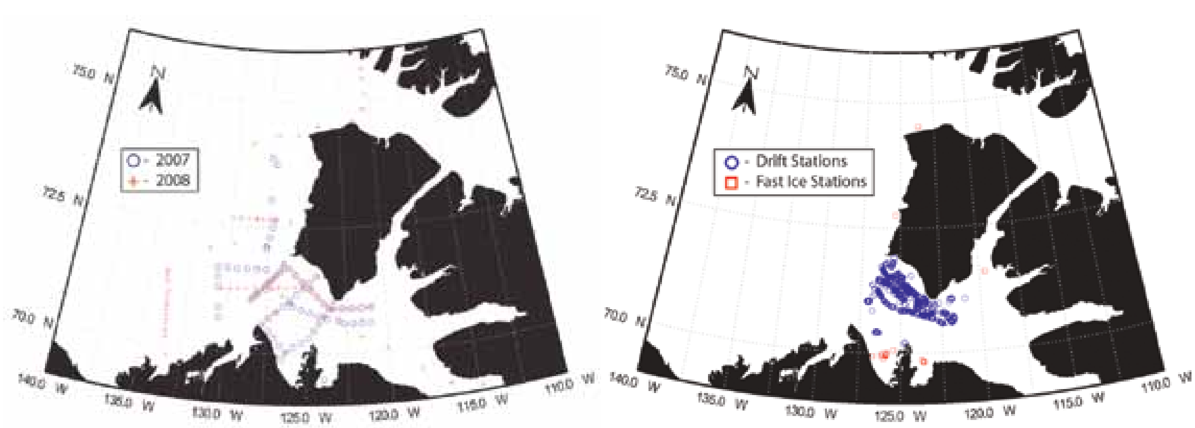

Fig. 2.2-16a. Distributed open-water sites sampled in the fall of 2007 and the summer of 2008. b. Drift stations and fast-ice stations sampled in the winter and spring of 2007–2008.

(Maps: David Barber)

multidisciplinary observations during the formation of a subsurface eddy.

Ice Edge Upwellings. Phytoplankton blooms are common events in polar waters where primary productivity greatly exceeds losses, resulting in a rapid accumulation of algal biomass. Due to their latitude, polar regions experience a strong seasonal pulse of insolation supplying one of the key elements for initiation of a vernal phytoplankton bloom. During winter in polar regions, mixing processes (e.g. wind, cold atmospheric temperatures and brine rejection during sea ice formation) and the lack of sufficient light for primary production permit replenishment of surface water nutrients. Nevertheless, the degree of new nutrient replenishment during winter depends on the balance between mixing forces and surface water stability. Polar Surface Water (PSW), categorized as low salinity (< 31.6 in the Beaufort Sea), low temperature (< -1°C) and nutrient-depletion, blankets most of the western Arctic Ocean, and the stability of the PSW is seasonally maintained by freshwater input from the perennial sea ice cover, by precipitation and by run-off from the numerous large rivers along the Eurasian and North American coasts. Furthermore, PSW has historically been protected from wind mixing forces due to the perennial ice cover. In the coastal Beaufort Sea, PSW is underlain by an intermediate layer (32.4 – 33.1 core salinity; < -1°C; ~250 m maximum depth) of relatively nutrient-rich (maximum values of ~15, 2 and 30 mmol m-3 for nitrate, phosphate and silicate, respectively) Pacific origin waters (IPW) (Carmack et al., 2004). IPW is of great importance to the Beaufort Sea and the Canadian Arctic for its potential to enhance biological production where it mixes into the PSW (Carmack et al., 2004). A recent annual study in the Canadian Beaufort Sea showed that winter mixing processes were too weak to overcome PSW stability (Tremblay et al., 2008) thus hindering the injection of nutrients from the IPW into the surface layer and limiting primary production. Nevertheless, we are now aware that passing eddies can locally enhance production by mixing IPW into surface waters; as with coastal upwelling, surface water divergence and upwelling of nutrients can be produced by winds blowing parallel to a relatively straight ice edge. The CFL program will examine the coupled physical-biological linkages associated with upwelling at ice edges and contrast this to the productivity of the marginal ice zone and open water of the polynya.

Concluding Remarks

This brief account has attempted to describe some of the main advances that were made in the difficult business of observing the Arctic and subarctic seas during the special focus period of IPY. It has also attempted to describe some of the main results and new ideas that are still emerging from these observations. A

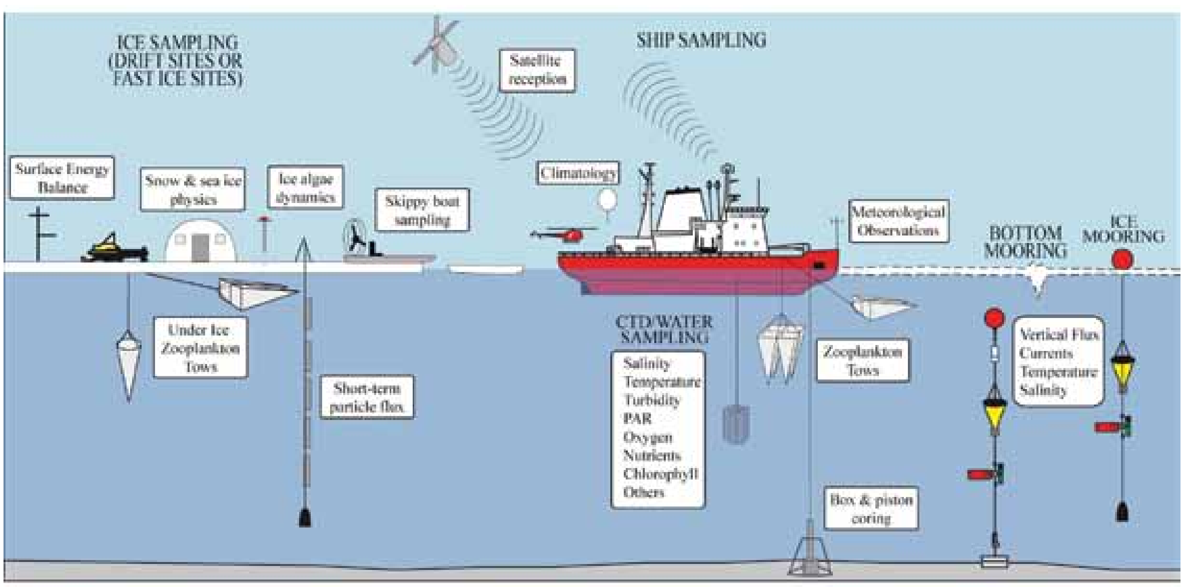

Fig. 2.2-17. Schematic of the scientific equipment used on the Amundsen and at ice camps nearby.
(Image: David Barber)

final third element, provided in *Chapter 3.3*, attempts to use these results and ideas to make the case for which mix of observations to sustain into the future. The reason for attempting such a forward look is clear: if we are to develop the predictive skills and utility of climate models, we will need to observe, understand and 'build in' a list of processes that are not yet represented realistically (or at all) in climate models. In fact, the list is quite long (Dickson et al., 2008). It is also clear that it will be the 'legacy phase' of IPY, sustained over years to decades, rather than the two-year project itself that will develop our understanding of these processes, their changes, their feedbacks and their likely climatic impacts to the point where they can be of practical use to climate models. We cannot continue everything; even if we could, it would surely be ineffectual simply to continue to observe the Arctic according to what we *thought* we knew before IPY. What have we *learned* in IPY that might help us design its observational 'legacy phase'? At the Arctic Science Summit Week (ASSW) in Bergen in March 2009, the Arctic Ocean Sciences Board (AOSB) set itself the task of developing a proposal for an integrated, sustained and pan-Arctic observing effort focused on the role of northern seas in climate in Oslo in 2010. To achieve maximum focus, this plan is being structured around the following three questions: *1) Following IPY, how would we now define the role of the Northern Seas in Climate? 2) What questions should we be testing to help us understand that role? 3) How should we design an ocean observing system to test these questions?*

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2.3 Southern Ocean

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Introduction

Recent scientific advances have led to growing recognition that Southern Ocean processes influence climate and biogeochemical cycles on global scales. The Southern Ocean connects the ocean basins and links the shallow and deep limbs of the overturning circulation, a global-scale system of ocean currents that influences how much heat and carbon the ocean can store (Rintoul et al., 2001). The upwelling of deep waters returns carbon (e.g. le Queré et al., 2007) and nutrients (e.g. Sarmiento et al., 2004) to the surface ocean; the compensating sinking of surface waters into the ocean interior sequesters carbon and heat and renews oxygen levels. The capacity of the ocean to moderate the pace of climate change is controlled strongly by the circulation of the Southern Ocean. The future of the Antarctic ice sheet, and therefore sea-level rise, is increasingly understood to be determined by the rate at which the relatively warm ocean can melt floating glacial ice around the margin of Antarctica (Rignot and Jacobs, 2002). The expansion and contraction of Antarctic sea ice influences surface albedo, air-sea exchange of heat and of gases, such as carbon dioxide and oxygen, and the habitat for a variety of marine organisms (Thomas and Dieckmann, 2002). The Southern Ocean is also home to unique and productive ecosystems and rich biodiversity.

Given the significance of the Southern Ocean to the Earth system, any change in the region would have impacts that extend well beyond the high southern latitudes. Recent studies suggest change is underway: the Southern Ocean is warming and freshening throughout most of the ocean depth (Gille, 2008; Böning et al., 2008); major currents are shifting to the south, causing regional changes in sea-level (Sokolov and Rintoul, 2009a,b) and the distribution of organisms (Cubillos et al., 2007), and supplying additional heat to melt ice around the rim of Antarctica (Jacobs, 2006); and the future of the Southern Ocean carbon sink is a topic of vigorous debate (le Queré et al., 2007; Böning et al., 2008). Climate feedbacks involving ocean circulation, changes in sea ice (hence albedo) and the carbon cycle have the potential to alter rates of climate change in the future, but the magnitude and likelihood of such feedbacks remains poorly understood.

Progress in understanding Southern Ocean processes has been slowed by the historical lack of observations in this remote part of the globe. Growing recognition of the importance of the Southern Ocean has resulted in an increasing focus on the region; at the same time, new technologies have led to great improvements in our ability to observe the Southern Ocean. International Polar Year 2007–2008 effectively harnessed the human and logistic resources of the international community and exploited technology developments to deliver an unprecedented view of the status of the Southern Ocean, provided a baseline for assessing change and demonstrated the feasibility, value and timeliness of a Southern Ocean Observing System (*Chapter 3.3*). During IPY, a circumpolar, multidisciplinary snapshot of the status of the Southern Ocean was obtained for the first time; many properties, processes or regions had not been measured before. Scientists from more than 25 nations participated in Southern Ocean IPY.

Here, we summarize the rationale, field programs and early scientific highlights from IPY programs in the Southern Ocean to show that the IPY has provided significant advances in our understanding of the Southern Ocean.

Southern Ocean Research During IPY

IPY activities in the Southern Ocean spanned a vast range of phenomena, in many disciplines. Some projects focused on the role of the Southern Ocean in the Earth system, through its influence on global climate and the carbon cycle; some projects focused on understanding the processes that control the biophysical and ecological systems, and their interactions; others were concerned with past or future change in the Southern Ocean system. For the purpose of this overview, it is useful to group IPY activities into four themes along broadly disciplinary lines, although most IPY projects had a strong interdisciplinary flavour:

1. Ocean circulation and climate
2. Biogeochemistry
3. Marine biology, ecology and biodiversity
4. Antarctic sea ice

We discuss the overall objectives, achievements and scientific highlights in each of these themes, with a focus on the larger projects of circumpolar scale. A total of 18 IPY projects with a Southern Ocean focus were endorsed (Table 2.3-1).

Table 2.3-1. IPY projects in the Southern Ocean. The projects are grouped by the primary theme to which they contribute, but many of the projects spanned disciplines and themes.

		Ocean Circulation and Climate
8	SASSI	Synoptic Antarctic Shelf – Slope Interactions
13	Sea level/tides	Sea Level & Tides in Polar Regions
23	BIAC	Bipolar Atlantic Thermohaline Circulation
70	UCAA	Monitoring Upper Ocean Circulation between Africa and Antarctica
132	CASO	Climate of Antarctica and the Southern Ocean
313	PANDA	Prydz Bay, Amery Ice Shelf & Dome A
Biogeochemistry		
35	GEOTRACES	Biogeochemical cycles of Trace Elements and Isotopes in the Arctic and Southern Oceans
Marine biology, ecology and biodiversity		
34	ClicOPEN	Impact of CLImate induced glacial melting on marine and terrestrial COastal communities on a gradient along the Western Antarctic PENinsula
53	CAML	Census of Antarctic Marine Life
71	PAME	Polar Aquatic Microbial Ecology
83	SCAR-MarBIN	The information dimension of Antarctic Marine Biodiversity
92	ICED	Integrated Climate and Ecosystem Dynamics
131	AMES	Antarctic Marine Ecosystem Studies
137	EBA	Evolution & Biodiversity in Antarctica: the Response of Life to Change
153	MEOP	Marine Mammal Exploration of the Oceans Pole to Pole
304	DRAKE BIOSEAS	SEAsonality of the DRAKE Passage pelagic ecosystem: BIOdiversity, food webs, environmental change and human impact. Present and Past
251	Circumpolar Population monitoring	Circumpolar monitoring of the biology of key-species to environmental changes
Sea Ice		
141	Sea Ice	Antarctic Sea Ice

Ocean circulation and climate

A number of major IPY projects aimed to improve understanding of the circulation of the Southern Ocean and its role in the climate system. The overall goal of CASO was to collect a circumpolar, multi-disciplinary snapshot of the Southern Ocean. SASSI had similar aims, with a focus on waters over the continental shelf and slope of Antarctica, including ocean interactions with the Antarctic ice sheet. A number of other individual projects contributed to these two large umbrella programs (e.g. BIAC, MEOP, Sea Level & Tides, UCAA, PANDA and ClicOPEN).

The ocean circulation and climate theme of Southern Ocean IPY was motivated by scientific questions such as: What is the strength of the Southern Ocean overturning circulation and how sensitive is it to changes in forcing? Where do water masses form in the Southern Ocean and at what rate are they subducted into the ocean interior? How and why are water properties and ocean current patterns changing in the Southern Ocean? What is the role of the Southern Ocean in the global transport and storage of heat, freshwater and carbon? How much mixing takes place in the Southern Ocean?

IPY observations

To answer these questions, observations spanning the entire Southern Ocean were required, extending

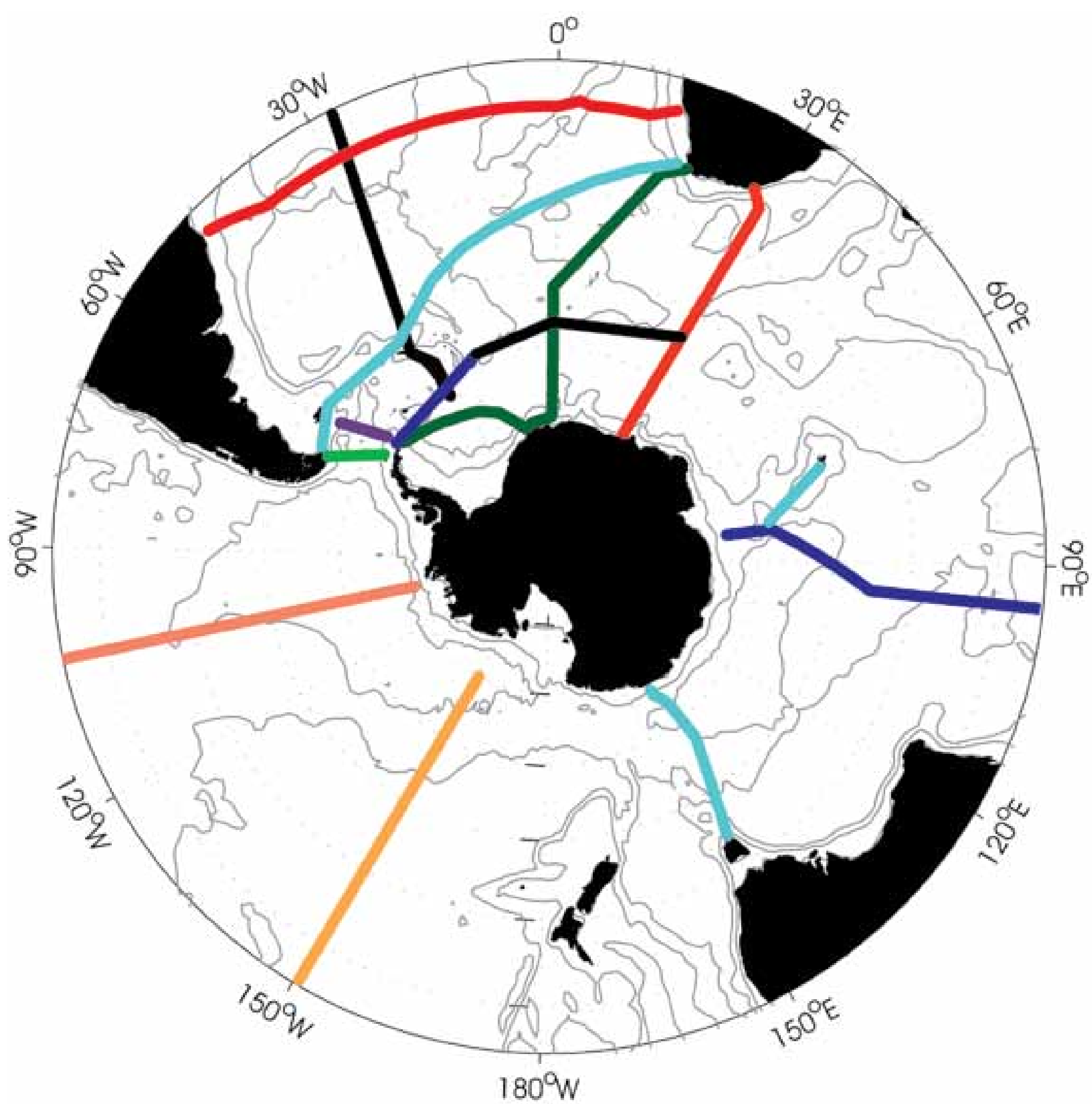


Fig. 2.3-1a. Location of deep hydrographic sections in the Southern Ocean completed between March 2007 and March 2009 as a contribution to IPY. Each of the sections includes full-depth measurements of temperature, salinity and oxygen and most included a broad suite of chemical tracers (e.g. nutrients, carbon, CFCs, trace elements and isotopes). Colors indicate voyages carried out by expeditions of different countries. (Base map: Kate Stansfield)

from the subtropical front to the Antarctic continental shelf and from the sea surface to the deep ocean. IPY used a variety of observational tools to complete the first synoptic, multi-disciplinary, circumpolar survey of the Southern Ocean:

- Hydrographic sections allowed a wide variety of physical, biogeochemical and biological variables to be sampled throughout the water column (Fig. 2.3-1a). Most of these sections repeated lines occupied during previous experiments like the World Ocean Circulation Experiment (WOCE) and the CLimate VARiability and predictability project (CLIVAR) of the World Climate Research Programme, allowing an assessment of rates of change in ocean properties. Additional hydrographic sections were completed over the continental shelf and slope of Antarctica as a contribution to the SASSI program (Fig. 2.3-1b). Underway multi-disciplinary measurements of surface and upper ocean waters, collected as part of the ongoing Voluntary Observing Ship program, extended the spatial and temporal coverage of IPY sampling (Fig. 2.3-1c).
- Argo profiling floats provided broad-scale, quasi-synoptic, year-round sampling of the upper 2 km of the Southern Ocean for the first time (Fig. 2.3-2). The floats drift with ocean currents, ascending typically every 10 days to measure a profile of temperature, salinity and sometimes of additional water mass properties, which is transmitted by satellite. In remote regions like the Southern Ocean, Argo floats

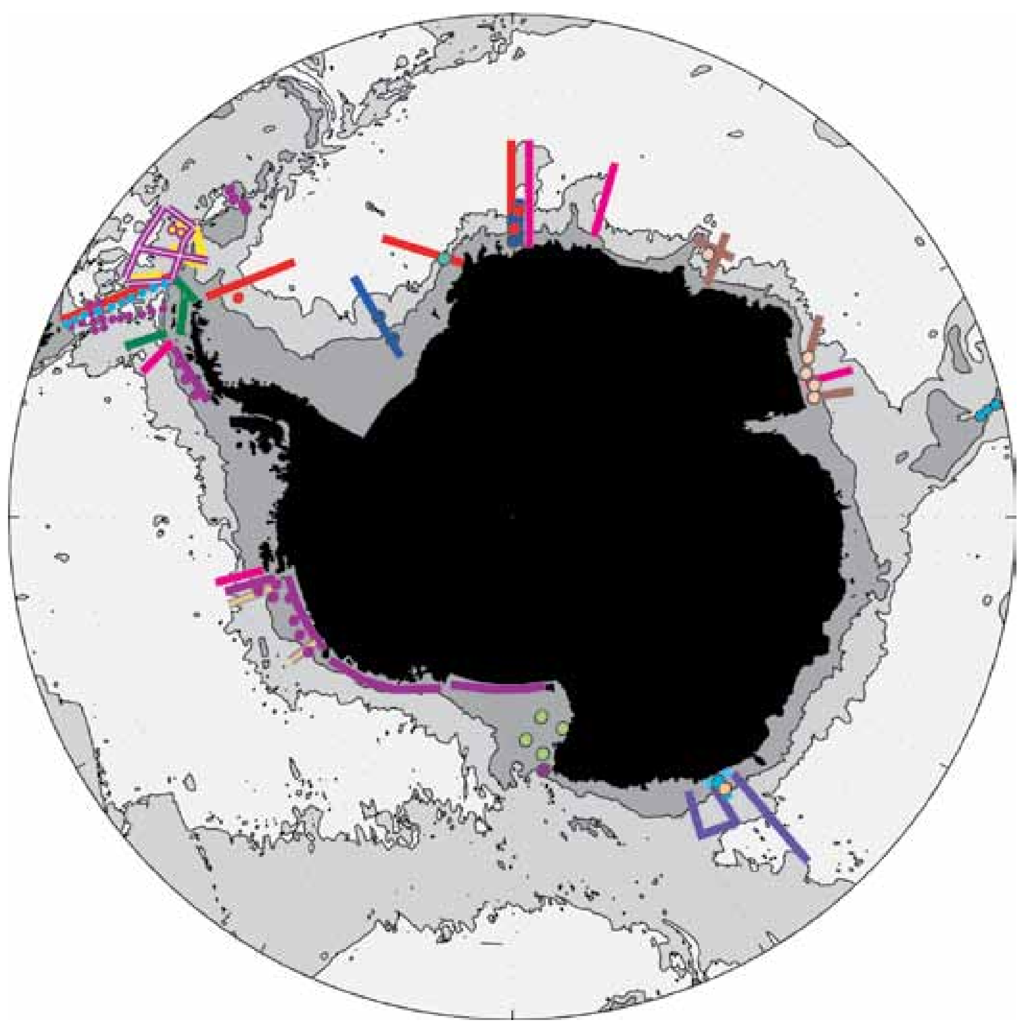


Fig. 2.3-1b. Hydrographic sections (lines) and moorings (circles) around the Antarctic margin completed during the IPY largely under SASSI. Colors indicate voyages carried out by expeditions of different countries. (Base map: Kate Stansfield)

are measuring the ocean interior on basin-wide scales and in all seasons (away from sea ice at least) for the first time. IPY provided an opportunity to enhance the coverage of the global Argo program in the Southern Ocean. Floats designed to stop their ascent to the surface when ice is present and to be tracked by acoustic ranging under the ice (Klatt et al., 2007) allowed data to be obtained in parts of the Weddell Sea that were previously inaccessible.

- Oceanographic sensors on marine mammals provide measurements from regions where traditional oceanographic instruments have difficulty sampling, including in the sea ice zone in winter. The MEOP program expanded the use of oceanographic tags on marine mammals, in particular seals, in the Southern Ocean, providing the first winter measurements from broad regions of the Southern Ocean (Fig. 2.2-3). Many more oceanographic profiles have now been collected south of 60°S using seal tags deployed by MEOP and the earlier SEaOS (Southern Elephant Seals as Oceanographic Samplers) program than in the entire history of ship-based oceanography.
- Moorings provided quasi-continuous time-series measurements in many locations during IPY, including dense water overflows and boundary currents, major currents like the Antarctic Circumpolar Current and the Antarctic Slope Front, and were used to measure coastal sea level (e.g. Fig. 2.3-1b). In many cases, IPY moorings provided the first time-

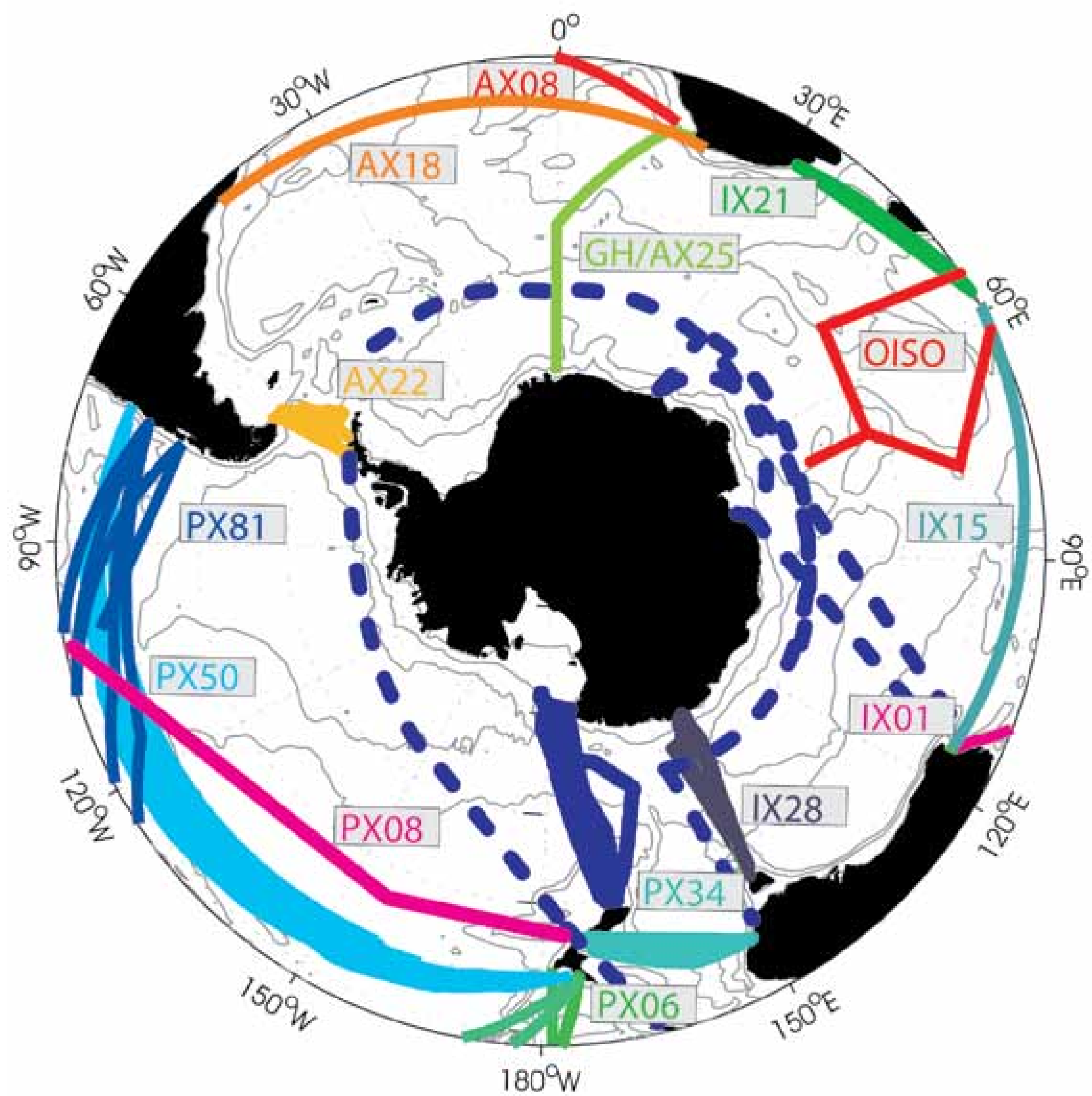
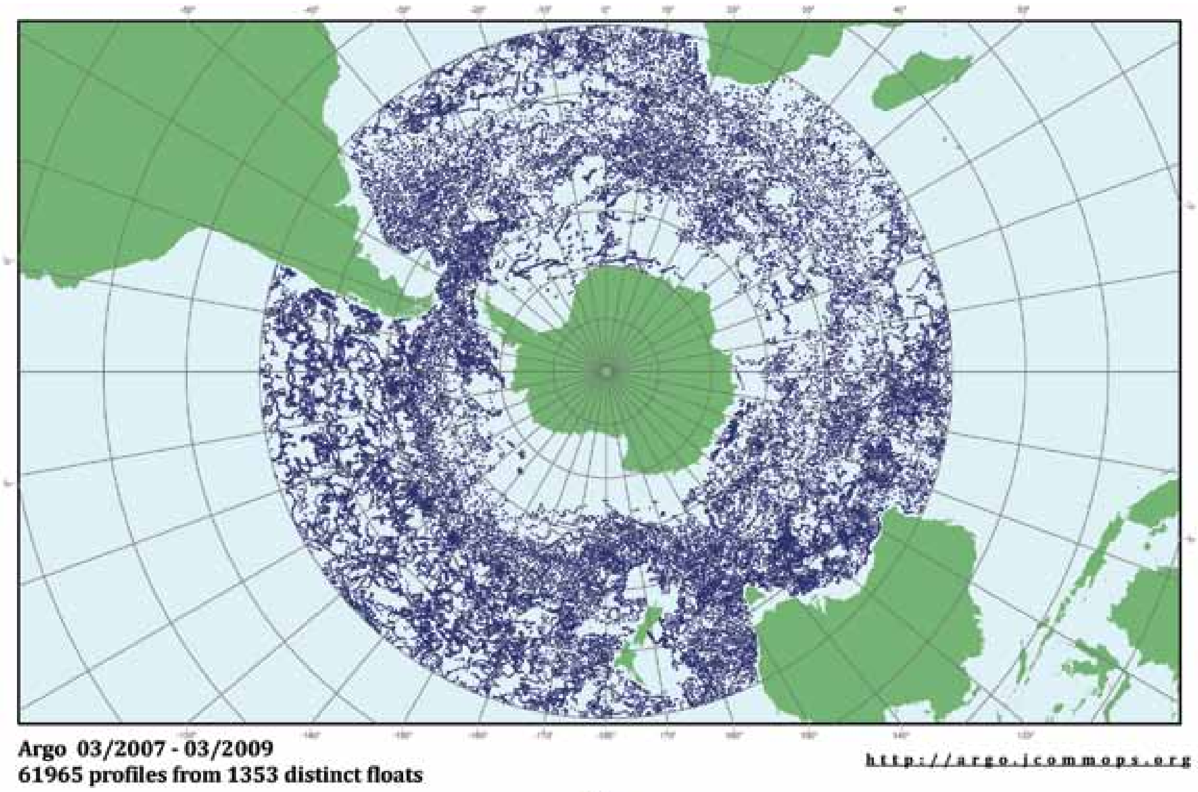


Fig. 2.3-1c. Underway measurements of physical, biogeochemical and biological properties in the surface and upper ocean were collected by Volunteer Observing Ships along these lines.
(Base map: Kate Stansfield)

Fig. 2.3-2a. A total of 61,965 profiles of temperature and salinity were collected by Argo floats during the IPY period (March 2007 – March 2009).

(Base map: M. Belbeoch, Argo Information Centre, JCOMMOPS)



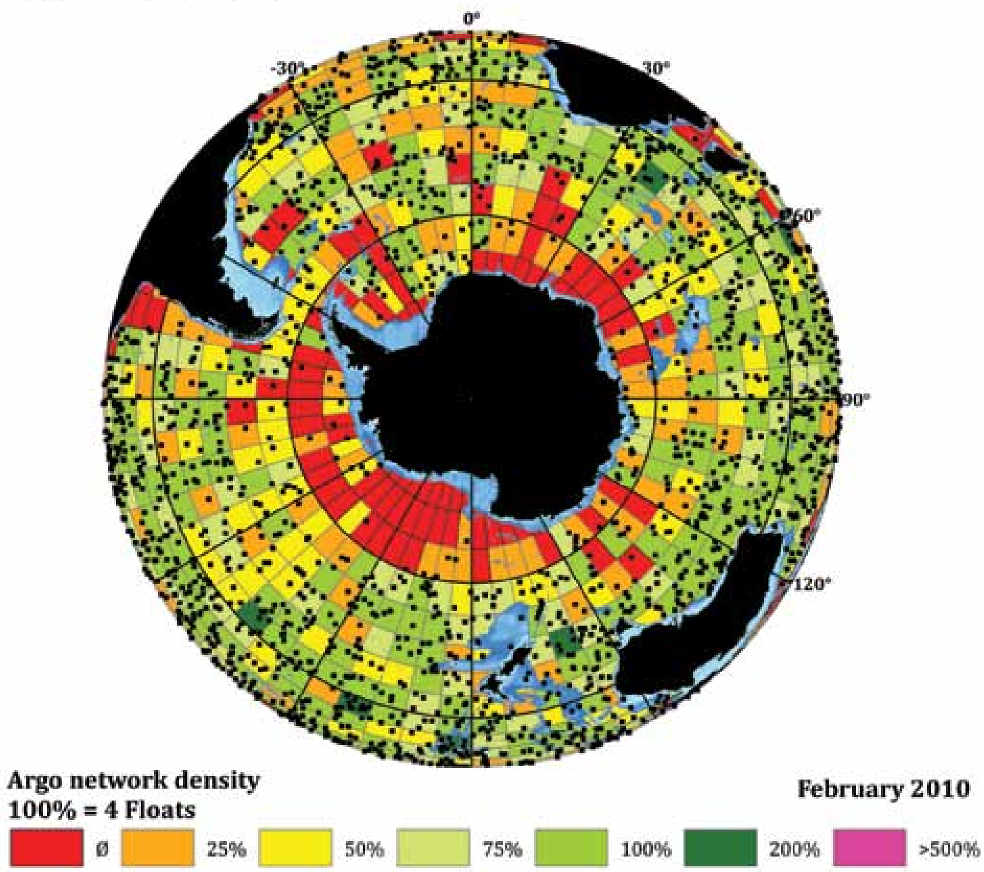


Fig. 2.3-2 (b). Estimate of density of float distribution. The IPY helped to enhance the coverage of Argo floats in the Southern Ocean, including the deployment of ice-capable floats in the sea ice zone. Nevertheless, the Southern Ocean remains significantly under-sampled (bottom).

(Base map: M. Belbeoch, Argo Information Centre, JCOMMOPS) series measurements ever made in these locations.

- Process studies were carried out at a number of locations. In particular, the first direct measurements of mixing in the deep Southern Ocean were made during IPY as part of the Diapycnal and Isopycnal Mixing Experiment in the Southern ocean (DIMES) and Southern Ocean FINEstructure (SO-FINE) projects.
- Measurements beneath the floating ice shelves and glacier tongues that fringe much of Antarctica were made at several locations. Observations within the sub-ice shelf ocean cavities are very scarce, due to the obvious difficulties of sampling the ocean beneath hundreds of metres of ice. Nevertheless, these measurements are needed to improve understanding of how the interaction between the ocean and the ice shelf can influence the dynamics of the Antarctic ice sheet and how ice shelf melt/ freeze processes modify the ocean water. The AUV Autosub3 made a number of long transits beneath the Pine Island Glacier, where thinning, acceleration and grounding line retreat have been observed by satellites, measuring water properties and the shape of the cavity (Jenkins et al., 2009). Access to the ocean can also be gained by drilling holes through the ice shelf and deploying oceanographic instruments. IPY measurements were made beneath the Amery Ice Shelf (70°E) and Fimbul Ice Shelf (Greenwich Meridian; Lars Smedsrud, pers. com.) as part of ongoing programs.
- Long-term sampling programs made a significant contribution to IPY goals, including underway measurements and remote sensing by satellites. Model studies were carried out under the IPY banner and contributed substantially to addressing the scientific questions identified above.

Research highlights

The unprecedented spatial coverage of IPY observations is providing new insights into the Southern Ocean and its connection to the rest of the globe. The deep hydrographic and tracer sections, Argo floats and animal sensors have delivered a circumpolar snapshot of the state of the Southern Ocean. The IPY repeat hydrographic sections continue time-series established in recent decades, allowing assessment of changes in a variety of parameters throughout the full depth of the Southern Ocean. Such studies have been used to document the uptake of anthropogenic CO_2 by the ocean (e.g. Sabine et al., 2004), and the warming (Johnson and Doney, 2006a,b; Johnson et al., 2007, Fahrbach et al., 2010) and freshening (Aoki et al., 2005; Rintoul, 2007) of Antarctic Bottom Water (AABW). For example, Fig. 2.3-4 shows that freshening of the Adélie Land and Ross Sea sources of AABW, observed in those earlier studies, has continued through the IPY

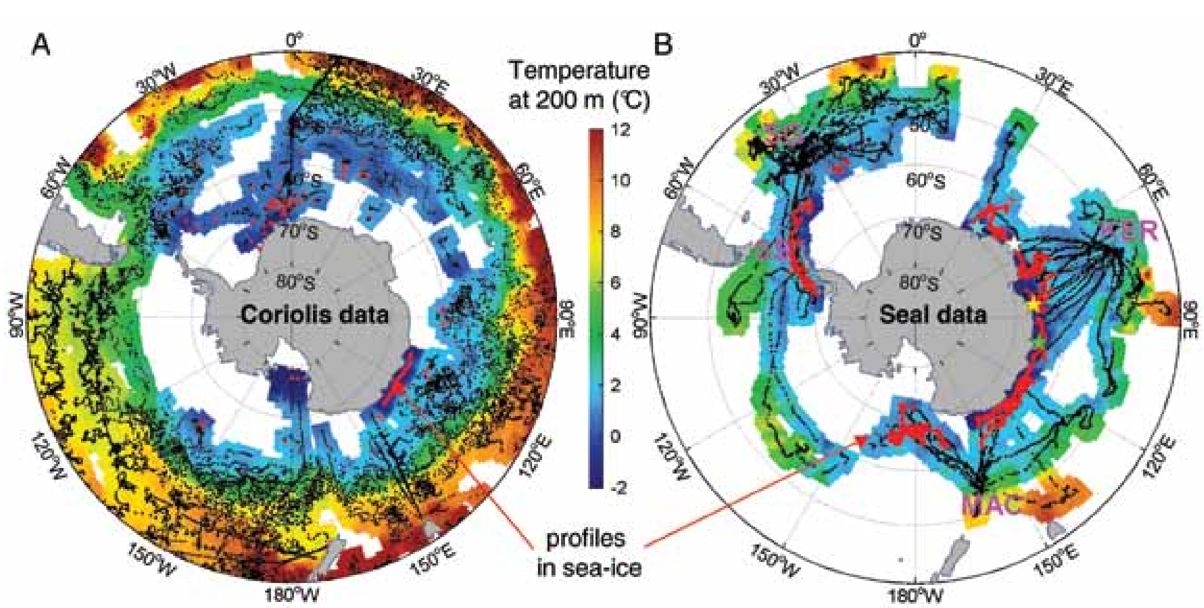


Fig. 2.3-3. Temperature at 200 m depth, as measured by traditional oceanographic platforms and provided by the Coriolis data centre (ships and floats, left) and by seals equipped with oceanographic sensors (right). The seals significantly increase the number of profiles obtained in the sea ice zone in winter (red). (Images: Charassin et al., 2008)

period. These previous studies underpinned the conclusion in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report that significant changes were underway in the Southern Ocean (Bindoff et al., 2007). Time-series collected during IPY also show that decadal and higher frequency fluctuations (Fahrbach et al., 2009; Gordon et al., 2010) and differences between regions (Heywood et al., 2009) can complicate the detection of longer-term trends.

The repeat hydrographic measurements have been used to develop proxies that allow the temporal and spatial variability of the Antarctic Circumpolar Current (ACC) to be assessed in unprecedented detail during IPY. For example, the hydrographic data reveal tight relationships between sea surface height, subsurface water mass properties, and the transport and structure of ACC fronts (e.g. Watts et al., 2001; Rintoul et al., 2002; Sokolov and Rintoul, 2007). Using these relationships and satellite measurements of sea surface height, variability of the ACC can be determined for the last 15 years with temporal resolution of a week and spatial resolution of about 100 km. These approaches have been used during IPY to measure ACC variability south of Africa (Luis and Sudhakar, 2009; Swart et al., 2008; Swart et al., 2010a,b) and along the circumpolar path of the current (Sokolov and Rintoul, 2009a,b).

During IPY, hydrographic measurements were also made in a number of locations where few or no measurements had been made in the past. Examples include the Fawn Trough, a deep gap in the Kerguelen Plateau, which as IPY measurements show, carries a substantial fraction (43 Sv out of 147–152 Sv) of the ACC transport (Park et al., 2009).

The SASSI program used moorings and profiling instruments (Conductivity-Temperature-Depth probes, CTDs) to measure the Antarctic Slope Front along much of the near-circumpolar extent of the current (Fig. 2.3-1b). The measurements have revealed an eastward undercurrent beneath the Antarctic Slope Front in the southeast Weddell Sea (Chavanne et al., 2010) and improved knowledge of the structure and the dynamics of the slope and coastal currents at the Greenwich Meridian (Núñez-Riboni and Fahrbach, 2009a,b). Eddies and upwelling events were shown to deliver heat to drive the melting of the glacial ice on the western Antarctic Peninsula. Closely spaced CTD sections were used to quantify the export of dense Weddell Sea waters across the South Scotia Ridge and

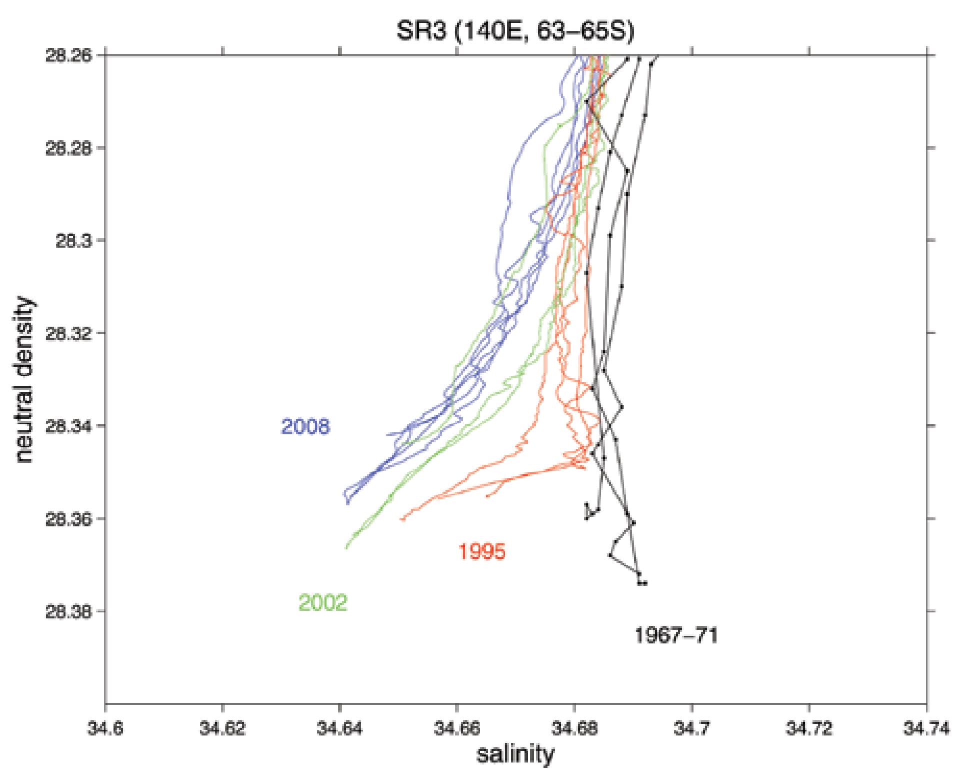


Fig. 2.3-4. Salinity of dense waters over the continental slope at 140°E, plotted as a function of neutral density. AABW formed in the Ross Sea and Adelie Land has freshened on density surfaces between the early 1970s, 1995 and the IPY section in 2008. The most extreme AABW has also become less dense with time.
(Graph: Stephen Rintoul)

the variability of the Antarctic Slope Front (Thompson and Heywood, 2008). A turbulence profiler was used to measure entrainment in the dense overflow for the first time. In the Prydz Bay area, along 15° E in the Riiser-Larsen Sea and in the Amundsen Sea, CTD surveys were carried out. In Prydz Bay, Ice Shelf Water was observed entering the region to the west of Prydz Channel (~72° E) to form Prydz Bay Bottom Water, which is colder and less saline than AABW (Antipov and Klepikov, 2007, 2008). The section in the Pine Island Bay, Amundsen Sea, shows significant penetration of Circumpolar Deep Water to the shelf area (Antipov et al., 2009a,b).

The Argo project has dramatically improved the observational coverage of the upper 2 km of the Southern Ocean. These observations have been combined with measurements from ships and satellites to document change and to quantify Southern Ocean processes that could not be measured using the sparse historical data. Comparison of Argo data to a historical climatology showed that the Southern Ocean as a whole has warmed and freshened in recent decades, reflecting both a southward shift of the ACC and water mass changes driven by changes in surface forcing consistent with expectations of a warming climate (Böning et al., 2008). Argo data have been used to resolve the seasonal cycle of the mixed layer depth (Dong et al., 2008), an important parameter for physical, chemical and biological studies, and its response to modes of climate variability (Sallée et al., 2010a). Variability of mode water properties has also been linked to modes of climate variability, like the Southern Annular Mode and El Niño (Naveira Garabato et al., 2009). The year-round coverage of Argo has also been exploited to quantify the rate at which surface waters are subducted into the ocean interior, revealing "hot spots" of subduction that help explain the interior distribution of potential vorticity, anthropogenic carbon and other properties (Sallée et al., 2010b).

IPY provided the first broad-scale measurements of the ocean circulation beneath the Antarctic sea ice. Several nations collaborated to acoustically track profiling floats beneath the sea ice in the Weddell Sea, resolving the current structure and water mass properties in greater detail than previously possible (Fig. 2.3-5, Fahrbach and de Baar, 2010). Oceanographic sensors deployed on southern elephant seals have revealed the structure of ocean currents in regions where traditional oceanographic platforms are unable to sample (Fig. 2.3-3 right, Charassin et al., 2008; Roquet et al., 2009; Boehme et al., in press; Costa et al., 2008). The increase in salinity beneath the ice has been used to provide the first estimates of the growth rate of sea ice from the open pack ice typical of the Antarctic continental shelf (Charassin et al., 2008).

Moorings deployed during IPY will provide robust transport estimates from a number of locations where direct velocity measurements did not exist. Examples include dense water outflows from the Weddell, Cape Darnley and Adélie Land coasts; the Antarctic Slope Front; the Weddell Sea; and the ACC at Drake Passage, south of Africa, the Fawn Trough and the Macquarie Ridge. The quasi-continuous measurements allow long-term trends in water mass properties to be distinguished from energetic low frequency fluctuations (Fahrbach et al., 2009; Gordon et al., 2010). A number of experiments conducted just prior to IPY also contribute to IPY goals. For example, a two-year deployment of moorings in the deep boundary current east of the Kerguelen Plateau showed that this current was a major pathway of the deep global overturning circulation, carrying 12 x 10^6 m^3 s^{-1} of AABW (potential temperature < 0°C) to the north, with 5 x 10^6 m^3 s^{-1} re-circulating to the southeast (Fukamachi et al., 2010).

Lack of knowledge of where and at what rate mixing takes place in the ocean remains a key gap in understanding the dynamics of the global ocean circulation. The interaction of the strong deep-reaching currents of the Southern Ocean with rough bathymetry may result in enhanced mixing levels there (Naveira Garabato et al., 2004). Two experiments set out to test this hypothesis during IPY. The DIMES experiment used a variety of tools (a deliberate tracer release, floats, moorings, ship transects and turbulence profilers) to measure mixing upstream of Drake Passage. The SO-FINE experiment carried out similar work where the ACC interacts with the northern end of the Kerguelen Plateau.

Preliminary results from the Autosub mission beneath the Pine Island Glacier show how sea floor topography modifies the inflow of warm Circumpolar Deep Water into the inner cavity and impacts the degree to which it mixes with the cooler melt water (Jenkins et al., 2009). Borehole observations from

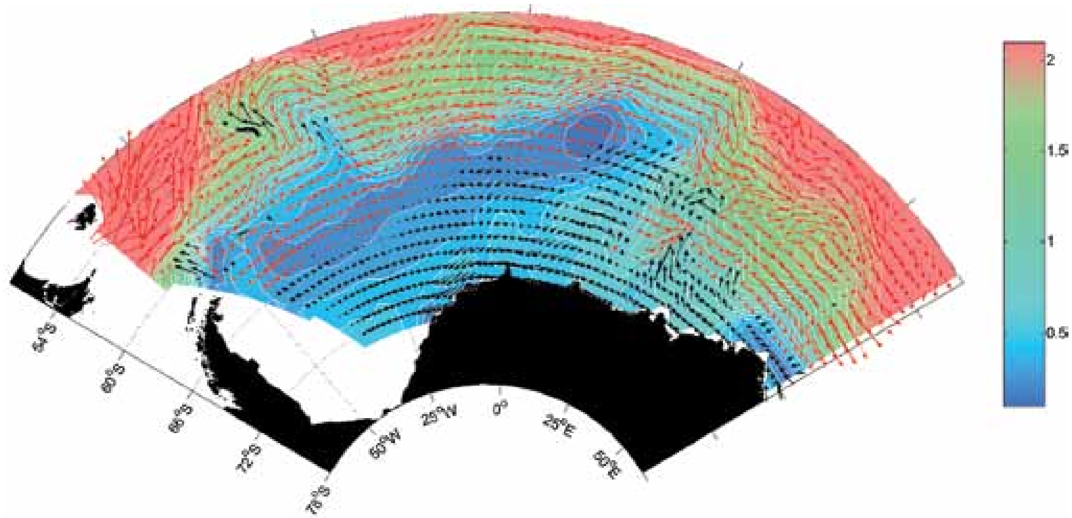


Fig.e 2.3-5. The Weddell gyre flow and *in situ* temperature in 800 m depth derived from the data of 206 ice-compatible vertically profiling floats between 1999 and 2010.
(Image: Fahrbach et al., submitted)

the Amery Ice Shelf have provided new insights into melting and re-freezing processes in that sub-ice shelf cavity (Craven et al., 2009). The Amery Ice Shelf experiences rapid melt rates near its grounding line. Most of this melt water re-freezes to the base of the floating ice-shelf, forming a marine ice layer up to 200 m thick. This marine ice layer is highly permeable, even at a distance of 100 m above the ice-shelf base. The permeability of the marine ice layer suggests that marine ice at the base of the ice-shelf may be particularly vulnerable to changes in ocean properties.

Biogeochemistry

Most of the deep hydrographic sections occupied by the CASO and SASSI programs also collected observations of biogeochemical parameters, including carbon and major- and micro-nutrients. In addition, IPY-GEOTRACES contributed to 14 research cruises in the oceans around Antarctica and the Arctic, as part of the overall GEOTRACES study of the global marine biogeochemical cycles of trace elements and their isotopes (Measures et al., 2007).

A primary goal of the biogeochemistry program during the IPY was to quantify the evolving inventory of carbon dioxide in the Southern Ocean and to understand how the physical and biological processes responsible for ocean uptake and storage of CO_2 might respond to climate change (Gloor et al., 2003; Hoppema, 2004; Takahashi et al., 2009). Another important issue in the Southern Ocean is the vulnerability of the cold surface waters to acidification. Here, the already low concentration of carbonate ion is further reduced by considerable uptake of anthropogenic CO_2, possibly leading to under-saturation of aragonite (a form of $CaCO_3$) within the next decades (Orr et al., 2005; McNeil and Matear, 2009). This in turn could have an impact on $CaCO_3$ utilizing organisms by reducing the rate of calcification. For example, pteropods, planktonic snails that form shells from aragonite, are a key part of the Southern Ocean food chain and may be at risk as the Southern Ocean becomes progressively more undersaturated in aragonite. Since not all organisms act similarly and the distribution of organisms around the circumpolar ocean is inhomogeneous, spatial variability of ocean acidification and its impact on the carbon cycle is expected. Measurements made during IPY are being used to document the evolving inventory of anthropogenic CO_2 and changes in ocean acidity.

The Southern Ocean is of particular interest to GEOTRACES as iron limits primary productivity in much of this region, and change in the delivery and availability of iron will arguably be the single largest forcing of Southern Ocean ecosystem productivity and health in the next century, and thus is intrinsically linked with changes in climate. Moreover, all living organisms require trace elements (such as zinc, copper, manganese and cobalt) for many functions including as co-factors in enzymes thus co-limitation by such elements in the Southern Ocean is likely under certain environmental conditions (Morel and Price, 2003).

The scientific questions of primary interest to the biogeochemical theme of Southern Ocean IPY included: How much CO_2 is absorbed (and released) by the Southern Ocean and how sensitive is the Southern Ocean carbon "sink" to climate change? How is the absorption of CO_2 changing the chemistry of the Southern Ocean, and what impact will acidification have on organisms and ecosystems? What is the distribution and supply of iron and other trace elements and isotopes, and what do they tell us about the sources and sinks of CO_2 and the control of primary productivity? What processes control the concentrations of geochemical species used as proxies for past environmental conditions, and what are the implications for interpretation of past climate?

IPY observations

Biogeochemical measurements (including oxygen, nutrients, carbon and tracers) were made along most of the hydrographic lines shown in Fig. 2.3-1a. IPY-GEOTRACES work was carried out on a number of additional sections shown in Fig. 2.3-6, including process studies in the Amundsen Sea, in the subantarctic and polar frontal zones to the south and east of Australia and New Zealand (e.g. Ellwood, 2008; Bowie et al., 2009) and in the sea ice zone (van der Merwe et al., 2009) as well as in the Atlantic sector and Drake Passage (Fahrbach and de Baar, 2010). The trace metal work required clean sampling techniques, which were widely used in the Southern Ocean for the first time during IPY. Water samples were collected using non-metallic rosettes and cables, with analyses conducted in special clean containers using agreed protocols (Johnson et al., 2007; Fahrbach and de Baar, 2010).

Research highlights

Knowledge about the carbon cycle of the Southern Ocean has increased significantly during IPY. Nevertheless, most of these data have still to be included in global studies to further improve estimates of interior ocean storage of anthropogenic CO_2 and the air-sea exchange of CO_2 that were determined in studies (Sabine et al., 2004; Takahashi et al., 2009) made before IPY. Le Quéré et al., (2007)

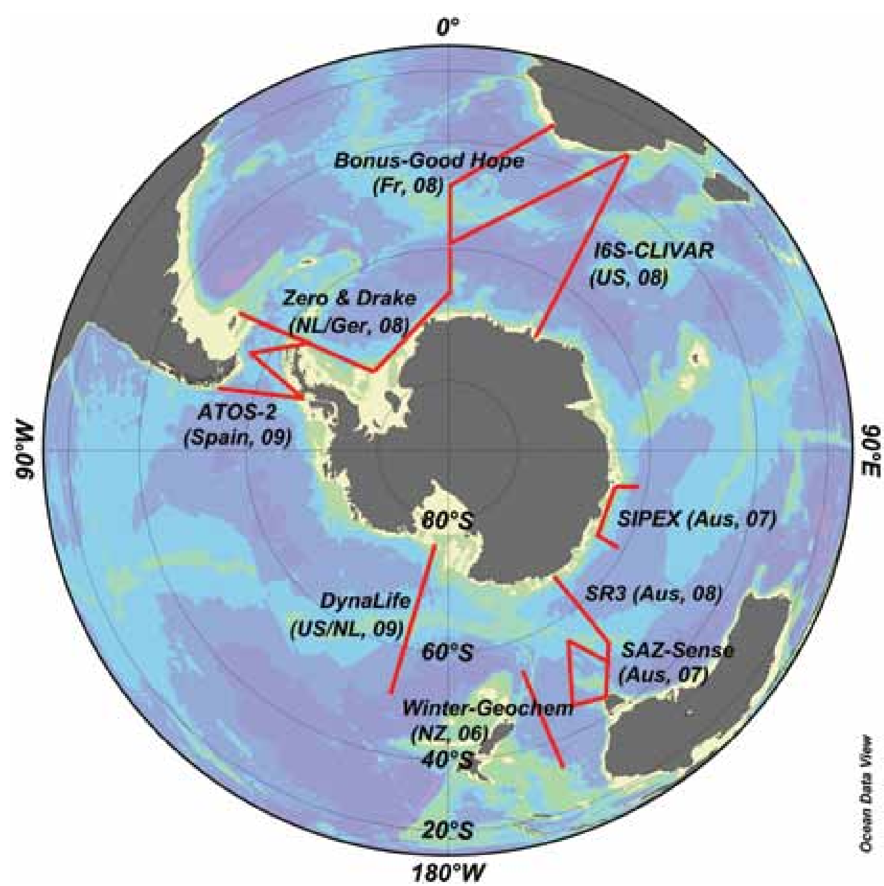


Fig. 2.3-6. GEOTRACES transects and process cruises in the Southern Ocean during IPY.
(Map: Andrew Bowie)

suggested that, based on atmospheric observations and modelling, the sink function has recently been decreasing due to a southward shift of the westerly winds associated with changes in the Southern Annular Mode. This suggestion in turn has been challenged by several investigators and is the subject of ongoing research. Although Le Quéré's conclusions have been supported by another modelling study (Lovenduski et al., 2008), it should be noted that Böning et al., (2008) have questioned this saturation of the Southern Ocean CO_2 sink, arguing that the effect of increased eddy formation could compensate for the extra energy imparted to the ocean by the winds, with no significant change in the overturning.

While the exploitation of the wealth of carbon data is still underway, first results are starting to emerge. The precipitation of $CaCO_{3.}6H_2O$ (ikaite) was observed for the first time in sea ice, a process likely to have a significant impact on the carbon cycle in ice covered areas (Dieckmann et al., 2008). CO_2 oversaturation was observed under the sea ice in the eastern Weddell gyre at the end of winter and early spring, with a shift to undersaturation within a few days as a result of biological activity thus preventing CO_2 outgassing to the atmosphere (Bakker et al., 2008). This mechanism may well be responsible for the annual sink function of this region. Drifters measuring pCO_2 in the surface ocean developed in the CARIOCA program (www.lodyc.jussieu.fr/carioca) indicated the Subantarctic Zone is a strong sink for atmospheric CO_2 (Boutin et al., 2008). Decadal trends of anthropogenic CO_2 in the Weddell Gyre were estimated from repeat sections along the prime meridian, providing a benchmark for future investigations (Hauck et al., 2010; Van Heuven et al., 2010).

A significant achievement of IPY was the first full-depth measurements of iron and other trace elements in the Southern Ocean (e.g. Klunder et al., 2010). For example, the distribution of dissolved iron along the SR3 section south of Tasmania (Fig. 2.3-7) shows maximum surface water concentrations between the latitudes of 60° and 65°S. The salinity (Fig. 2.3-7, lower left panel) and oxygen (Fig. 2.3-7, lower right panel) distributions along this section indicate that high salinity, low-oxygen, nutrient-rich circumpolar deep water upwells within this latitude band. These results, in combination with much lower dissolved iron concentrations north of 60°S, support the view that upwelling is more

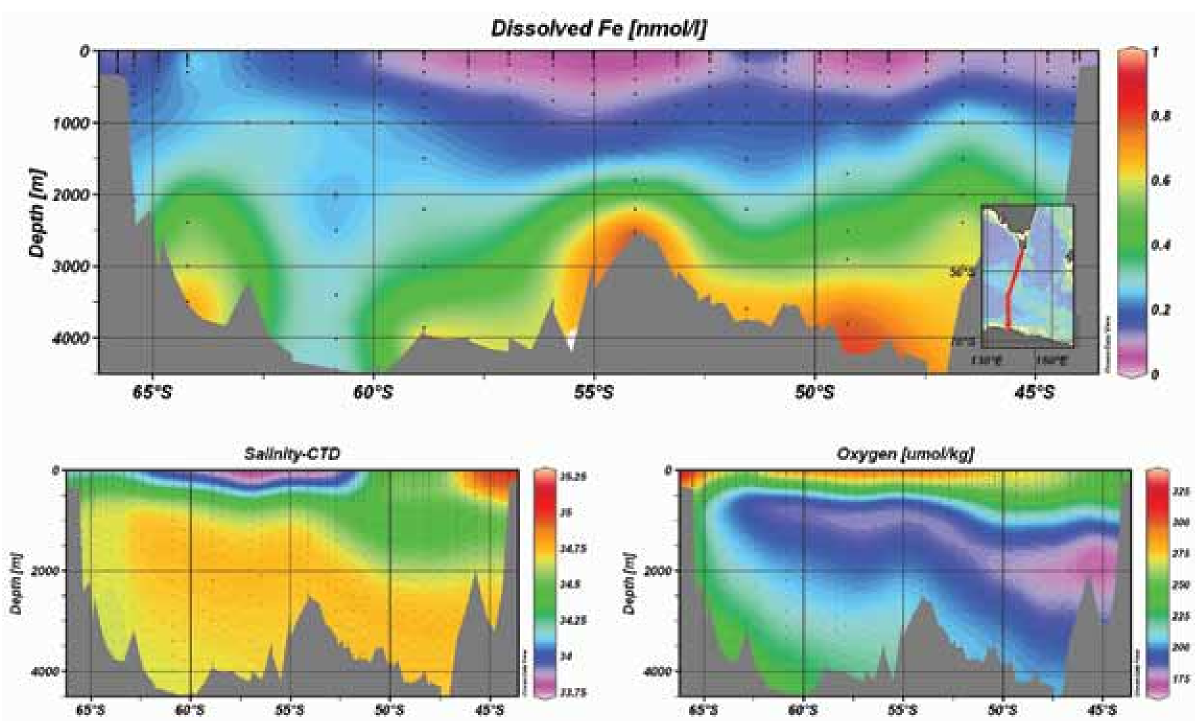


Fig. 2.3-7. Dissolved iron, salinity and oxygen distributions in the full-water column along the SR3 transect between Tasmania and Antarctica. The position of the transect is shown in the insert in the upper panel.
(Image: Bowie et al., unpublished data)

significant than deposition of aerosols as a source of iron to this polar region during autumn. Furthermore, the iron distribution indicates the importance of bottom sediments and hydrothermalism as sources of iron to the deep Southern Ocean (Tagliabue et al., 2010), sources that have been neglected in previous biogeochemical models for the region. Distributions of total dissolvable iron (TDFe), dissolved iron (DFe) and soluble iron (SFe) were investigated during the BONUS-GoodHope cruise in the Atlantic sector of the Southern Ocean (34°S/17°E, 57°S/0°E) along a transect from the subtropical domain to the Weddell Sea Gyre, in February-March 2008. The highest concentrations of DFe and TDFe were observed in the sub-tropical domain, where continental margins and dust input might be the main Fe sources. Complexation with ligands from biological and continental origin could explain the distributions of SFe and CFe along the transect (Chever et al., submitted).

The first measurements of methylmercury in the Southern Ocean were made during IPY, showing high concentrations and an increase in the ratio of methylmercury to apparent oxygen utilization in Antarctic waters (Cossa et al., submitted). The distribution can be explained by the co-location in Antarctic waters of a large atmospheric source of mercury (through mercury depletion events mediated by halogens released during sea ice formation), bacterial decomposition of organic matter produced by intense phytoplankton blooms and upwelling of methylmercury-enriched deep water. These results have improved our understanding of the global mercury cycle, confirmed evidence of open ocean methylation and helped explain the elevated mercury levels observed in Antarctic biota.

IPY experiments in the Australasian region revealed that subantarctic phytoplankton blooms during summer were driven by both seasonal iron supply from southward advection of subtropical waters and by wind-blown dust deposition, resulting in a strong decoupling of iron and nutrient cycles (Bowie et al., 2009). These observations have important longer-term climatic implications since the frequency and scale of dust emissions and the poleward extension of western boundary currents are both predicted to increase in the future, resulting in a greater influence of subtropical water on the subantarctic zone.

The origin of the iron in the ocean can be derived by correlating properties of related trace metals such as aluminium and manganese. Dissolved aluminium in the surface waters is a tracer of aeolian dust and dissolved manganese can help to trace iron input from the bottom. On the Greenwich meridian the near surface concentration of aluminium is low (Fig. 2.3-8 top), whereas manganese displays a maximum over the mid-ocean ridge (Fig. 2.3-8 bottom) correlating with dissolved iron (not shown) suggesting an iron input from hydrothermal activity (Middag et al., 2010a,b).

A comprehensive examination of the distribution, speciation, cycling and role of iron in fuelling sea ice-based and pelagic algal communities showed that primary productivity in seasonally ice-covered waters around Antarctica is primarily driven by temporal variations in iron supply (seasonal and inter-annual, driven by sea ice formation and melting processes) rather than large-scale spatial forcing (van der Merwe et al., 2009), with strong vertical iron resupply during winter, rapid release from sea ice and uptake during spring, and substantial depletion during summer (Lannuzel et al., 2010).

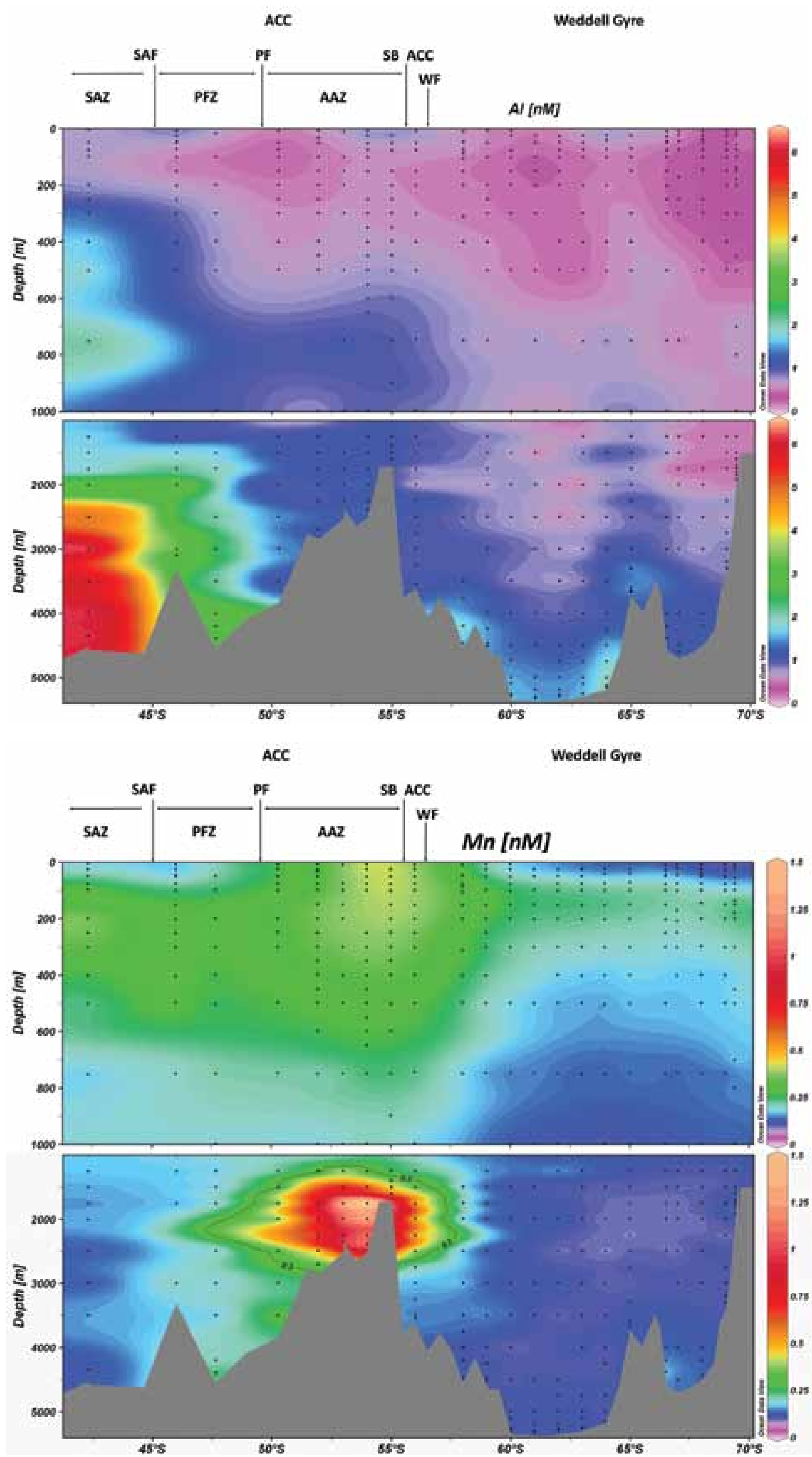
Marine biology, ecology and biodiversity

Several major programs, CAML, EBA, ICED, MEOP and SCAR-MarBIN, numerous individual IPY projects, PAME, AMES and certain components of PANDA, focused on the broad issue of marine biology, ecology and biodiversity in the Southern Ocean. These overarching programs included contributions from numerous regional programs, such as DRAKEBIOSEAS and ClicOPEN, which focussed on the effect of climate change on coastal communities at the western Antarctic Peninsula.

The objective of the SCAR project Census of Antarctic Marine Life (CAML, see www.caml.aq) was to determine the distribution and abundance of life in the Southern Ocean around Antarctica, providing a benchmark against which future change can be assessed. The Arctic and the Antarctic Peninsula are currently experiencing rapid rates of change (IPCC, 2007; Steig et al., 2009; Mayewski et al., 2009; Convey et al., 2009). The uniquely adapted organisms of the polar regions may be vulnerable to shifts in climate and ocean circulation patterns. The major scientific question for CAML is how the marine life around

Fig. 2.3-8. Vertical distribution of aluminium (top) and of manganese (bottom) in nM on a transect along the Greenwich Meridian.

(Image: Middag et al. in press, (a) and (b))



Antarctica will be affected by change and how change will alter the nature of the ecosystems of the Southern Ocean. More specific questions include: How does biophysical coupling in the marine environment drive biological diversity, distribution and abundance of species? Which species hold the key to ecosystem functioning? What are the critical ecological processes and historical factors affecting diversity? How will communities respond to future change (and how have they responded to past change), including warming, acidification, increased UV irradiance and human activities? What is the role of the Southern Ocean in driving marine speciation to the north? As a contribution to CAML, ANDEEP-SYSTCO (ANtarctic benthic DEEP-sea biodiversity: colonisation history and recent community patterns - SYSTem COupling) builds on the precursor program ANDEEP, moving the focus from distributional patterns of the largely unexplored abyssal benthos in the Southern Ocean to processes in the abyssal ecosystem and their connections to the atmosphere and water column (Brandt and Ebbe, 2009).

The Integrating Climate and Ecosystem Dynamics (ICED) program is focused on integrating Southern Ocean ecosystem, climate and biogeochemical research (Murphy et al., 2008; 2010). The multidisciplinary activities and collation of past studies undertaken as part of ICED-IPY have already furthered our understanding of ecosystem operation in the context of climate processes, physics, biogeochemistry, food web dynamics and fisheries (www.iced.ac.uk). For example, the Synoptic Circum-Antarctic Climate-processes and Ecosystem (SCACE) study identified clear changes in the food web across water mass boundaries. These changes are related to carbon fluxes associated with blooms and to changes in sea ice cover. AMES including the Antarctic Krill and Ecosystem Survey (AKES, Krafft et al., 2008) focused on the abundance, size structure and demographic characteristics of krill, a major component of the Antarctic ecosystem. In addition AKES also focused on acoustic properties of salps (Wiebe et al., 2009), krill and mackerel icefish. VIRPOL (The significance of VIRuses for POLar marine ecosystem functioning) a contribution to PAME investigated the abundance and composition of viruses and their hosts at both poles, with the goal to identify the significance of viruses and their impact on microbial mortality and geochemical cycling, and to unravel the impact of climate and global change on viruses and their role in the marine ecosystem.

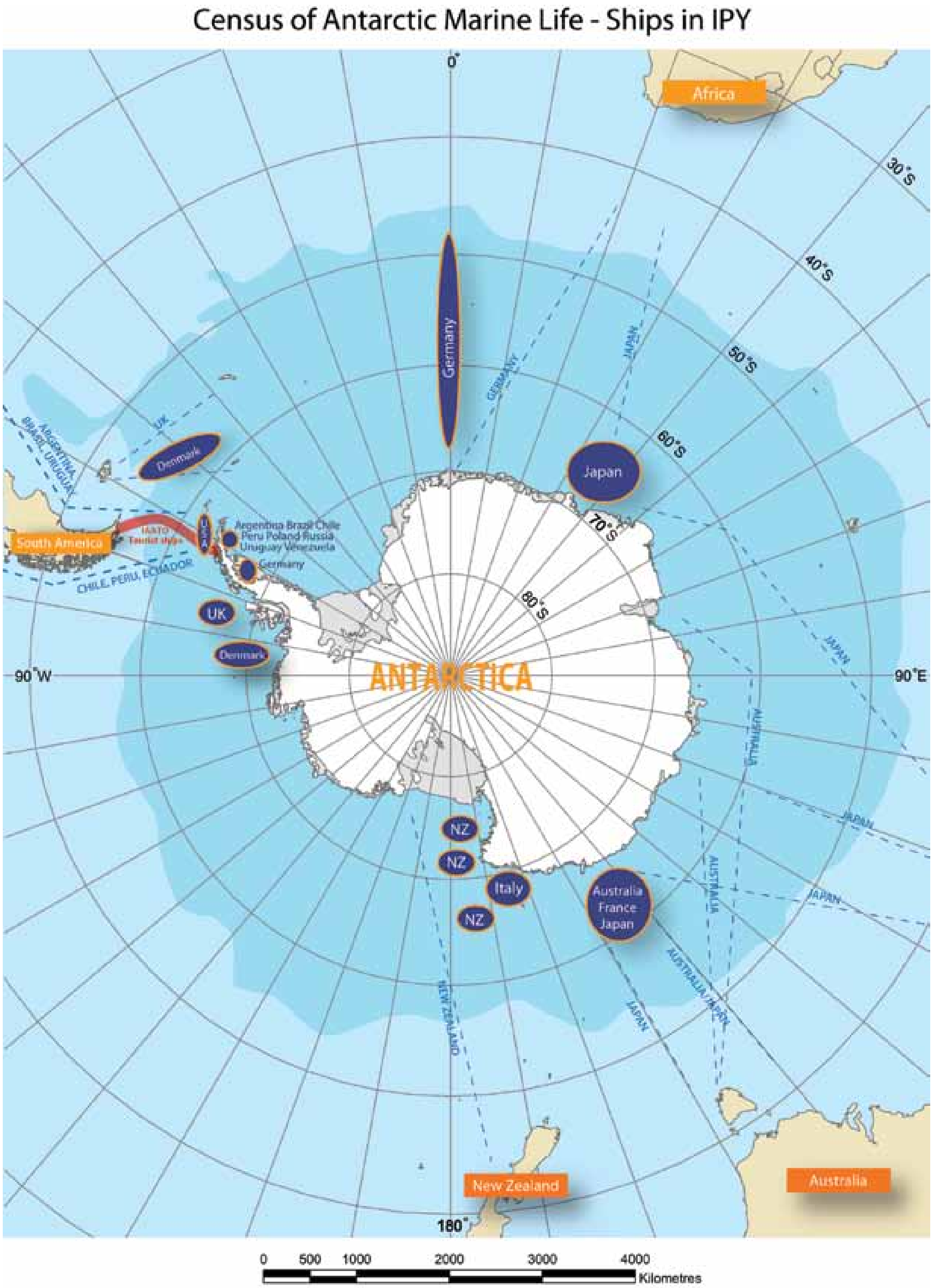
IPY Observations

During the CAML, 18 vessels sampled biodiversity in the Southern Ocean (Fig. 2.3-9). Sampling and observation methods included shipboard gear such as towed video and camera systems, continuous plankton recorders, nets and benthic grabs; biologgers on seals; and systematics and DNA barcoding. Many of these voyages were carried out in partnership with IPY projects focused on physics and biogeochemistry (e.g. CASO, SASSI and GEOTRACES), providing a unique multidisciplinary data set to relate patterns of biodiversity to physical and chemical processes. A larger number of vessels completed underway sampling, including continuous plankton recorder transects across the Southern Ocean at many longitudes. A major legacy of CAML is the SCAR-MarBIN data portal, which contains data collected on some 15,500 species.

Close cooperation of pelagic and benthic specialists allowed investigation of many aspects of abyssal ecology during the ANDEEP-SYSTCO cruise (Bathmann, 2010). SYSTCO scientists aimed to study the biology of abyssal species, the role of the bottom-nepheloid layer for recruitment of benthic animals, the influence on abyssal life of the quantity and quality of food sinking through the water column, feeding ecology and trophic relationships of abyssal animals. The effects of topography, sedimentology and biogeochemistry of sediment and pore water on benthic life and microhabitat formation were investigated. As the benthic fauna depends on deep carbon export from the pelagic production and particle sedimentation, a station was re-occupied on the return leg to estimate seasonal and episodic variability of the particle flux (Bathmann, 2010). The spatial distribution of the fluxes (Fig. 2.3-10) could be derived on the basis of pre-IPY and IPY data (Sachs et al., 2009).

In the context of AMES a multidisciplinary survey targeting the pelagic ecosystem was carried out in 2008 in the Atlantic sector of the Southern Ocean. Various sampling strategies and new observation techniques, as well as on-board experiments, were used to study abundance and population characteris-

Fig. 2.3-9. CAML ship sampling during IPY, dark blue areas denote benthic sampling, following the plan at www.caml.aq. The locations are shown for each national program. The dashed lines are transects using the Continuous Plankton Recorder. The shaded red area near South America was sampled by tourist vessels under the International Association of Antarctica Tour Operators IAATO. The boundary between the darker and lighter of the two ocean colours indicates the position of the Subantarctic Front.
(Map: Victoria Wadley)



tics and their relationship to the physical environment. High phytoplankton abundance seems to be related to fronts and bathymetric features that also govern regional circulation patterns. The abundance, size structure and demographic characteristics of the Antarctic krill, *Euphausia superba,* varied systematically throughout the study region. VIRPOL carried out two major campaigns in the Southern Ocean: one survey in the Australian sector of the Southern Ocean (Evans et al., 2009) and a second campaign in the Atlantic sector (Evans et al., 2010). During both cruises, comprehensive measurements of the abundance of a range of microbes including viruses and bacteria (with high and low DNA), cyanobacteria and eukaryotic algae were made. In addition, a range of incubation experiments were conducted to determine viral mortality and grazing of bacteria and picophytoplankton.

Research highlights:

The CAML investigated the evolution and function of life around Antarctica, stimulating new areas of enquiry about the biodiversity of the Southern Ocean. Over one million geo-referenced species records are already available in the data portal. These records include species inventories of the Antarctic shelf, slope and abyss; of the benthic fauna under disintegrating ice shelves; of the plankton, nekton and sea ice-associated biota at all levels of biological organization from viruses to vertebrates; and assessed the critical habitats for Antarctic top predators.

Results from the CAML have challenged the concept that the diversity of marine species decreases from the tropics to the poles; the Antarctic boasts unparalleled diversity in many taxonomic groups and, in the Arctic, an unexpected richness of species compared to the tropical oceans has been documented (Clarke et al., 2006; Barnes, 2008). New species have been discovered in all ocean realms, notably deep-sea isopods (Brandt et al., 2007). The multiple bioregions described by Hedgpeth (1969) have been overturned in favour of a single bioregion united by the Antarctic Circumpolar Current, at least for sessile benthic invertebrates (Clarke et al., 2006; Griffiths et al., 2009). The ANDEEP-SYSTCO program discovered differences in benthic diversity and abundance in different locations of the Weddell Sea (Brandt and Ebbe, 2009), including a distinct bivalve-dominated fauna on Maud Rise, suggesting high availability of particulates to support filter feeders there, and low diversity and abundance beneath the Polar Front (Bathmann, 2010). The findings support

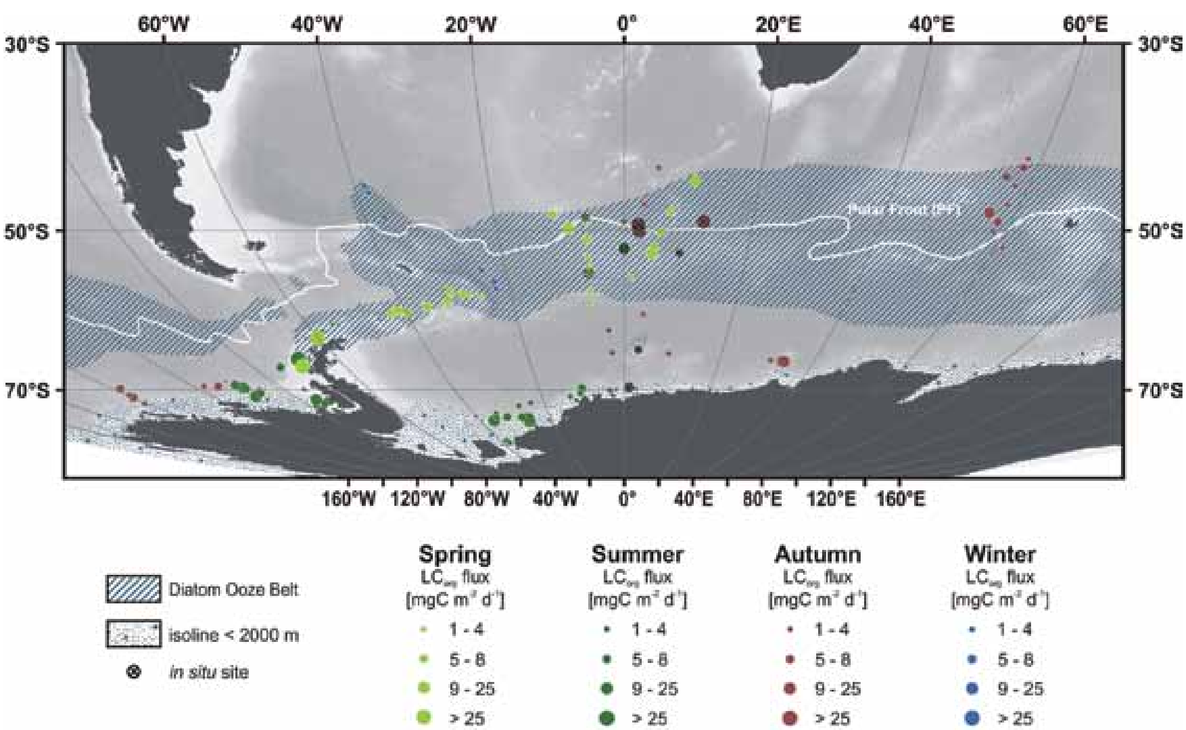


Fig. 2.3-10. Spatial distribution of the fluxes of organic carbon (LC_{org}) from the water column into the seafloor derived from measurements in the water column and the sediment during the IPY DOMINO project which is a contribution to ICED.

(From Sachs et al., 2009 and references cited therein) the theory that the high diversity found in some deep-sea taxa could have been developed and sustained through the occupation of distinct ecological niches. In addition to detritus originating from phyto- and zooplankton, foraminifera seem to play an important role in the nutrition of certain polychaete and isopod families. Bacteria were not found to play a significant role in the diet of any polychaetes analysed.

The effect of a dramatically changing environment on the benthic realm was observed by monitoring the former ice shelf sea floor with a Remotely Operated Vehicle (ROV, Fig. 2.3-11) after the Larsen A and B ice shelves had collapsed. Species that were adapted to the oligotrophic under-ice conditions will become extinct in that area. Immigration and growth of pelagic key organisms and benthic pioneers contribute to a potential new carbon sink in such areas (Peck et al., 2009). Nevertheless, it will require centuries if not millennia before complex benthic communities like those observed in the Eastern Weddell Sea are established (Gutt et al., 2008).

Octopuses provide unequivocal molecular evidence of the colonization pathway from the Antarctic to the deep sea (Strugnell et al., 2008). The research suggests that the Antarctic provides a frozen incubator of biodiversity, which has radiated to other oceans with the advent of the global thermohaline circulation, as Antarctica cooled at the end of the Eocene (37 million years ago). With the sibling IPY project, Arctic Ocean Diversity (ArcOD), CAML has discovered 251 "bipolar" species that are shared by both the Arctic and Antarctic oceans. The question of whether they are genetically the same, or simply look alike, is being answered with DNA barcoding.

Russian studies of the marine ecosystem in Nella Fjord, Prydz Bay, contributed to the goals of ICED. Observations were focused on both sea ice cores and under ice water samples at a profile across the Nella Fjord. It was shown that sea ice flora consists of mainly dinoflagellate cysts. Marine diatoms were present only as single cells, probably caused by freshening associated with the formation of sea ice (Melnikov and Gogorev, 2009; Melnikov et al., 2010).

Observations collected from Southern Ocean marine mammals by the MEOP program and its predecessor SEaOS have provided new insights into the foraging behaviour of seals and other marine mammals and the factors influencing their population dynamics (as well as the oceanographic discoveries mentioned above). Changes in the rate of ascent or descent during passive drift dives have been used to infer the distribution of productive and unproductive foraging areas visited by southern elephant seals (Biuw et al., 2007). The study concludes that the decline in elephant seal populations at Kerguelen and Macquarie Islands relative to those at South Georgia can be related to the greater energy expenditure required to reach more distant Antarctic foraging regions.

The VIRPOL cruises showed viruses were abundant throughout the Southern Ocean and the virus data correlated well with the distribution of their potential microbial hosts (bacteria, cyanobacteria and eukaryotic algae). Higher virus and microbial concentrations were observed in the Subantarctic Zone (SAZ) with concentrations decreasing near the Polar Front (PF). Microbe concentrations were relatively low in the Antarctic Zone (AZ), but elevated at costal stations. Levels of viral production indicated that viral infection of bacteria was very high in the Southern Ocean relative to other open ocean environments, particularly in the SAZ.

ClicOPEN examined the effect of regional rapid warming on the coastal biota of the Western Antarctic Peninsula (WAP) region and concluded that local sediment discharge and iceberg scouring are the two major effects, whereas changes in sea water temperature and salinity have little impact. At King George Island and other WAP areas the volume of fresh water discharged from the land has doubled between 2002-2006, with highest monthly yields in glacial catchment areas measured in January (Dominguez and Eraso, 2007). As a consequence of both fresh water release from melting land glaciers and starvation of the animals due to reduced primary production under the coastal sediment run-off plume, dead krill were washed on to the beach (Fig. 2.3-12). The annual disturbance of the sea floor by icebergs from 2001 to the present day was quantified (Smale et al., 2008). Iceberg scour disturbance on the benthos was found to be inversely proportional to the duration of local sea ice, as icebergs become immobilized by solid sea ice cover. Results of hydrographic and sediment monitoring programs can be linked to observed

Fig. 2.3-11. Sea floor organisms observed with an ROV after the Larsen A/B ice shelves collapsed (left and centre) and in the Eastern Weddell Sea (right). Species that were adapted to the oligotrophic under-ice conditions (stalked brittle stars, left) will become extinct in that area. Pelagic key organisms and benthic pioneers (sea-squirts, centre) immigrate and grow. Complex benthic communities, as in the Eastern Weddell Sea (sponges, right), will establish in centuries.
(Photo: J.Gutt ©AWI/MARUM, University of Bremen)

shifts in coastal marine productivity and biodiversity. Surveys on the colonization of newly ice-free areas under water and on land were conducted. Species like the Antarctic limpet, *Nacella concinna,* expand the time during which they stay in the Antarctic intertidal zone. Near the U.K. Rothera station, limpets were shown to overwinter in the intertidal zone (Waller et al., 2006), while at King George Island this is still not absolutely clear. Adaptive strategies under environmental strain include self-induced hypoxia in limpets trapped outside the water during low tides. Limpets lacking the adaptation in shell morphology could not produce the hypoxic response when exposed to air (Weihe and Abele, 2008).

Antarctic sea ice

Two major Antarctic sea ice field programs were undertaken under the umbrella of "Antarctic Sea ice in IPY". The Sea Ice Physics and Ecosystem eXperiment (SIPEX) was an Australian-led program that took place in East Antarctica (115-130°E). The Sea Ice Mass Balance of Antarctica (SIMBA) experiment was a U.S.-led program that focussed on the Bellingshausen Sea region (80-120°W). The voyages were near coincident in time and provided a unique opportunity to examine regional differences in sea ice conditions.

The experiments were highly multi-disciplinary, with the overarching goals of improving our understanding of the relationships among the physical sea ice environment, the biological systems within the ice habitat and the broader links to Southern Ocean ecosystem dynamics and top predators. Key questions that motivated the effort during the IPY include: What is the relationship between ice thickness and snow thickness over spatial scales measured by satellite laser altimetry? How is the distribution of sea ice algae and krill under the ice related to the ice and snow thickness distribution? How is biological primary and secondary productivity affected by winter sea ice extent and properties? And what are the drift characteristics, and internal stresses, of sea ice in the region?

IPY observations

Sea ice and snow thickness affect the interaction between atmosphere and ocean, biota and ocean circulation, and are therefore essential measurements of any sea ice field campaign. In both programs, the thickness of snow and ice were measured in a number of different ways including drill-hole measurements across ice floes (Fig. 2.3-13), airborne altimetry and ship-based techniques such as electromagnetic induction, underway observations using the ASPeCt (www.aspect.aq/) protocol and downward-looking video cameras.

Satellite laser altimetry calibration and validation using a combination of in situ and aircraft-based measurements was a key goal of both programs. The schedule of NASA's Ice Cloud and land Elevation Sat-

Fig. 2.3-12. Dead krill on the beach at King George Island as a consequence of increased fresh water and sediment discharge.
(Photo: Eva Philipp)

ellite (ICESat) was adjusted to ensure that the 33 day L3I mission of the onboard laser altimeter coincided with the two IPY field programs thus ensuring near-coincident field and satellite overpass data. The possibility of collecting coincident data in the field was, unfortunately, thwarted by bad weather, but regional calibration and validation studies were possible.

Under-ice measurements were made using a ROV during SIPEX to determine the abundance of algae under the ice, along transects marked out from the surface. Additionally, a Surface and Under-ice Trawl (SUIT) system was specially made to trawl for krill under ice floes adjacent to the ship's track.

Process studies formed an integral part of both the SIPEX and SIMBA programs, including the deployment of two arrays of GPS-tracked drifting buoys to measure ice drift and dynamics (SIPEX) and ice mass balance stations to measure *in situ* changes in ice and snow thickness over a 30 day period (SIMBA). Geophysical measurements assessed the presence of flooded sea ice; ice structure, including the presence of snow ice, was determined from laboratory analysis of sea ice cores. Biogeochemical analyses were conducted to measure, among other things, the accumulation of iron in the sea ice and the processes by which it is concentrated from the water column during ice growth. The brine channel structure of the ice and its importance for biological and biogeochemical processes was also examined using standard geophysical techniques.

Research highlights

The IPY programs afforded a rare opportunity to conduct coincident field studies in the Antarctic pack ice, on different sides of the continent. The results show that the sea ice in east Antarctica was more dynamic, swell affected and more heavily deformed in some areas than in west Antarctica where more compact, homogenous ice was encountered, particularly at the southern-most end of the ship transect. The *in situ* ice and snow thickness data show generally good agreement with the satellite data, but provide new insights into the buoyancy theory calculations used to calculate sea ice thickness from satellite freeboard measurements (Worby et al., in press; Xie et al., in press). In particular, the relationship between ice and snow thickness varies between the two study regions. Negative ice freeboards were common in both east and west Antarctica, as was the formation of flooded layers and snow ice, however, an empirical relationship equating mean freeboard to mean snow thickness appears to hold generally for west Antarctica, but not for the heavily ridged areas in east Antarctica. The regional differences in sea ice and snow thickness distribution, and their formation processes, indicate that a regionally (and perhaps seasonally) varying empirical relationship for converting satellite-derived snow freeboard to ice thickness must be developed. Field results from SIPEX showing the use of radar for measuring ice freeboard and the complications caused by internal layering of the snow cover have been reported by Willatt et al., (2010). Intrusions of warm air can cause surface melt and the subsequent formation of icy layers within the snow structure. These, in addition to the effects of floe ridging caused by larger-scale ice dynamics, also result in seasonal changes that must be taken into account when interpreting satellite altimetry data (Giles et al., 2009).

Stammerjohn et al., (in press) showed a regional and circumpolar assessment of sea ice conditions from satellite data during IPY that provides the contextual environmental setting for the field campaigns. The results show clearly how winds, sea ice drift, sea surface temperature and precipitation affected regional ice conditions during IPY. The *in situ* measurements reflect a number of these regional changes. For example, Meiners et al., (in press) shows for the SIPEX region in east Antarctica that bottom ice algal biomass has a wide range of values and is generally dominated by pennate diatoms. Chlorophyll A concentrations in the lower-most 0.1 m of the sea ice contributed, on average, 63% to the integrated sea ice standing stocks. Nevertheless, the results indicate that East Antarctic sea ice has generally low algal biomass accumulation due to a combination of effects, including low snow-loading, low porosity and a relatively early break-up that prevents the development of significant internal and surface communities. The more southerly, consolidated, less dynamic sea ice in the SIMBA region of west Antarctica was generally thicker and had a heavier snow cover (Lewis et al., in press).

A key research activity as part of IPY has been the development by the Australian program of an airborne imaging capability that integrates a laser altimeter, snow radar and digital camera with an inertial navigation system. The system is designed to fly in a helicopter and, when fully operational, will provide regional ice and snow thickness data over horizontal scales of tens of metres to hundreds of kilometres (Fig. 2.3-14). IPY has provided a genuine push in the development of the system, which provides an intermediate scale

Fig. 2.3-13. An ice thickness transect across an ice floe in East Antarctica out during the IPY project SIPEX onboard Aurora Australis, between 110°E and 130°E in September-October 2007. Sea ice and snow cover thickness were measured *in situ* and related to aircraft measurements. The black strip at the beginning of the transect is mesh sheet that acts as a radar reflector for the aircraft.
(Photo: Anthony Worby)

and resolution of data between highly localised *in situ* measurements and coarser resolution satellite data. The work conducted during IPY will be crucial for the calibration and validation of new satellite sensors, such as the radar altimeter aboard CryoSat-2 which came online during 2010.

Turner et al., (2009a) analysed sea ice patterns in relation to climate parameters to show that the growth in Antarctic sea ice extent, by around 1% per decade since the late 1970s, seemed to be controlled by a 15% increase in the strength of circumpolar winds, which were in turn driven by winds propagating down to the surface from the polar vortex around the ozone hole in summer and autumn. The stronger winds also accentuate the Amundsen Sea Low, which brings warm air south down the Antarctic Peninsula, melting or delaying the onset of sea ice there. These winds then pass over West Antarctica cooling as they go, to emerge cold over the Ross Sea where they cause sea ice to grow. The decrease in sea ice in the one area is more or less balanced by the increase in the other area.

Summary and Legacy

During IPY, the Southern Ocean was measured in a truly comprehensive way for the first time. IPY measurements spanned the circumpolar extent of the Southern Ocean, from the subtropical front to the Antarctic continental shelf. Many measurements (e.g. Argo, marine mammal tags and moored time-series) covered the full annual cycle. New technologies allowed many characteristics of the Southern Ocean to be measured for the first time, including ocean currents and properties beneath the sea ice, trace metal concentrations throughout the full ocean depth and the discovery of many new species. Perhaps most importantly, the IPY activities spanned all disciplines of Southern Ocean science, providing the integrated observations that are essential to address questions of high relevance to society, including climate change, ocean acidification and the future of the Southern Ocean ecosystem. The multi-disciplinary view of the state of the Southern Ocean obtained during IPY provides a benchmark against which past and future measurements can be compared to assess rates of change. This achievement was the result of the work of hundreds of scientists from numerous nations.

IPY aimed to determine the present environmental status of the polar regions; to understand past and present change in the polar regions; to advance our understanding of polar-global teleconnections; and to investigate the unknowns at the frontiers of science

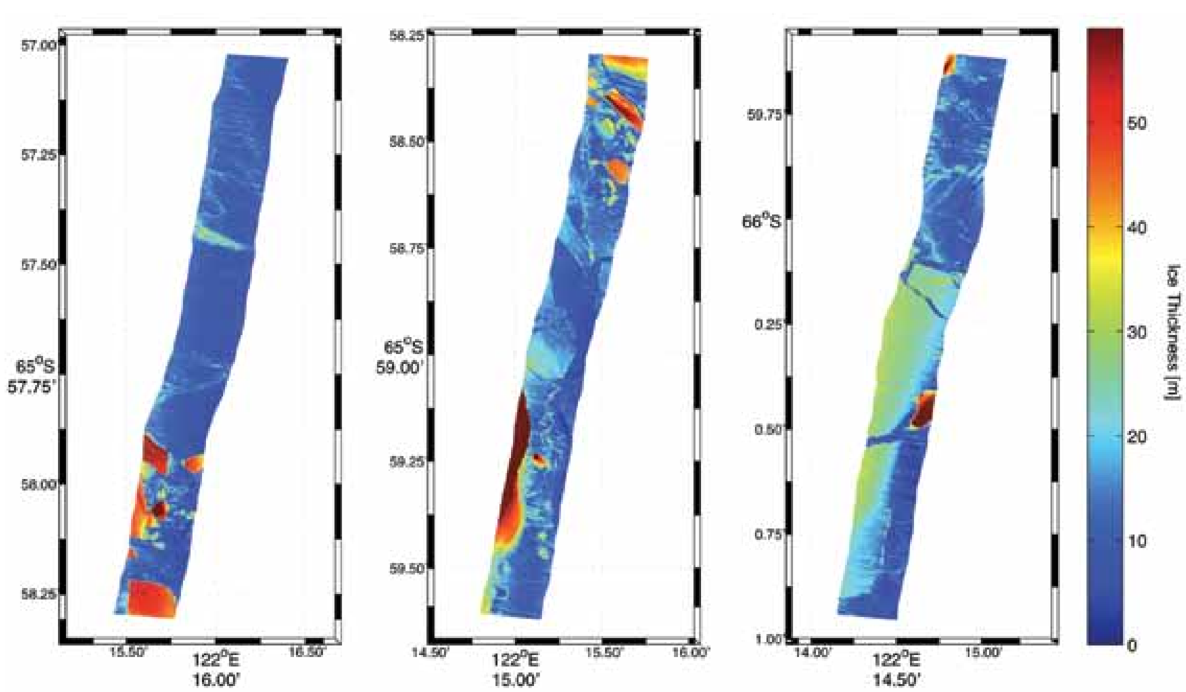


Fig. 2.3-14. Laser altimeter swath over Antarctic fast ice (and grounded icebergs) during the IPY SIPEX experiment, showing freeboard height (the height of the ice or snow surface above sea level).
(Graph: J. Lieser)

in the polar regions. Southern Ocean IPY has made a significant contribution to achieving all four of these aims. Much of the research in the Southern Ocean has been closely coordinated with similar activities in the Arctic, which together provide the integrated bipolar perspective required to address the goals of IPY.

Southern Ocean IPY leaves a number of legacies. First and foremost, Southern Ocean IPY has demonstrated that an integrated, multi-disciplinary, sustained observing system is feasible, cost-effective and urgently needed (Rintoul et al., 2010a,b; Turner et al., 2009b). Other legacies include a circumpolar snapshot to serve as a benchmark for the assessment of past and future change; models capable of simulating interactions among climate, ecosystems and biogeochemical cycles, providing vastly improved projections of future change; a well-integrated interdisciplinary and multi-national polar research community; and inspiration to a new generation of polar researchers.

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2.4 Greenland Ice Sheet and Arctic Glaciers

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Background

The Arctic Climate Impact Assessment (ACIA, 2005), which was released at the time that IPY 2007–2008 was being planned, provided an exhaustive compilation of the ongoing warming in the Arctic and the consequent decrease in sea ice, increased surface melt on the margins of the Greenland Ice Sheet, shrinking Arctic glaciers, degradation of permafrost, and many impacts on ecosystems, animals and people. The Arctic was observed to be warming much faster than temperate regions of the planet, possibly because of the positive surface albedo feedback whereby reduced sea ice, in particular, increases solar heat absorption. There were indications that, in the decade prior to IPY, the rate of reduction of many Arctic terrestrial ice masses had accelerated.

The IPY *Framework* document (Rapley et al., 2004) clearly identified determination of the status and change to Arctic ice as a key objective. The total terrestrial ice volume in the Arctic is estimated at 3.1 million km^3 (Dowdeswell and Hagen, 2004), or about 8 m of sea level equivalent, most of which is in the Greenland ice sheet, the largest body of freshwater ice in the Northern Hemisphere. Greenland will be highly susceptible to continued warming over coming decades and centuries, and quantification of the ice sheet mass balance and the consequent changes to global sea level were a key goal of IPY.

Improved estimates of the Greenland mass balance would be based upon a variety of techniques including large-scale surface and airborne observational projects, in conjunction with space observations. Satellite-borne sensors would provide a unique snapshot and new satellite systems available during IPY included the laser altimeter on ICESat and the Gravity Recovery and Climate Experiment (GRACE) satellite mission. Airborne and over-snow surveys would also image ice sheet internal features and, together with the ground measurements, could be used to link the data records from the major deep ice core sites on the ice sheet. Automatic instruments would be deployed in remote regions by air or during over-snow surveys.

As noted above, the future response and stability of Greenland to ongoing warming need to be better understood to project future global sea level rise. Warming above a certain "threshold" level will cause the surface mass balance of the ice sheet to become negative every year, with more mass lost by surface melt than is gained from snowfall. The ice sheet would thus thin and reach a state of "irreversible" decline. This mass loss from surface processes could be compounded by increased ice discharge to the ocean. Over the past decades, many of Greenlands fast-flowing glaciers and ice streams have accelerated dramatically, with observations showing that ice discharge can double within one to two years, and may also be slowed. The dynamic processes controlling the discharge are poorly understood, but possible causes are the impact of relatively warm ocean currents on the stability of glacier termini and the effect of surface melt water penetrating to the glacier base and enhancing ice flow by lubrication. These issues were also identified as IPY topics.

The Greenland Ice Sheet contains an important archive of palaeoclimatic information within the ice. Previous deep ice core drilling and analysis programs in Greenland have provided an outstanding record of so-called Dansgaard-Oeschger events; very abrupt, millennial-scale, climatic shifts that occurred during the last glacial period. Understanding the cause of these events has implications for predicting future change. Nevertheless, none of the previous ice cores from Greenland provided an undisturbed climate record of the last interglacial, the Eemian, which occurred between about 115,000 and 130,000 years ago and was warmer in the Arctic than our present interglacial period. Obtaining a record of this period from Greenland was an important IPY target.

About 50% (in number) of all world glaciers and ice caps are found in the Arctic and, although the surface area of the Greenland ice sheet is about four times the area of all other Arctic glaciers and ice caps, the smaller ice masses are generally at lower elevation and have warmer mean annual temperatures, and so are susceptible to greater percentage mass loss in response to warming. Globally, glaciers and ice caps, including those surrounding the Greenland and Antarctic ice sheets, store ~ 0.5 to 0.7 m of sea level equivalent, and are currently contributing at about the same rate to sea level rise as the combined contributions from the ice sheets in Greenland and Antarctica (IPCC, 2007). They will continue to contribute into the 21st century and beyond. Many of the Arctic glaciers and ice caps terminate in the oceans and 30-40% of their mass loss is from iceberg calving. Nevertheless, the uncertainty both in the surface mass balance and the calving fluxes of the Arctic glaciers is still large. Hence, IPY aimed to obtain baseline glaciological data on extent, dynamics and mass balance of the irregularly distributed Arctic ice masses in regions such as Alaska, the Canadian Arctic, Iceland, Svalbard, Franz Josef Land, Novaya Zemlya, Severnaya Zemlya and northern Scandinavia. The variations in space and time of the monitored ice bodies in polar and mountain regions could then be extrapolated to estimate regional contributions to sea level change and linked to the global hydrological cycle.

Developing Greenland and Arctic Glacier IPY projects

The ICSU-WMO call for "Expressions of Intent" (EoI) for IPY projects elicited approximately 30 EoIs between November 2004 and January 2005 which were focused on the terrestrial ice masses of the Arctic. These can be broadly categorized into five groups.

- Characteristics and status of the Greenland ice sheet. This group included EoIs 74, 94, 581, 607, 883, 933, 951 and 1120.[1] Two geoscience EoIs, 763 and 784, were also linked to this group as they planned to share logistics to explore the geophysics of Greenland, including characteristics of the bedrock beneath the ice sheet.
- Future response and stability of Greenland. This included EoIs 69, 136, 187, 245, 334, 381, 418 and 765.
- The record of past environments from Greenland ice cores; EoIs 62, 203 and 561.
- Satellite remote sensing of the Greenland ice sheet; EoI 910, which was bipolar and also included study of the Antarctic ice sheet.
- Changes to Arctic glaciers and ice caps; EoIs 30, 233, 654, 684, 756 and 1007.

Over the next several months the proponents of these EoIs, encouraged by the IPY Joint Committee and the International Programme Office, worked to combine their ideas and resources into larger full IPY proposals. Ultimately, seven full proposals that dealt with the Arctic ice sheets and glaciers were endorsed by the IPY Joint Committee (JC) in 2005–2006 (Allison et al., 2007; *Chapter 1.5*).

Two of these (no. 91 and no. 125 - see below) were satellite remote sensing projects that also included investigation of the Antarctic, and two were "umbrella" projects submitted on behalf of international organizations. These latter projects, which generally did not propose specific research activities but sought to synthesize the results of other relevant projects in the Arctic and Antarctic, were no. 105 (State and Fate of the Polar Cryosphere) linked to the WCRP Climate and Cryosphere (CliC) Project, and no. 117 (International Partnerships in Ice Core Science - International Polar Year Initiative) linked to the International Partnerships in Ice Core Science.

IPY projects on the Greenland ice sheet

IPY project no. 118 (The Greenland Ice Sheet – Stability, History and Evolution), led by scientists from Denmark and U.S.A., was a very large and multi-faceted study that linked palaeoclimate, observational and modelling components to investigate past and future stability of the Greenland Ice Sheet, ice dynamics, sea level change and change in fresh water supply to the ocean, which affects the global thermohaline circulation of the ocean. Airborne measurements with a radar capable of array processing in the cross-track direction and synthetic aperture radar (SAR) processing in the along-track direction for sounding of ice and imaging the ice-bed interface, and scanning laser ranging (lidar), were planned to provide baseline measurements of the discharge of ice from outlet glaciers around the margin of the Greenland Ice Sheet. These measurements would also allow detection of elevation changes by comparison to earlier airborne missions and to satellites (CryoSat, ICESat). Automatic weather and mass balance stations were to be located on the ice in order to relate mass balance changes with meteorological conditions and to investigate the ablation processes in detail. In addition, the radar profiles would be used to map the melting under the ice in north Greenland and under the fast moving glaciers and ice streams, allowing inclusion of basal melt in the mass balance of the ice sheet. Traverses and field camps were proposed to collect GPS and geophysical data (magnetic, gravity), seismic profiles, and borehole logging and ice drilling along air survey routes. Combined with satellite data, they would be used to determine the crustal structure in Greenland and history of the sub-ice bedrock and sediments, and hence to map the heat flow and basal melt beneath the ice sheet. The dynamics of the ice stream Jakobshavn Isbrae, which has recently accelerated, was to be investigated using borehole instrumentation reaching to the base. Detailed studies of the response of ice dynamics in West Greenland to changes in surface melt through the penetration of runoff to the glacier bed were also proposed (Fig. 2.4-1).

The North Eemian Ice Core Project (NEEM) was a major component of the overall work plan of "The Greenland Ice Sheet – Stability, History and Evolution" project. NEEM aimed at retrieving an ice core from northwest Greenland (77.45°N, 51.06°W) reaching back through the previous interglacial, the Eemian, during part of which the Arctic was warmer than the Holocene, thus offering an analogy for the conditions expected in the Arctic due to an anthropogenically-warmed world. It was also hoped that the Holocene period from this deep ice core would provide a better isotopic record of the present climate than those from

Fig. 2.4-1. Surface melt water penetrating the interior of the Greenland Ice Sheet via a moulin. (Photo: K. Steffen)

other Greenland ice cores. The deep NEEM core was to be supplemented with a series of shallow to intermediate length ice cores providing information on the climate during the last thousand years. Many of these were planned at existing core sites, which would be revisited, to extend the available climate records from these up to modern times with new shallow cores.

Another endorsed IPY project focused on the Greenland Ice Sheet was called 'Measurement and Attribution of Recent Greenland Ice Sheet chaNgeS' (MARGINS, IPY no. 339), led by researchers from the U.S.A. and U.K. This sought to improve communication, coordination and collaboration among a diverse collection of proposed research initiatives, which were aimed at understanding the changes in surface elevation and discharge speed in outlet glacier systems along the margins of the Greenland Ice Sheet. These studies covered a range of activities from expansions of ongoing efforts to new projects, from individual investigators to consortia of several nations, and a range of observational and modeling techniques exploiting evolving capabilities in atmospheric modeling, remote sensing for measurement of ice motion and surface conditions, and surface-based and aircraft-based measurements.

IPY 2007–2008 occurred at a time when new sophisticated and dedicated space-borne instruments were available to directly detect changes to the Greenland and Antarctic ice sheets by measuring gravitational and surface elevation changes. These missions had been initiated well before IPY and, although the scientists involved in these worked closely with those IPY projects making *in situ* ice sheet observations, they did not generally seek IPY endorsement. One exception, however, that did seek and receive IPY endorsement was the project "Antarctica & Greenland ice and snow mass balance by GRACE satellite gravimetry" (IPY no. 125) led by France.

Nevertheless, a very significant contribution to IPY was the coordination of diverse satellite observations made within the 'Global Inter-agency IPY Polar Snapshot Year' project (GIIPSY, IPY no. 91). The objective of GIIPSY was to coordinate space-borne observation of the polar regions and polar processes in order to maximize the scientific benefit and to obtain a benchmark of processes during IPY. The GIIPSY science community was linked to national and international space agencies through the Space Task Group (STG) of the IPY Subcommittee on Observations (*Chapter 3.1*). The GIIPSY project aimed to target satellite data acquisitions towards those science problems best served by a focused, time-limited data campaign and by the availability of diverse but integrated observations. A primary data acquisition objective was to obtain pole-to-coast multi-frequency interferometric SAR measurements for determining the ice surface velocity over Greenland and Antarctica. GIIPSY planned to contribute to other IPY activities by making the resulting data and derived products available to the international science community.

IPY projects on Arctic glaciers and ice caps

The status of, and changes to, Arctic glaciers and ice caps were addressed by the project 'The dynamic response of Arctic glaciers to global warming' (GLACIODYN, IPY no. 37), coordinated by the Netherlands and Norway. The overall aim of GLACIODYN was to reduce the uncertainties in estimates of the contribution of Arctic glaciers and ice caps to sea level change.

A key question was to what extent a warmer climate may also change the dynamics of the glaciers and not only near-surface processes such as snow accumulation, refreezing both internally and of superimposed ice, and ablation. This involves including iceberg calving in mass budget calculations, improving understanding of calving and basal sliding processes and including dynamics in modeling the future response of glaciers. The specific objectives to achieve this were to: (1) study the current mass budget of selected target glaciers, including the surface mass balance and the calving flux where applicable; (2) study sub-glacial processes such as sliding and basal hydrology; (3) study calving processes; (4) include the dynamics in modeling of future response; and (5) predict future changes of the ice cap or glacier.

Predictions of future mass balance and dynamic response require knowledge of boundary conditions such as the thermal structure of the ice, the surface mass balance, meteorological data, surface and bed topography, and ice flow. These were addressed by field and remote sensing investigations.

The GLACIODYN proposal was based on an already established network of glaciologists who were members of the IASC Working Group on Arctic Glaciology (IASC-WAG; now called the IASC Cryosphere WG). The annual IASC-WAG meetings and subsequent GLACIODYN workshops were the main venues for discussion of results, planning of combined fieldwork and shaping of the output. A GLACIODYN workshop has been held every year during and since IPY.

Research groups from 17 countries contributed to GLACIODYN. However, the funding was derived from national research councils and varied considerably from country to country. Strong support was received in Canada, The Netherlands, Norway, Denmark, Russia and Poland, with more limited support in Sweden, Finland, Germany, U.K., Iceland and U.S.A., however, all 17 countries contributed in some way to the project.

IPY field and analysis activities of Arctic terrestrial ice, 2007–2010

The Greenland ice sheet

Numerous resources were allocated to augment our understanding of the mass and energy balances of the Greenland ice sheet through improved data on snow-ice accumulation, run-off and bottom melting as well as iceberg production. In 2007, 19 different field teams were deployed and active on the ice sheet; 13 of them funded by the National Science Foundation and headed by U.S. scientists, and six funded by Europe and headed by scientists from Denmark, United Kingdom, Norway and the Netherlands.

In addition, NASA regularly made low-level flights with laser altimeters over the ice sheet to update data on ice volume changes. The U.S., Denmark and Greenland shared efforts to operate more than 20 automatic, satellite-linked weather stations that monitor and record climate parameters on all parts of the ice sheet (Fig. 2.4-2).

An increasing research focus was directed to the surging glaciers in southeast Greenland and, in particular, to Ilulissat Glacier that had shown remarkable change in the five years prior to IPY. Research teams from the U.S., Germany and Denmark measured the ice stream dynamics, mapped the morphology of the extensive sub-glacial trough beneath the trunk, calculated the annual discharge and the catchment area, and modelled how this unique glacier may behave in the future.

Scientists from 14 nations participated in the NEEM ice coring activity, the most international ice core effort to date. More than 300 ice core researchers, including many young scientists, rotated through the NEEM camp during the four years of field operations. Like all deep ice coring projects, NEEM was a multi-year effort requiring massive logistic support. In

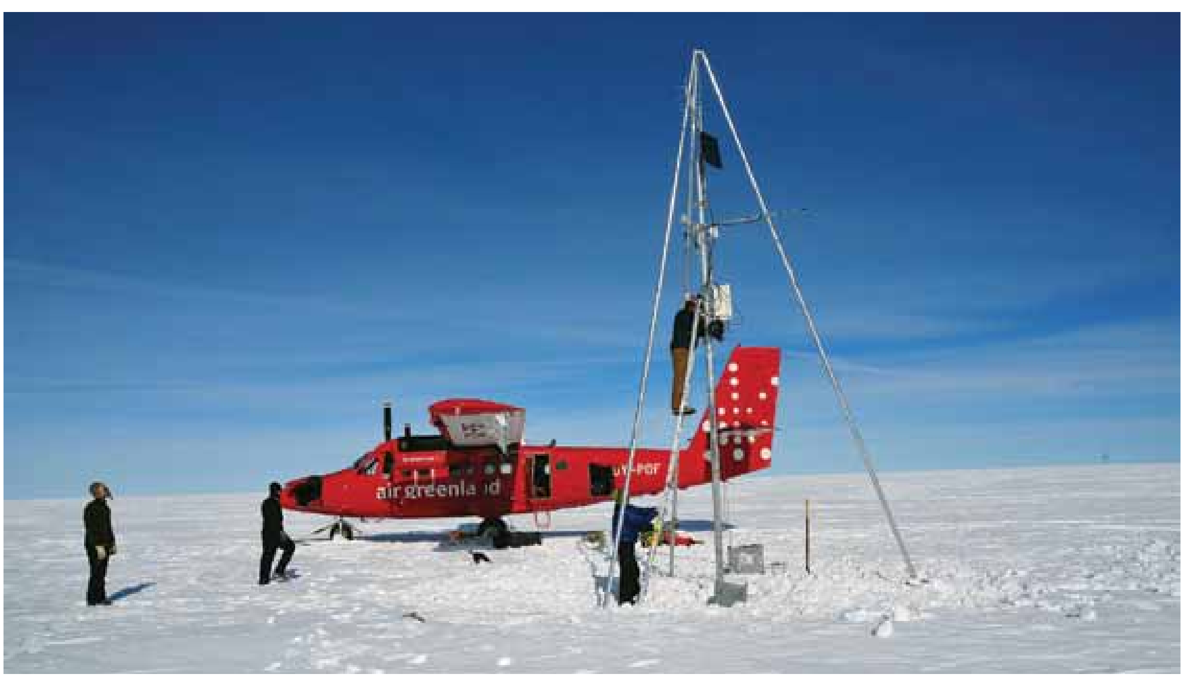


Fig. 2.4-2. Deploying an automatic weather station on the Greenland ice sheet during IPY. (Photo: K. Steffen)

Fig. 2.4-3. The newly completed NEEM camp, August 2008.
(Photo: NEEM ice core drilling project, www.neem.ku.dk)

Fig. 2.4-4. Drilling a shallow ice core near the NEEM site on the Greenland Ice Sheet, July 2008.
(Photo: NEEM ice core drilling project, www.neem.ku.dk, Henning Thing)

July 2007, the first IPY year, an international traverse team transferred heavy equipment from a previous Greenland deep drilling site (NGRIP) to the NEEM site. They undertook radar and GPS surveys and collected shallow ice cores along the route, and made a detailed radar survey over a 10-km by 10-km area to locate the best site for the NEEM core. A seed camp and a skiway were constructed at the chosen site. In 2008, the living, drilling and core analysis facilities were established at the NEEM site (Fig. 2.4-3). Shallow test cores were collected at the NEEM site in the 2008 season (Fig. 2.4-4), but it was not till mid May 2009, after the end of the formal IPY fieldwork and observation period that the deep ice coring commenced at NEEM. Drilling continued more or less continuously throughout the 2009 season and by the end of the season in October, the borehole depth had reached 1758 m. Bedrock was not finally reached, at 2537 m depth, until 27 July, 2010. The full core contained ice from the warm interglacial Eemian period, 130,000 to 115,000 years before present, and even older ice was recovered. The bottom 2 m of ice contained rocks and other material that has not seen sunlight for hundreds of thousands of years, and is expected to be rich in DNA and pollen that can tell us about the plants that existed in Greenland before the site became covered with ice, perhaps as long as 3 million years ago.

Detailed measurements were made on the NEEM core in a sub-surface science trench as the core was extracted. State-of-the-art laser instruments for water isotopes and greenhouse gases, online impurity measurements and studies of ice crystals are among the impressive instruments deployed at the NEEM site, at one of the most inaccessible parts of the Greenland ice sheet. Full laboratory analysis of the NEEM ice core, however, has only just commenced.

In September 2007, a survey of the ice sheet was conducted out of Thule and Sondrestrom from a NASA P-3B (Orion) aircraft as a part of the NASA Instrument Incubator Program and as a continuation of NASA measurements to monitor the Greenland ice sheet. A 150/450 MHz ice radar system, developed by the Center for Remote Sensing of Ice Sheets (CReSIS) at the University of Kansas, was used to conduct this survey, with six receiving antennas and two transmitting antennas, which enabled formation of interferometric SAR images with variable baselines. The project was a collaborative effort between the Ohio State University, the Jet Propulsion Laboratory, VEXCEL Inc. and the University of Kansas, and was aimed at demonstrating the concept of sounding ice and imaging the ice-bed interface with orbital radars. The aircraft was flown at altitudes as high as 6700 m above sea level and as low as 500 m above the ice sheet surface. Flight lines were designed to capture surface clutter conditions across outlet glaciers discharging into the ocean, down the length of the floating portions of Petermann and Jakobshavn glaciers, and to cross from the wet percolation facies of the ice sheet into the dry snow zone. A flight extending from Camp Century to Dye-2 passing over the NEEM, NGRIP, GISP-2, GRIP and DYE-2 ice-core sites was also conducted with the primary objective of connecting all the deep ice cores with the radar operating at 150 MHz. The 2007 flight lines are shown in Fig. 2.4-5.

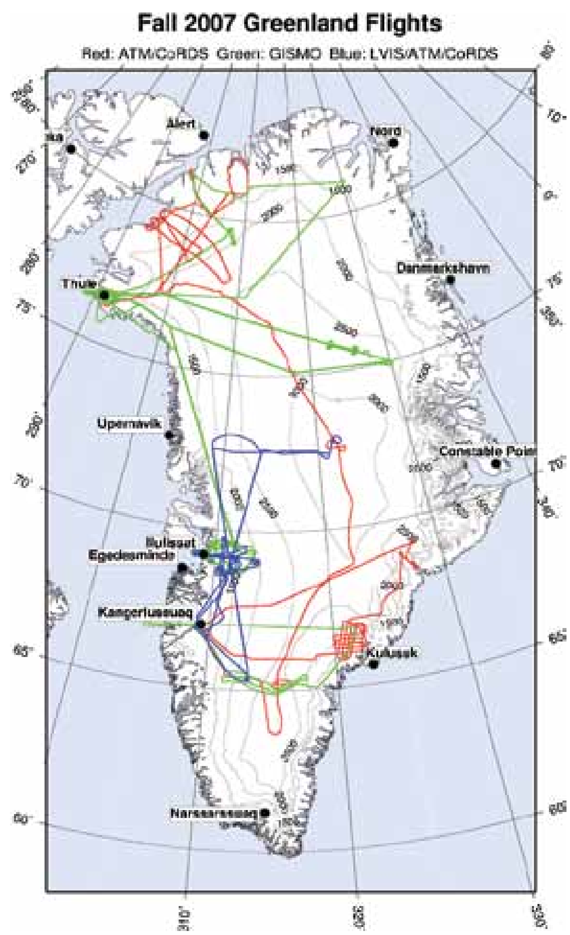


Fig. 2.4-5. Greenland aerial radar survey lines in 2007 (IPY no. 118). The red central flight line, extending from Camp Century to Dye-2, was flown to obtain radar data to connect ice cores.
(Courtesy: Center for Remote Sensing of Ice Sheets, U. Kansas)

In July-August 2008, a Twin Otter aircraft fitted with the CReSIS radars and a NASA Airborne Topographic Mapping laser system was deployed to Ilulissat, Greenland. This undertook an extended survey of the Jakobshavn Isbræ (Fig. 2.4-6) which involved 88.9 flying hours and the collection of 9.0 Terabytes of data along more than 19,000 kilometers of survey grid. Despite severe surface melt conditions, the radar was able to map the basal channel of the ice stream. This survey was supplemented with additional Twin Otter flights during April 2009 over three major outlet glaciers — Jakobshavn, Helheim and Kangerdlugssuaq — to more accurately define the bed topography. The data collected during 2007-2009 over these glaciers have been combined with earlier measurements made as a part of the NASA Program for Arctic Climate Assessment (PARCA) to produce bed topography maps for these glaciers. Figs. 2.4-7 and 2.4-8 show the resulting bed maps for Jakobshavn and Helheim glaciers, respectively.

A small, surface survey grid around the NEEM coring site was made with sled-mounted InSAR radar to map the ice sheet bed in order to ensure the suitability of the drilling site for obtaining undisturbed Eemian ice. These data are processed to generate the 3-D topography of the ice bed (Fig. 2.4-9). Surface radar traverses were also made toward the NGRIP and Camp Century former drilling sites.

Arctic glaciers and ice caps

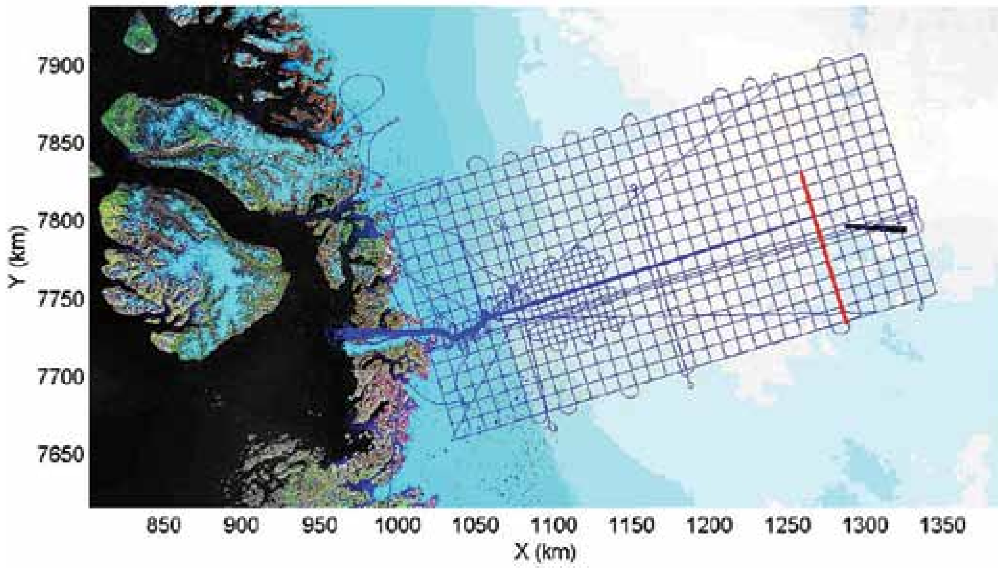
The GLACIODYN project identified a set of target glaciers for intensive observations (*in situ* and from space) for the period 2007-2010 (Fig. 2.4-10). These glaciers covered a wide range of climatic and geographical settings and took maximum advantage of prior long-term studies. The target glaciers were:

- Academy of Sciences Ice Cap (Severnaya Zemlya, Russia)
- Glacier No. 1 (Hall Island, Franz Josef Land, Russia)
- Austfonna (Svalbard, Norway)
- West Svalbard tidewater glaciers: Hansbreen, Kronebreen (Fig. 2.4-11), Kongsvegen, Nordenskiöldbreen, Norway
- North Scandinavia transect: Langfjordjøkelen, Storglaciären, Marmaglaciären (Norway and Sweden)
- Vatnajökull, Hofsjökull and Langjökull icecaps (Iceland)
- Kangerlussuaq basin (West Greenland)
- Hellheim Glacier (East Greenland)
- Devon Ice Cap (Canada)
- McCall Glacier (Alaska, U.S.A.)
- Hubbard Glacier and Columbia Glacier (Alaska, U.S.A.).

Since the funding varied in different countries the field programs on these glaciers also varied in scope.

The two large ice caps, Devon Ice Cap (14,400 km^2) in the Canadian Arctic and Austfonna Ice Cap (8,000 km^2) on Svalbard were both studied in detail for the first time. These are two of the largest ice masses outside the polar ice sheets. Similar field programs were conducted on both ice caps, and included measurements of surface mass balance by ablation stakes, snow cover distribution by ground penetrating radar, topography changes by surface GPS profiles combined with airborne data and satellite data, and ice dynamics studied by ground GPS-stations running continuously year round combined with remote sensing data (Fig. 2.4-12). Both ice caps were also selected as calibration/validation sites for the new ESA CryoSat II altimetry satellite that was launched in April 2010 and these investigations continue beyond IPY. An analysis of changes since the IGY in the extent of all Yukon Glaciers, Canada, was also made as part of the "State and Fate of the Cryosphere" project (IPY no. 105).

Russian scientists contributed to the work of GLACIODYN through three sub-projects. The subproject *Current state of glaciers and ice caps in the Eurasian Arctic* investigated the area changes, mass balance, hydrothermal state and potential instability of glaciers and ice caps in the Russian Arctic islands and Svalbard. The main fieldwork during IPY included airborne and surface radio echo-sounding surveys of ice thickness, bedrock and surface topographic surveys of ice caps and glaciers, which were supported by analysis of satellite remote sensing data. The subproject *Formation, dynamics and decay of icebergs in the western sector of the Russian Arctic* collected new data on the formation, distribution and properties of icebergs in the Barents and Kara Seas, and estimated the current state of outlet glacier fronts in the Russian Arctic archipelagos. In September 2007, iceberg-producing glaciers on Franz Josef Land, Novaya Zemlya and some other islands were surveyed from the Russian research vessel *Mikhail Somov*. Helicopter



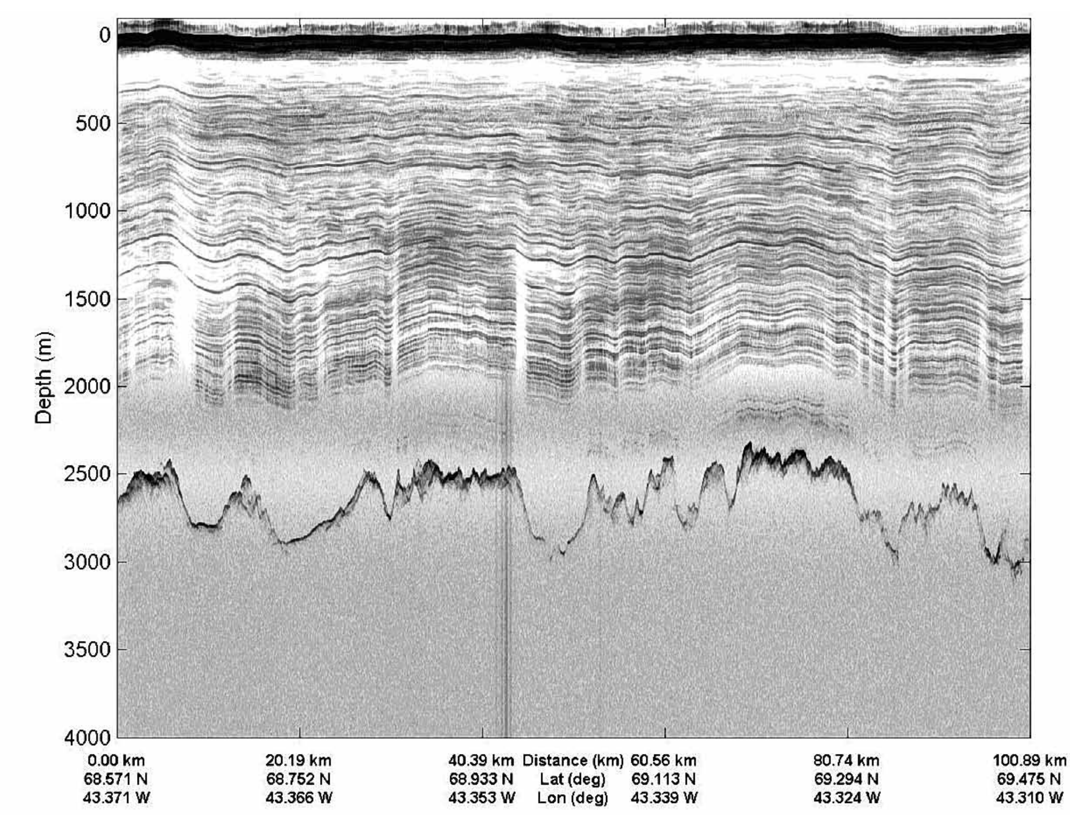
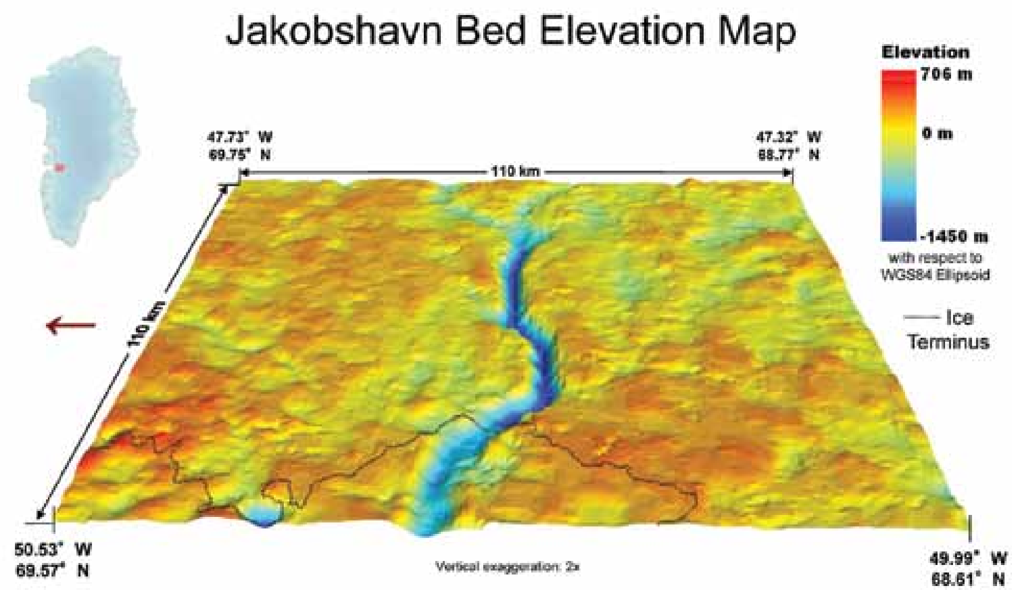


Fig. 2.4-6. Grid over which data were collected for Jakobshavn Isbræ during 2008 (top) and a sample echogram for one of the flight lines highlighted in red (bottom).

(Courtesy: Center for Remote Sensing of Ice Sheets, U. Kansas)

Fig. 2.4-7. Bed topography map for Jakobshavn Isbrae generated by combining 2008 and 2009 radar data with other data sets [Plummer et al., in review].
(Courtesy: Center for Remote Sensing of Ice Sheets, U. Kansas)



radio echo sounding and aerial photography surveys were made of glaciers across the Franz Josef Land archipelago, on Prince George Land, Salisbury Island, Luigi and Champ Islands, Hall Island and Wilczek Land. Observations were also made on some glaciers of ice movement, the vertical distribution of ice temperature (down to 20 m depth) and surface energy balance. The glaciological studies were supplemented with oceanographic temperature and salinity profiling in the Franz Josef Land straits. A similar survey, which was repeated in fall 2008, was undertaken of the glaciers of the northern end of the Northern Island of Novaya Zemlya (Buzin et al., 2008). Another Russian sub-project, *Climatic factors in the contemporary evolution of Northeast Siberia glaciations,* continued studies of climate–glacier interactions in the poorly explored region of Northeast Siberia. The climate of this region is influenced by both Atlantic and Pacific air masses. Climatic changes such as weakening of the Siberian High, increase of surface temperature and changes in the cryosphere have recently been detected there.

In Iceland, a major IPY activity involved digital terrain mapping of the surface topography of Icelandic ice caps with lidar. The results from this work, which continues after IPY, will be used to compare photographic maps from 1990s to quantify the ice volume changes that have occurred to these ice caps over the last 10-20 years.

Research Highlights

The Greenland ice sheet

Since 1985, West Greenland has experienced a warming of 2 to 4°C, primarily driven by winter temperature anomalies. The few and scattered direct climate records from observations on the Greenland Ice Sheet also reveal a warming trend since 1985. As a result, the mass balance of the Greenland Ice Sheet has changed. The high interior parts of the ice sheet have thickened because of the increased snowfall, with the area above 2000 m elevation having gained an average of 5 (±1) cm in altitude each year since 2000. This has added 60 (±30) Gt of mass to the ice sheet annually.

Nevertheless, this mass gain is more than offset by the increased loss of ice mass from melting and by discharge into the ocean. About half of the total mass loss from the Greenland Ice Sheet is caused by surface melt and run-off, but the area experiencing surface melting has increased significantly in extent since 1979. The annual net gain in surface mass (snowfall minus mass lost by melt), has a 50-year average value of 290 Gt, but has been reduced by 45 Gt over the past 15 years, a trend that is above the background variability caused by normal fluctuations in climate. Mass is also lost at the margin of the Greenland Ice Sheet, mostly from fast-flowing outlet glaciers and ice streams that discharge into the ocean. Many of these have experienced accelerated flow and the annual mass loss through ice discharge has increased by 30%, from 330 Gt in 1995 to 430 Gt in 2005.

The total loss in ice sheet mass, the difference between net surface mass balance and ice discharge, has increased in recent years from 50 (±50) Gt/yr in the period 1995-2000, to 160 (±50) Gt/yr (equivalent to 0.44±0.14 mm/yr of sea level rise) in the period 2003-2006.

An improved regional atmospheric climate model, with a horizontal grid spacing of 11 km and forced by ECMWF re-analysis products, has been developed to better represent processes affecting ice sheet surface mass balance, such as melt water refreezing and penetration (Ettema et al., 2010). This was used to simulate 51 years (1957–2008), and the temporal evolution and climatology of the model was evaluated against *in situ* coastal and ice sheet atmospheric measurements of near-surface variables and surface energy balance components. The model has been shown to be capable of realistically simulating the present-day near-surface climate of Greenland, and is a suitable tool for studying recent climate change over the ice sheet.

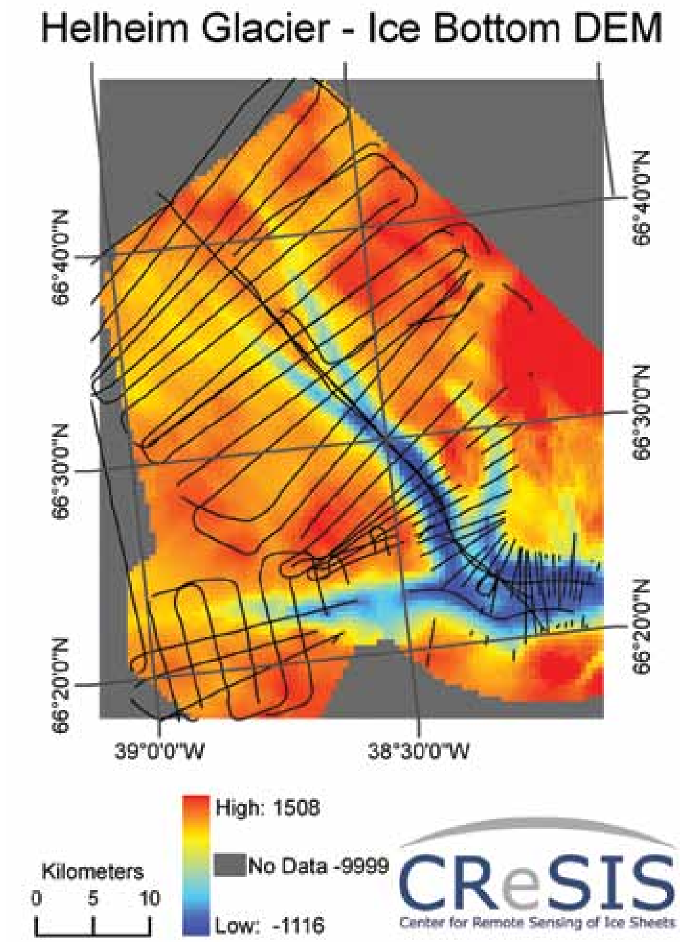


Fig. 2.4-8. Ice-bed topography for the Helheim Glacier with superimposed flight lines over which discernable bed echoes were obtained. These data were collected from a Twin Otter aircraft by CReSIS during April 2009.

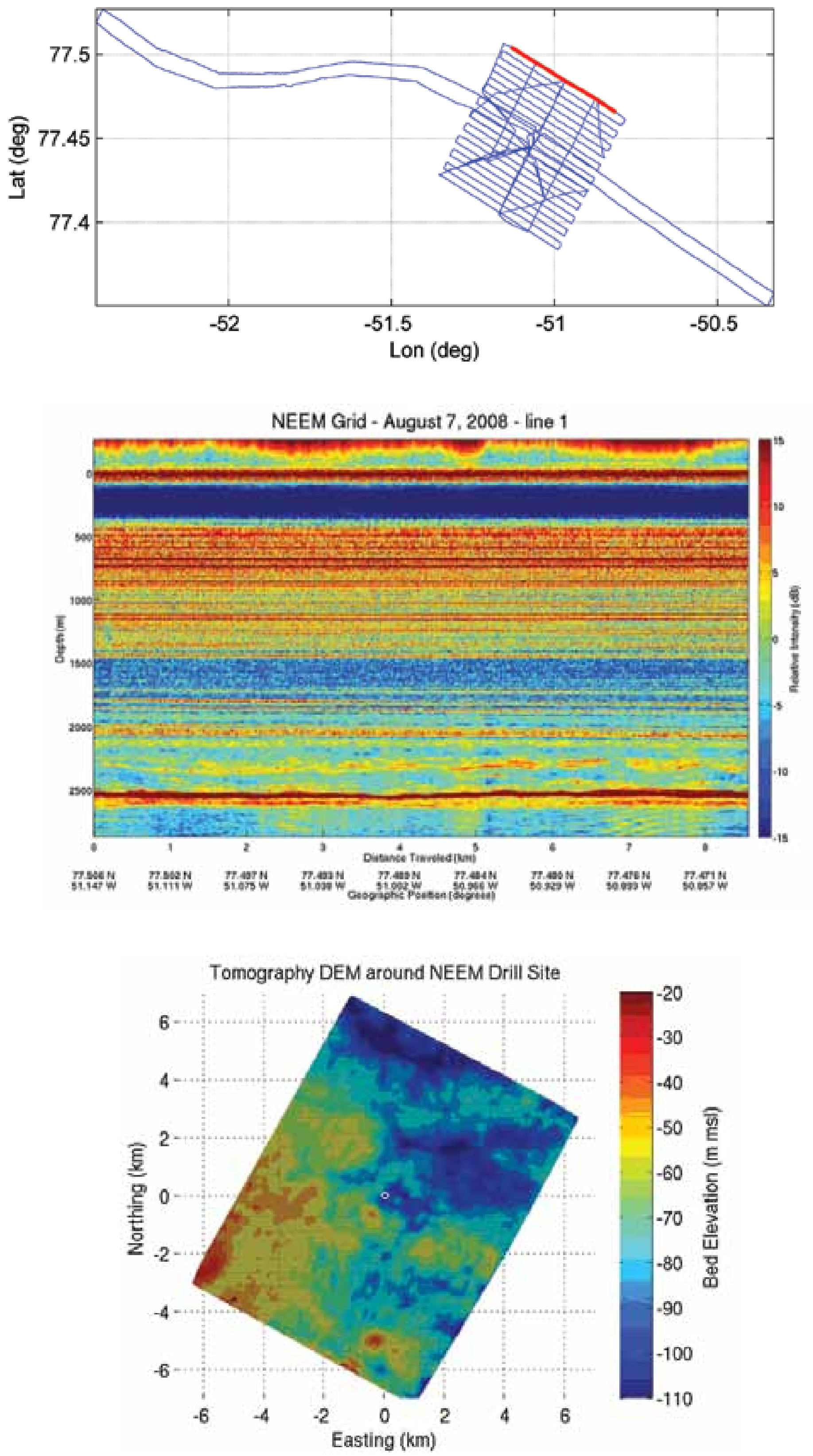
(Courtesy: Center for Remote Sensing of Ice Sheets, U. Kansas)

Projections of the future response of the Greenland Ice Sheet to climate warming indicate that the loss of mass will increase. The IPCC climate scenarios for the high Arctic region predict temperature increases around 50% higher than those predicted globally (IPCC, 2007). This will increase the length and intensity of the summer melt season and so will increase the extent of the area experiencing summer melt. Current climate models estimate that Greenland's surface mass balance will become negative with a global warming of 3.1 ± 0.8 °C (a warming over Greenland of 4.5 ± 0.9 °C). Current projections with coupled ice sheet and climate models indicate an annual average mass loss of the order of 180 Gt for the 21st century, equivalent to a 5 cm sea level rise by 2100, primarily due to increased melting and run-off. First attempts to include in the models the increasing ice discharge via the marine outlet glaciers have predicted an additional 4.7 cm of sea level rise by 2100.

Nevertheless, new studies on previously collected ice core records indicate that the Greenland ice sheet melted much more rapidly as a result of warmer temperatures in the recent past than previously estimated. The ice sheet lost 150 m in height at its centre and shrank by 200 km at the edges during an unusually warm period between 9000 and 6000 years ago when temperatures were 2–3 °C warmer than today (Vinther et al., 2009). Present ice sheet models do not show this behavior and future warming could have more dramatic effects on the ice than estimated. The NEEM ice core record from the warmer Eemian period should help to further resolve this response of the ice sheet.

With sustained warming over Greenland, the ice sheet will likely contribute several meters to sea level rise over the coming millennium.

Fig. 2.4-9. The grid over which data were collected at the NEEM drill site (top); an echogram generated with traditional processing of data collected over one of the grid lines (middle); and a 3-D topography derived from array and SAR processing techniques described in Paden et al., [2010] (bottom). The drill site is marked by a circle in the bottom figure. (Courtesy: Center for Remote Sensing of Ice Sheets, U. Kansas)



The wealth of satellite data collected under coordination of the IPY GIIPSY project is now enabling new SAR image mosaics, interferometrically derived ice sheet velocity fields at various frequencies, and high-resolution SPOT Digital Elevation Models for Greenland to be produced and distributed.

Arctic glaciers and ice caps

The Arctic glaciers and ice caps in most regions are experiencing strong thinning at low elevations, while the pattern at higher elevations varies from slight thinning to slight thickening (Moholdt et al., 2010a, b; Nuth et al., 2010). There are also examples of local anomalous elevation changes due to unstable glacier dynamics such as glacier surging (Sund et al., 2009).

For the Austfonna ice cap on Svalbard, the net surface mass balance is slightly negative (-0.1 m water eq. yr^{-1}), but less negative than for the westerly ice masses in Svalbard (Moholdt et al., 2010a). Iceberg calving is important and contributes 30-40% of the total mass loss, so the overall mass balance is a loss of ~2 Gt yr^{-1} (Dowdeswell et al., 2008), however, the elevation change measurements on Austfonna show a thickening in the interior of ~ 0.5 m yr^{-1}, and an increasing thinning closer to the coast of 1-2 m yr^{-1}, indicating a large dynamic instability (Dunse et al., 2009; Moholdt et al., 2010a). This dynamic instability is not seen on the Devon Ice cap.

Results from several IPY related research projects have contributed significantly to characterizing short- and long-term variations in the flow of several major tidewater glaciers in the Canadian high Arctic. RADARSAT-2 Fine and UltraFine beam mode data acquired over the Devon Ice Cap since early 2009 reveal sub-annual cycles of alternating accelerated/reduced flow along the upper/lower reaches of Belcher Glacier. Analysis of the LandSat image archive over major outlet glaciers that drain the Devon Ice Cap and Manson and Prince of Wales Ice Fields, indicates significant (up to a factor of 4) inter-annual variability in tidewater glacier velocities since 2000. Some, but not all, of this is surge-related. Repeat mapping of glacier velocity fields over the Devon Ice Cap from 1995 ERS 1/2 and RADARSAT-1 data and 2009 RADARSAT-2 Fine beam data indicates that (within limits of error) there has been no net change in ice discharge from the ice cap as a whole over this period of time. Finally, annual glacier velocity measurements derived from RADARSAT-1 and RADARSAT-2 Fine beam data indicate a net decrease in the rate of flow of 11 target glaciers across the Queen Elizabeth Islands between 2000 and 2010. This trend was driven primarily by a few surge-type glaciers entering the quiescent mode of glacier flow. Ongoing IPY related glaciological research in Canada is focused on understanding linkages between external climate forcing and glacier dynamics and the impact of changing glacier dynamics on the net mass balance and geometry of ice caps in the Canadian Arctic.

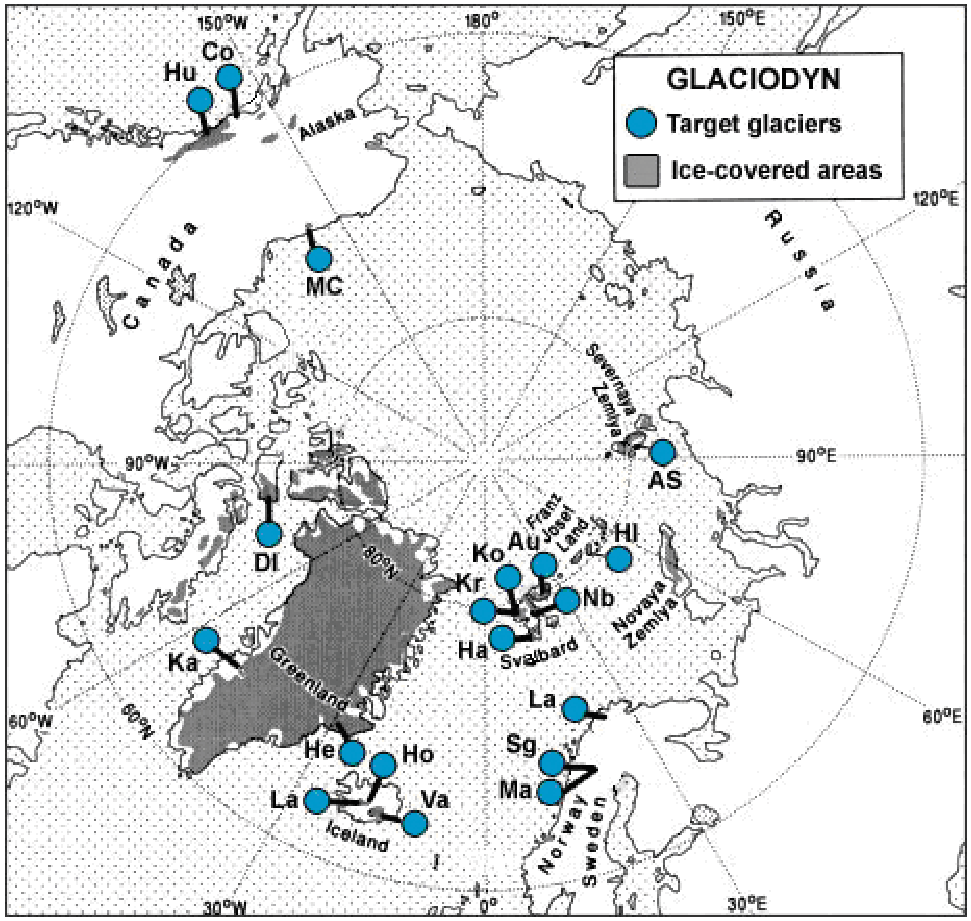
Continuous GPS-receivers were used to monitor several valley glaciers and outlet ice streams from the ice caps, mainly in Svalbard and the Canadian Arctic. Clear linkages between high melt events and increased flow velocities can be seen at all (Ouden et al., 2010).

The recent increase in mass loss from the Canadian ice caps is a result of strong summer warming, especially since 2005, that is largely confined to the North American side of the Arctic and also affects northern and western Greenland. The IPY boreal summers 2007 and 2008 were two of the warmest five observed since 1948. This warming seems to be attributable to anomalously warm sea surface temperatures in the NW Atlantic, and development of a high pressure anomaly that extends from Iceland over the northern 2/3 of Greenland and the Canadian Arctic islands and into the Canada Basin (sometimes reaching Northeast Siberia). The circulation anomaly associated with this latter feature favours atmospheric heat transport from the northwest Atlantic up Baffin Bay into the areas where strong warming in summer is detected.

An impact of this warming has been a major change in the firnification regime of the Canadian ice caps such that any semblance of a dry snow zone has been eradicated and the upper limit of the wet snow zone has risen substantially. Rates of firnification have probably increased along with this.

On the basis of radio echo-sounding surveys of glaciers on Franz Josef Land and Novaya Zemlya and satellite altimetry data, characteristic heights and thicknesses of glacier fronts producing icebergs have been determined. This includes data for Glacier No. 1 and the Moscow Ice Cap on Hall Island, the northern part of the glacier complex on George Land (Franz Josef Land), and the glaciers in the Inostrantsev Bay area, Novaya Zemlya. New criteria for the estimation

Fig. 2.4-10. Target glaciers for the GLACIODYN project (IPY no. 37).
(Courtesy: Jon Ove Hagen)



of iceberg hazards from the glaciers of Novaya Zemlya and Franz Josef Land have been developed. Franz Josef Land has the greatest potential for regular formation of icebergs with thicknesses of up to 150-200 m and extents of more than 1-2 km (Kubyshkin et al., 2009). Photogrammetry has been used to reconstruct the geometry of glacier fronts and the above-water parts of icebergs. Several groups of large tabular icebergs with a weight of over one million tonnes were found not far from their calving areas (Elena Guld Bay on Wilczek Land, the straits between Salisbury, Luigi and Champ islands, Geographers' Bay on Prince George Land). The majority of large icebergs were already drifting. Under favourable meteorological conditions, some of them may drift to the Barents Sea through the deep straits.

In Northeast Siberia, meteorological parameters were measured along a transect from Magadan to Oymyakon, and in the northern massif of Suntar-Khayata (Fig. 2.4-13). A study of glacier change in the region based on modern satellite images and data from the USSR Glacier Inventory has been completed. Infrared, visual and aerial photo surveys have been made for the Suntar-Khayata glaciers in order to update the Glacier Inventory (Ananicheva and Kapustin, in press).

Remote sensing data combined with the field validation results show a negative mass balance over most of the Arctic. The largest losses occurred in the Canadian Arctic, with increased loss since the mid 1990s and accelerating loss after 2005. This is in good agreement with coincident mass balance estimates from GRACE satellite gravity measurements, with surface mass balance field data and with mass balance modelling using meteorological reanalysis data (Boon et al., 2009; Gardner et al., in press).

Several GLACIODYN PhD projects were focused on the calving of glaciers both in Svalbard and the

Canadian Arctic, on glacier surge dynamics, on subglacial hydrology and on different aspects of geodetic mass balance from space-data and ground data. More than one hundred presentations have been made by GLACIODYN partners at different meetings during and after IPY.

Summary and Legacy

Overview of achievements

An important outcome of IPY activities on the Greenland ice sheet and Arctic glaciers has been the wide use of IPY results in the Arctic Council's cryosphere project – *Snow, Water, Ice and Permafrost in the Arctic* (SWIPA; *Chapter 5.2*). The project is coordinated by the Arctic Council Arctic Monitoring and Assessment Programme (AMAP) in cooperation with the International Arctic Science Committee (IASC), the International Arctic Social Sciences Association (IASSA) and the Climate and Cryosphere (CliC) Project of WCRP.

The SWIPA report on the Greenland Ice Sheet (Dahl-Jensen et al., 2009) was the first in a series of the AMAP reports presenting the results of the SWIPA project. Although the SWIPA Greenland report was not an IPY project *per se*, most experts involved in IPY Greenland Ice Sheet projects contributed to the report and the results and findings of IPY research on the Greenland Ice Sheet were included in it. Future SWIPA reports will include an update of the information concerning the Greenland Ice Sheet, in particular the sections dealing with potential impacts on biological systems and human populations.

Work undertaken on Arctic terrestrial ice during IPY 2007–2008 will undoubtedly also contribute to the next IPCC assessment of climate change.

Legacy for the future

Most Arctic cryospheric activities during IPY provided enhanced project opportunities and funding to support post-graduate students. A large number of Ph.D. students, many of whom will go on to become the next generation of leading polar researchers,

Fig. 2.4-11. Time-lapse cameras were used to monitor ice flux and calving on Kronebreen, Svalbard. (Photo: Monica Sund)

Fig. 2.4-12. Airborne lidar and ground-based measurements on Austfonna, Svalbard.
(Photo: Andrea Taurisano)

Fig. 2.4-13. Three glaciers of the Suntar-Khayata Range, a continuation of the Verkhoyansky Range, in the Sakha Republic, Northeast Siberia. Little was known about the glaciers in this region prior to IPY 2007–2008.
(Photo: Maria Ananicheva)

participated and were trained within the IPY projects.

The NEEM project has provided a deep ice core reaching back beyond the Eemian period that will provide a record to advance our knowledge of the North Atlantic climate and to provide needed data for a bipolar comparison. This ice core record will continue to be exploited over the next decade or longer. NEEM has also helped to reignite interest in using the last interglacial in both polar regions as a constraint on the likely environmental impacts of a sustained polar temperature a few degrees warmer than present. The IPICS consortium continues to operate, and is in the process of expanding its NEEM priority project into a more general study of the last interglacial.

Improved observational facilities include a network of weather stations on the Greenland ice sheet and long-term monitoring systems of the fast-moving Greenland outlet glaciers. The example of cooperation and coordination between national space agencies established through the GIIPSY project, and the continuation of the Space Task Group beyond IPY (*Chapter 3.1*), will continue to provide high quality satellite data for polar operations, research and international monitoring activities such as the Global Cryosphere Watch (*Chapter 3.7*).

The GLACIODYN network continues through the IASC group, now restructured and renamed as the IASC Network of Glaciology. New projects have been established by the GLACIODYN network as follow-ups to the IPY efforts. Some examples include:

1) Six former partner groups in GLACIODYN are now working together in the EU-project ice2sea (2009–2013), which aims to reduce the uncertainty of sea level contribution from both ice sheets and glaciers and ice caps.
2) In the Nordic countries a new Nordic Center of Excellence in Climate and Cryosphere called SVALI (Stability and Variations of Arctic Land Ice) has been funded by the Nordic Ministry for the period 2011 to 2015. The 17 partners consist mainly of former GLACIODYN groups and the established network during IPY was the basis for the new center.
3) Seventeen former GLACIODYN groups from ten European countries have recently started a new project with focus on Svalbard glaciers (SvalGlac). This is under the umbrella of European Science Foundation (ESF) program PolarCLIMATE for the period 2009 to 2012 and was launched as a direct successor to IPY.
4) Steps have been taken to establish a new modeling initiative to include dynamics in predictive models as a contribution to the ice2sea project. This is a direct follow up of the aims of GLACIODYN which included development of robust, predictive models that include key dynamic processes. The inclusion of ice dynamics in predictive models of future glacier response would represent a significant advance from current mass balance models.

On the wider global stage, International Polar Year 2007–2008 provided a unique opportunity to develop polar observing systems and, by doing so, begin to close one of the most significant gaps in global observations. The Integrated Global Observing Strategy (IGOS) Cryosphere Theme and the Global Cryosphere Watch (GCW, *Chapter 3.7*) are major outcomes of IPY.

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Notes

[1] The titles and details of individual EoIs may be found at http://classic.ipy.org/development/eoi/

2.5 Antarctic Ice Sheet

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Historical Background

During the First Polar Year (1881-1884), scientists worked with incomplete knowledge of the horizontal extent of the polar ice. Ice sheets were empty voids on the scientists' maps. Seventy-five years later, during the International Geophysical Year (IGY), the horizontal extent of the ice sheets was reasonably well known, but the thickness and volume of the ice sheets remained unknown. Leveraging the technology and infrastructure developed during World War II, IGY traverse teams made measurements of the depth of the Antarctic Ice Sheet using seismic measurements revealing that the ice sheet was in places over 3 km thick (Bentley, 1964). This discovery of the tremendous volume of ice stored in the polar regions shifted forever the understanding of the ice sheet's role in the global climate system. The ice stored in Antarctica is capable of rising sea levels globally almost 60 m. During IGY, the common view was that ice sheets were generally static and could not change on human timescales. Fifty years later, during the planning for IPY 2007–2008, both the Greenland and Antarctic ice sheets had displayed surprisingly dynamic behavior. Accelerating large outlet glaciers (Joughin, 2003), ice shelves disintegrating within a month (Rignot, 2004) and rapidly thinning ice at the ice sheet margins (Zwally, 2005) were all observed; all astonished even the experts. Large polar ice masses changing at human timescales were unfamiliar and troubling given their potential effect on coastal areas around the world where much of the world population lives. A major focus for IPY 2007–2008 quickly emerged to understand the Antarctic Ice Sheet's current status, how it is changing and how it will change in the future. These larger IPY programs were elicited to attempt to reach beyond the ongoing vigorous research programs of many countries into some of the same areas of research. In many cases, these original programs were expanded through more ambitious goals or by combining similar national efforts. In other cases the IPY programs were new and the underlying research continued (Fig. 2.5-1, Table 2.5-1).

Framework for IPY 2007–2008 Antarctic Ice Sheet Studies

The IPY 'Framework' document outlined six major themes for IPY 2007–2008: Status, Change, Global Linkages, New Frontiers, Vantage Point and Human Dimensions at the Poles. The IPY studies of the Antarctic cryosphere spanned the first four of these six Framework document themes.

The New Frontiers theme targeted basic discovery and exploration of the unknown regions of the poles from the genomic scale to the continental scale. The New Frontiers title was used to avoid the sense of exploitation often associated with the term "exploration". The targeted cryospheric frontiers outlined in the framework documents included the study and exploration of subglacial lakes and the exploration of the Gamburtsev Mountains. Both of these targets became major IPY programs. The study of subglacial lakes is addressed in *Chapter 2.6* while the program targeting Antarctica Gamburtsev Province (AGAP) is discussed here and in the solid earth studies section. During the planning phases of IPY, the linkage between the exploratory aspects of subglacially focused programs and the relevance of their discoveries to understanding the changing cryosphere began to emerge as the awareness of the dynamic nature of subglacial hydrology become apparent. An ongoing and similar explor-

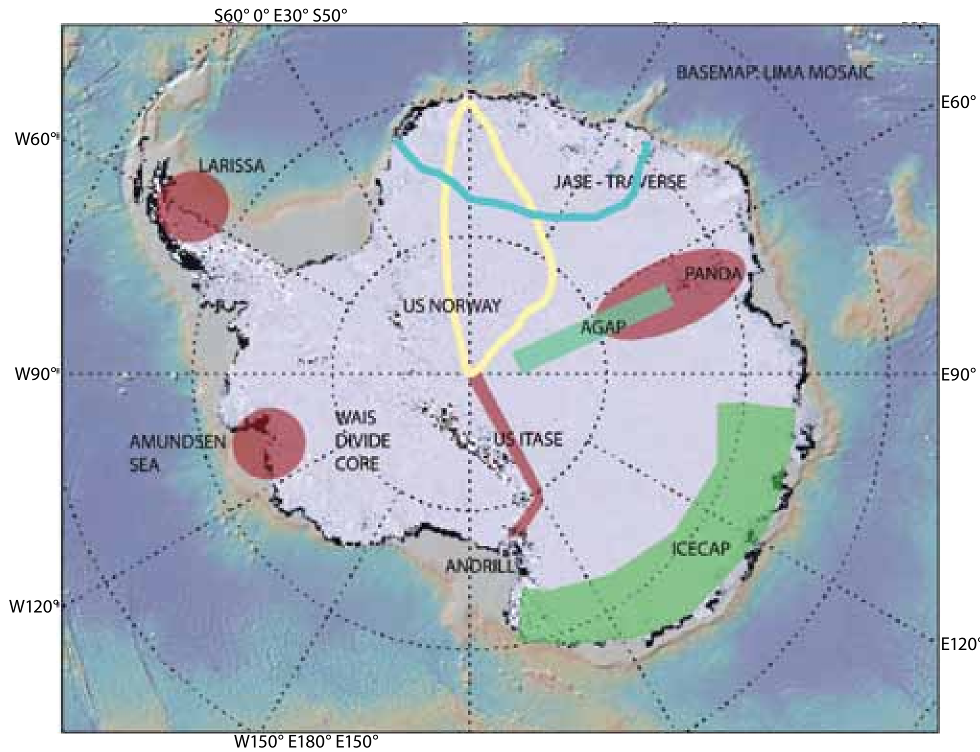

Fig. 2.5-1. Schematic illustration of Antarctic cryosphere activities in IPY 2007–2008 on the LIMA Mosaic. Projects that encompassed the entire ice sheet such as LEGOS are not identified on this map.
(Map: Robin Bell)

atory effort (ICECAP) into the interior of the Aurora and Wilkes basins in East Antarctica is also supporting improved understanding of both the structure of the East Antarctic continent while providing fundamental boundary conditions to ice sheet models. While the New Frontier programs are providing entirely new views of the Antarctic continent, the Global Linkages programs are revealing new aspects of the fundamental links between the dynamics of the Antarctic cryosphere and the global ocean and the northern hemisphere ice sheets. In Antarctica, much of IPY 2007–2008 Global Linkages efforts came from ice cores. Ice cores capture an accurate and invaluable record of ancient atmospheric composition. Insights into the record of greenhouse gases, such as methane and carbon dioxide, can only be measured from ice cores providing a cornerstone of climate change research. The IPY ice coring effort included shallow cores along the coast, a deep core in West Antarctica and site surveys searching for the oldest ice on the planet.

The framework's identification of documenting the Status of the Antarctic cryosphere as a key theme during IPY 2007–2008 carried with it the establishment of benchmarks for measuring future change. During IPY, important new measurements on the surface of the ice sheet, the mass of the ice sheet and velocities of the major outlet glaciers established these benchmarks. In addition to these well-established characteristics, other benchmarks are being or have been created, such as mapping the hydrostatic line (the critical interface where the ice sheet goes afloat and is in contact with the ocean), constructing a true color Landsat Image Mosaic of Antarctica (LIMA), and improving the estimate of discharge of ice through mapping previously unknown areas such as the Aurora and Wilkes basins as well as the Gamburtsev Mountains.

The framework theme of Change targeted quantifying and understanding past and present natural environmental change in the Antarctic cryosphere in order to improve projections of future change. Programs targeted at understanding the past stability of the Antarctic Ice Sheet recovered sediment cores such as those from the ANDRILL program in the Ross Sea achieved fruition during IPY 2007–2008. Satellite monitoring and use of satellite technology in establishing new geometric networks are providing heretofore impossibly precise insights into ongoing change. The interpretations of change observed from satel-

Title	IPY Project no.	Nations
AGAP-Antarctica's Gamburtsev Province	67	U.S.A., U.K., Germany, Australia, China, Japan, Canada
ICECAP-Investigating the Cryospheric Evolution of the Central Antarctic Plate	97	U.K., U.S.A., Australia, France
IPICS-International Partnerships in Ice Core Science-International Polar Year Initiative	117	Austria, Belgium, Brazil, Canada, Denmark, Estonia, France, Germany, India, Italy, Japan Netherlands, New Zealand, Norway, Russia, Sweden Switzerland, U.K., U.S.A.
LIMA-Landsat Image Mosaic of Antarctica	461	U.S.A., U.K.
ASAID-Antarctic Surface Accumulation and Ice Discharge	88	U.S.A., Australia, Germany, Italy, New Zealand, U.K., Norway, Russia
TASTE-IDEA-Trans-Antarctic Scientific Traverses Expeditions – Ice Divide of East Antarctica	152	Originated by Germany: implemented through the next two projects
JASE-Japanese-Swedish Antarctic Expedition	Contributed to objectives of 152	Sweden, Japan, Russia
US- Norway Traverse	Contributed to objectives of 152	Norway, U.S.A.
PANDA- The Prydz Bay, Amery Ice Shelf and Dome A Observatories	313	China, Australia, U.S.A., U.K., Japan, Germany
ITASE-International Trans-Antarctic Scientific Expedition	Linked to 88, 117, 152	Established prior to IPY with up to 20 national participants
WAIS Divide Core	-	U.S.A.
ACE-Antarctic Climate Evolution	54	China, Germany, Italy, New Zealand, Poland, Spain, U.K., U.S.A., Argentina, Australia, Belgium, Canada, France, Netherlands and Sweden
ANDRILL	256	U.S.A., New Zealand, Italy, U.K., France, Australia, Germany
Multidisciplinary Study of the Amundsen Sea Embayment	258	U.S.A., U.K.
LARISSA-Larsen Ice Shelf System, Antarctica	-	U.S.A., Belgium, Korea, U.K.
LEGOS	125	France, Australia, Germany, U.S.A.

Table 2.5-1. projects referred to in this Chapter.

lites, like ICESAT's measurements of elevation change and GRACE's measurements of mass change, emerged during IPY. Simultaneously, the SCAR supported ACE effort built a new community bridging between the paleooceanographic and modeling communities to interpret and support robust model development of past and future ice sheet change. Current change was also directly addressed through programs focused on ice shelves, the floating fringe of the ice sheet, where observations suggest strong interactions between the ice sheet and its surrounding waters on the continental shelf, ultimately connected to the deeper ocean. Thus IPY has enabled completely new means to measure change along with the research communities to interpret these changes just at the time when these changes are of most importance to societies across the globe. It is easy to view IPY as having arrived on the scene at the most critical time: the cryosphere is beginning to exhibit change previously not witnessed by humans, yet human behaviour will need to understand and accommodate these changes.

IPY Investigations of the Antarctic Ice Sheet

a. New Frontiers

The New Frontiers of IPY 2007–2008 were mostly hidden beneath the thick ice of the Antarctic Ice Sheet. During IPY the knowledge that subglacial hydrologic systems can change and influence ice sheet dynamics became evident and the groundwork was laid for upcoming exploration of several subglacial lakes (*Chapter 2.6*). The other efforts focused on understanding the last unknown tectonic systems on our planet: the deep basins beneath the ice sheet and the hidden mountain ranges.

The study of Antarctica's Gamburtsev Province (AGAP, no. 67) was a collaborative effort of seven nations (U.S., U.K., Germany, Australia, Germany, China and Canada) bringing together their resources and technologic knowledge to study the Gamburtsev Mountains hidden beneath Dome A in the center of East Antarctica. Using two research Twin Otters aircraft the team collected 130,000 km of data, equivalent to flying the aircraft around the globe three times. The team also installed 26 seismometers around Dome A that will record global seismic events. The seismic data will be used to determine the deep earth structure beneath Dome A. The aerogeophysical data has revealed a rugged mountain range incised by fluvial river valley in the south and truncated by the landward extension of the Lambert Rift to the North. Capturing measurements of some of the thickest ice (over 4600 m) and some of the thinnest ice in the center of the ice sheet (less than 400 m) this work is changing the view of the tectonics and the nature of the ice sheet. Evidence is emerging for complex interconnected system of subglacial water and extensive subglacial freezing at the base of the ice sheet. Well-resolved internal layers facilitate the identification of the oldest ice close to the Dome A.

East of the Gamburtsev Moutains, the collaborative ICECAP program began a multi-year program (U.K., U.S. and Australia) using an instrumented long-range aircraft to survey the portion of the East Antarctic Ice Sheet underlain by the Wilkes and Aurora subglacial basins. The ice drainage from these regions is dominated by the Byrd and Totten Glacier systems. This program is acquiring a combination of flow-line-oriented and gridded aerogeophysical observations over this portion of the East Antarctic Ice Sheet that is grounded on a bed below sea level, prompting questions of its regional stability. During IPY, the program flew over 30,000 km acquiring ice thickness and internal layers to support of ice sheet modeling to observe flow regime change and to study crustal geology and subglacial hydrological systems. These data will inform future studies on the processes controlling both past and future change of the East Antarctic Ice Sheet.

b. Global Linkages

The Global Linkages theme sought to advance the understanding of the links and interactions between polar regions and the rest of the globe. IPY 2007–2008 efforts in this aspect of the Antarctic cryosphere sought to use the climate record held within ice cores to link the climate record from Antarctica to global climate systems. The IPY ice coring efforts included shallow cores along the coast and ongoing deep cores in the interior. During IPY, the relatively new International Partnerships in Ice Core Sciences (IPICS) supported focused site surveys and beginning the West Antarctic Ice Sheet (WAIS) divide core. IPICS partnered in the major aerogeophysical programs (AGAP and ICECAP) that collected the data to be used to locate and identify the oldest ice available in Antarctica—hopefully at least one million years old—providing data that will be fundamental to understanding the orbital forcing of climate change.

The ice core recovered from the divide of the West Antarctic Ice Sheet will facilitate the development of climate records with an absolute, annual-layer-counted chronology for the most recent ~40,000 years. This ice core record will have a very small offset between the ages of the ice and the air (i.e. gases) trapped in the ice enabling a decadal-precision climate chronology relative to the Greenland ice cores. In addition to providing the most detailed record of greenhouse gases possible for the last 100,000 years and determining if the climate changes that occurred during the last 100,000 years were initiated by changes in the northern or southern hemisphere, the WAIS core project will investigate the past stability of the West Antarctic Ice Sheet and contribute to efforts to predict its future. During IPY 2007–2008 the deep drilling system was installed and drilling began.

c. Status

Determining the present environmental Status of the polar regions during IPY 2007–2008 was crucial to establishing benchmarks for documenting future change. In the Antarctic cryosphere key targets were the exact location of the edge of the ice sheet, the rate of accumulation of snow and the rate at which ice is being discharged. Several projects using techniques ranging from traverses crossing the continent with snow vehicles to detailed analysis of satellite images addressed these goals.

High resolution imagery is a commonly used data set to visualize a region and, in Antarctica, often replaces maps. Surprisingly, before IPY, the highest resolution data set of Antarctica used radar, not visible, imagery. As IPY approached, a joint U.S.-U.K. effort to produce the Landsat Image Mosaic of Antarctica (LIMA, http://lima.usgs.gov) began. During IPY, LIMA was released, capturing the status of the of the Antarctic Ice Sheet surface for the period 1999-2003. Extensive image processing was completed to rigorous scientific conditions to produce a scientifically valuable mosaic data set of surface reflectances. The outcome of this IPY project gives the public and educators a new, exciting and flexible tool to increase their familiarity with Antarctica (http://lima.nasa.gov). LIMA has been used extensively in the classroom and by media to add a real-look dimension to Antarctic activities. LIMA also serves the science research community with a new research tool of meaningful surface reflectances to facilitate not just field planning and exploration of the Antarctic surface, but also quantitative analyses that utilize surface reflectance data. LIMA offers parallel views of the surface with synthetic aperture radar from the co-registered Radarsat data set. The LIMA interface allows interested users to download either the mosaiced data or the individual scenes. Two biologists used the LIMA mosaic to map penguin rookeries over all of Antarctica, finding a number of previously unknown rookeries and identifying some abandoned rookeries based on the spectral (true color) signature of rookeries (Fretwell, 2009).

Following from the LIMA and during the LIMA period of 1999-2003 was the project ASAID defining the precise position of the Antarctic grounding line by including ICESat and SAR data at 15 meters resolution and, from it, the total ice discharge from the Antarctic continent. Scientists from Norway, the U.K., New Zealand, Italy, Germany, Australia and the U.S. produced a comprehensive estimate of the surface accumulation and ice discharge for the Antarctic cryosphere. Additional products were the first-ever mapping of the "hydrostatic line" where floating ice is in hydrostatic equilibrium, the first complete mapping of surface velocity across the grounding line. Previous estimates of the Antarctic discharge flux had been limited to the fast moving outlet glaciers. Some field data collected during IPY by the British Antarctic Survey was used for validation. Each of these new data products are benchmark data sets that will be used to measure change of the cryosphere in the future. New techniques were employed to derive surface elevations from Landsat imagery using ICESat altimetry as control while customized software was developed to provide analysts with tools for combining these data and drawing and editing the grounding line.

Russian research during IPY included Antarctic Ice Sheet and sea water interaction, geophysical investigations of ice stream-lines and subglacial lakes, and surface ice accumulation and discharge. During IGY, surface traverses across the Antarctic Ice Sheet were used to generate the first accurate estimates of the volume of ice stored on the continent.

During IPY 2007–2008, surface traverses were used to make key *in situ* measurements of the ice sheet in locations many of which had not been visited for decades. During the planning phases of IPY, one of the first concepts offered (by Heinz Miller of AWI under the title IDEA) was traverses along the divides of the ice sheets collecting shallow ice cores to capture the accumulation record and to provide the logistical infrastructure for other detailed work such as aerogeophysics. Much of this concept was implemented, although not always under the umbrella of IDEA. The long running ITASE program targeted where and how Antarctic physical and chemical climate has or has not changed over the last several hundred years with a view toward assessing future climate change over Antarctica. ITASE continued into IPY with traverses extended from McMurdo to the South Pole and from Dronning Maud Land to Dome F and on to the Japanese Base Syowa. Traverses were also completed by a joint Norwegian-U.S. team that covered one of the major ice divides and surveyed major sub-glacial lakes, as well as one component of the PANDA program that traveled from the coast to Dome A.

Making use of mobile platforms in the interior of Antarctica, the Japanese-Swedish Antarctic Expedition, JASE (November 2007 – February 2008), made continuous surveys of different parameters, including sampling and snow and ice radar surveys. The JASE traverse began in Dronning Maud Land, East Antarctica at the Swedish base Wasa and reached the Japanese base Syowa via the deep drilling sites at Kohnen and at Dome Fuji. Data collected included radar soundings for ice depth and snow layering, air sampling, snow sampling for chemical analyses, snow sampling for physical property measurements, snow pit studies for snow sampling, firn coring for various analyses and 10 m temperature, weather observations, GPS-measurements and ground truth surveys for satellite data. The traverse enabled extensive ground truth sampling of physical snow properties such as snow grain size. Snow grain size is determined by moisture content and air temperature, and shows decreasing size towards the center of Antarctica and larger grains in the coastal areas. The grain size and shape results are correlated with coincident and historical satellite data including SAR imagery from ENVISAT ASAR, QuikSCAT scatterometry and optical-thermal satellite data (MERIS & MODIS) over the study area. Preliminary results indicate that the black carbon content in air and snow over the Antarctic plateau is higher than expected. The concentration in air is higher than found near the coast, and the content in snow is about 10 times larger than used in published climate simulations, albeit with large spatial variations. Subglacial landforms that may be relicts from the initiation of the Antarctic glaciation about 30 million years ago were described and continuous measurements of aerosols, bed topography, ice layering, snow layering and surface topography were measured en route.

The Norwegian-U.S. Scientific Traverse of East Antarctica completed two seasons (2007 and 2008/2009) of overland traverses of East Antarctica beginning at the Norwegian Troll Station, following an ice divide to the South Pole and returning to Troll by a route over the Recovery Subglacial Lakes. The main research focus of the program was to examine climate variability in Dronning Maud Land, East Antarctica on time scales of years to a 1000 years by a series of shallow cores, firn studies and temperature profiles. The team has been able to establish spatial and temporal variability in snow accumulation over this area of Antarctic both through ice cores and linking the surface based studies to satellite measurements. Results from new ice cores are providing new constraints on the accumulation in East Antarctica for the past 2000 years. Analysis of the surface radar has enabled a robust relationship between the surface and space observations. Detailed snow pits enable new insights into the impact of atmospheric and oceanic variability on the chemical composition of firn and ice in the region. The physical properties of snow and firn, from crystal structure to mesoscale strata morphology, reveal a complicated East Antarctic climate history. Five 90 m-long *in situ* thermal profiles obtained from automated, satellite-uplinked stations provide an independent, new assessment of climate trends in the remotest parts of Antarctica.

d. Change

The planners of IPY envisioned that programs targeted at Change in the Polar Regions would seek to quantify, and understand, past and present natural environmental change in the polar regions, and to improve projections of future change. IPY 2007–2008 programs addressing change covered the spectrum of past change through present change to projections of future change.

The existing Antarctic Climate Evolution (ACE, www.ace.scar.org) activity, a Scientific Research Project (SRP) of the Scientific Committee on Antarctic Research (SCAR) emerged as a core IPY project and was an umbrella for many smaller projects fitting beneath. ACE's mission is to facilitate the study of Antarctic climate and glacial history through integration of numerical modeling with geophysical and geological data. The overall goal of ACE is to facilitate those model-data interactions for better understanding of Antarctic climate and ice sheet variability over the full range of Cenozoic (last ~65 million years) timescales. Over the last five years, ACE has made major contributions to the understanding of the early development of the Antarctic Ice Sheet in the Oligocene and its variability through the Miocene. Much of this work has led to a new appreciation for the importance of atmospheric greenhouse gas concentrations relative to other potential forcing mechanisms (e.g. orbital forcing, ocean circulation, etc.) in controlling the onset of glaciation and magnitude of subsequent ice volume variability.

A direct outcome of ACE was the ANDRILL project that included a major drilling field campaign integrated with a numerical modeling effort. During IPY, ANDRILL completed its first two seasons of sedimentary drilling in the Ross Sea. The drilling effort recovered over 2400 meters of high quality core in two locations: under the McMurdo Ice Shelf and in the Southern McMurdo Sound. The McMurdo Ice Shelf core ranges in age from recent to Pliocene, while the Southern McMurdo Sound core is mostly older, providing an expanded Miocene record. While the science associated with Southern McMurdo Sound is still evolving, important discoveries have already been made, including the recognition of exceptional Antarctic warmth in the middle Miocene (Sophie Warny, 2009). The McMurdo Ice Shelf effort and associated numerical modeling has made several important discoveries, including the recognition of a highly variable, orbitally paced West Antarctic Ice Sheet (WAIS) throughout the Pliocene and early Pleistocene (Naish et al., 2009). Based on a combination of sediment analysis and numerical ice sheet-shelf modeling, it is now clear that WAIS is capable of sudden retreats (collapses) within a few thousand years, mostly in response to relatively modest increases in ocean temperature and sub-ice shelf melt rates (Pollard and DeConto, 2009). The most recent WAIS collapse evident in the ANDRILL core occurred around 1 million years ago (Marine Isotope Stage - 31). At that time, WAIS appears to have retreated to the small sub-aerial islands of the West Antarctic archipelago, the Ross Sea was open water (with no ice shelf), mean annual sea surface temperatures were several degrees above freezing and there was little seasonal sea ice in the Ross Embayment.

Numerical modeling of Cenozoic ice sheets has been greatly improved in recent years by ACE-facilitated geophysical surveys (e.g. AGAP and ICECAP), providing improved subglacial boundary conditions. New working groups within ACE including Circum-Antarctic Stratigraphy and Paleobathymetry (CASP) and ANTscape have been particularly active over the IPY period, producing new paleotopographic and paleobathymetric reconstructions of the continent and offshore margins at key time slices in the past including the Eocene-Oligocene boundary (34 Ma), Last Glacial Maximum and Holocene.

Early in the planning stages of IPY, the Amundsen Sea Embayment was identified as a key location where rapid change was underway. The spatial pattern of change revealed the ocean as the driver of this change and, during IPY, a multi-national program (U.S. and U.K.) began targeting a sustained study of the impact of warm water circulating in the ice cavity adjacent to the Pine Island Glacier, a major WAIS outlet glacier. The targeted ice shelf turned out to be so heavily crevassed that it was unable to support landings by fixed wing aircraft. An alternative strategy using helicopters has introduced a delay; this multidisciplinary study, begun in early 2008, will continue through 2014. The Amundsen Sea program will be the first sustained sampling of sub-ice shelf circulation in a "warm-ice-shelf" cavity. The instruments lowered through borehole drilled in the floating ice shelf in 2011 will record the high basal melt rates thought to exceed 100m/yr in a region known to be changing rapidly. The Pine Island Glacier, feeding this floating ice shelf, is thinning, accelerating and retreating. Novel technology will be deployed enabling improved imaging systems and small-diameter ocean profiling instruments. The science outcomes are anticipated to be accurate measurements of the temperature, salinity and current changes in the incoming and outgoing water. These sub-ice shelf data will complement IPY data from ocean moorings placed on the continental shelf of the Amundsen Sea.

Other well-documented changes are continuing in the Antarctic Peninsula, particularly on the ice shelves and their feeding glaciers. A new interdisciplinary program to investigate environmental change in the LARsen Ice Shelf System, Antarctica (LARISSA) was initiated during IPY 2007–2008. Also delayed because of complex logistical requirements, it will provide a comprehensive approach to questions concerning the past, present and future of this rapidly changing region. Catastrophic ice shelf loss associated with rapid regional warming has resulted in large scale changes in the physical and biologic environment. The LARISSA Project represents an Earth Systems approach to describe and understand the basic physical and geological processes active in the Larsen embayment that contributed to the present phase of massive, rapid environmental change; are participating in the coupled climate-ocean-ice system; and are fundamentally altered by these changes. While observations of modern glacial, oceanic and biological dynamics will address the response of this polar system to global change, marine and terrestrial geologic data in combination with ice core data will provide the context of a paleo-perspective making it possible to address a suite of questions over a variety of time scales. Existing geologic data indicate the likely existence of a stratigraphic record from prior to the Last Glacial Maximum; this record will further our understanding of the Larsen System under climatic conditions of the penultimate interglacial, when globally, sea level was higher and average climate warmer than today. Sea floor mapping and strategic marine sediment coring combined with land-based geomorphologic work will be used to reconstruct the configuration of the northern Antarctic Peninsula Ice Sheet during the Last Glacial Maximum and the subsequent retreat. Sediment coring coupled to field observations and satellite imagery will be used to evaluate the controls on the dynamics of ice-shelf grounding-line systems.

On a much larger spatial scale, the present rate of ice and snow mass change continues to be estimated using multiple satellite approaches. GRACE accomplishes this monitoring role by measuring gravity variations created by regional mass redistributions within the ice sheets. The LEGOS project engaged scientists from four nations, namely France, Australia, Germany and U.S., to analyze GRACE data. The results of this work have documented an important mass loss from the ice sheets for recent year equivalent to an increase of global sea level at ~1mm/yr with recent increases in contributions from the southeast and northwestern coasts of Greenland. A major result is evidence of an increased contribution from the two ice sheets over the past five to seven years. The ice sheet contribution was estimated to be equivalent to about 15% of the total sea-level change for the 1993-2003 decade (IPCC AR4). These studies have shown that it increased to 30% since 2003. The total land ice contribution (ice sheets plus glaciers) amounts to 75% for the 2003-2009 time span (Cazenave, 2009). Post glacial rebound remains the major source of uncertainly in these studies with the modeling of the rebound in Antarctica being the least accurate. POLENET (Polar Earth Observing Network - *Chapter 2.8*) is another IPY project that includes as one of its geodetic products a much-improved measurement of the spatial pattern and magnitude of post-glacial rebound. This product will directly and significantly improve the correction of GRACE measurements of ice sheet mass loss.

Satellite laser altimetry is an independent means of monitoring ice sheet change and IPY fell within the 2003-2009 lifetime of ICESat-1, NASA's laser altimetry mission. ICESat data mapped Antarctic ice thinning and thickening rates with greater spatial acuity than GRACE, producing similar results. West Antarctica, especially the Amundsen Sea Embayment remains the region of greatest thinning, with thinning also apparent over the Antarctic Peninsula regions having recently lost ice shelves, allowing an acceleration and thinning of feeding glaciers. East Antarctica has experienced modest thickening over much of the interior during the ICESat period, but the area is so vast the mass balance of the East Antarctic Ice Sheet appears to be positive (+68 +/- 52 Gt/a) in contrast to the significantly negative mass balance (-51 +/- 4 Gt/a) of West Antarctica. The corresponding mass balance for the Antarctic Peninsula is (-25 Gt/a) brings the continental total to near balance.

Looking to The Future of the Antarctic Ice Sheet

As in earlier polar years, IPY enabled scientists to make advances that would have been impossible without the collaborative framework of the major international effort. Escalating fuel costs threatened many programs, but the strength of the IPY collaborations and the conviction of the diverse teams enabled remarkable efforts to be launched and completed. The polar environment proved to be a challenge in 2007-2009 as it has in earlier years and some of the work has yet to be finished. For example, the plans to instrument the water beneath the ice shelf in front of the Pine Island Glacier had to be reconfigured to minimize the dangers to field personnel. Similarly the high altitude and cold temperatures encountered by the Norwegian-U.S. traverse along the ice divides challenged the vehicles and threatened to end the program early. In the first traverse Antarctic field season the team had to leave their vehicles 300 km away from South Pole before the winter set. For the AGAP project, over four years of planning spanning all seven continents resulted in an effort requiring nine aircraft, dozens of traverse vehicles, four airdrops and two major high altitude field camps (Figs. 2.5-2 and 2.5-3). Again the compelling nature of the cryospheric science forged within the collaborative framework of IPY provided the neces-

Fig. 2.5-2. USAP Twin Otter aircraft lands at the AGAP North field camp during IPY.
(Photo: Carl N. Robinson, BAS)

Fig. 2.5-3. Two scientists from the AGAP Project team, Beth Burton (USGS) and Adrienne Block (LDEO) and work on the new data sets collected under the AGAP field program.
(Photo: Robin Bell, 2009)

sary environment to continue these programs even as daunting challenges were encountered.

New insights from IPY are just now emerging. Multiple projects have contributed various aspects of a much more dynamic ice sheet both in the past and at the present time. We can expect continued dynamic behavior in our future from the Antarctic Ice Sheet. Some of the cryospheric programs have produced terra bytes of data.

It is worth remembering that even though IGY insights were based on single data points or a few wiggly lines on a seismic record on paper in the field, these data still figure into new scientific insights. We should only expect vastly more expansive insights to follow from the manipulation and visualization of these large, complex digital data sets collected during IPY 2007–2008 and that these data will support scientific research for decades to come.

IPY 2007–2008 fostered collaboration between scientists, engineers, students and logistics operators. The entire fabric of the Antarctic community has been strengthened by the groups reaching beyond the easy "normal" collaborations to new, challenging collaborations.

Even as this document is being written, IPY programs are in the field and some will be continued for the next two years. The POLENET program is just installing the lion's share of their instruments and the LARISSA program, trying to reach the western side of the Antarctic Peninsula, is struggling against extreme ice conditions. The ICECAP program will continue to map the margins of the East Antarctic Ice Sheet for another field season and the IPY initiated effort in the Amundsen Sea area will finally deploy the instrument into the ocean below the Pine Island Ice Shelf in 2011.

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