EuroGOOS Arctic Task Team

Planning Document

Draft

Edited by S. Sandven, E. Fahrbach, E. Buch, O. M. Johannessen, H. Cattle, L. Toudal and T. Vihma

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1 Summary

1.1 State-of-the-art

The Arctic climate of the 20th century has undergone major fluctuations which are characterised by a significant warming in the last two decades. The main features of these fluctuations are a substantial warming between 1925 and 1945, a marked cooling in 1950–1970 and finally an ongoing warming trend which started around 1980 (Johannessen *et al*., 2003). These events have not been restricted to the Arctic, but the strength of the warming has by far been most pronounced in the Arctic region, as the climate models predict. The warming predicted for the high Arctic is 3–4 °C in winter during the next 50 years, more than twice the global average, while the ice cover is predicted to reduce by ~40% during summer and ~10% during winter according to ECHAM4[1] and HadCM3[2] simulations (Johannessen *et al*., 2004a). This suggests that the Arctic may be the location of the most rapid and dramatic climate changes during the 21st century, with major ramifications for mid-latitude climate. Examples of model predictions of air temperature and sea ice extent are shown in Figure 1.

The Arctic region has over the last 2–3 decades warmed more than other regions of the world, and in the same period the sea ice cover has decreased by ~10% (Johannessen *et al*., 1999; 2004a) whereas the ice thickness has decreased up to 40% (Rothrock *et al*., 1999). Other observed changes include a warming of the Atlantic water in the Arctic Ocean (Morison *et al*., 1998), increased precipitation in the Arctic regions and higher river discharge into the Arctic ocean (Peterson *et al*., 2002). During the last decades detected changes include a significant freshening of the deep North Atlantic Ocean (Dickson *et al*., 2002), warming in the deep water of the Nordic Seas (Østerhus and Gammelsrød, 1999) and a decrease in deep overflow in the Faeroe Bank Channel (Hansen *et al*., 2001). The oceanic fluxes of heat and freshwater between the North Atlantic, Nordic Seas and Arctic Ocean are a key component of the high-latitude climate system (Oliver and Heywood, 2003).

1. ECHAM4: Max Planck Institute for Meteorology's climate model (http://www.dkrz.de)
2. HadCM3: The Hadley Centre climate model http://www.metoffice.co.uk

The Arctic Ocean plays a major role concerning the surface energy and freshwater budgets, because it is a large and effective heat sink, and it exports a significant amount of freshwater into the North Atlantic, into areas of deep water formation like the Greenland, Irminger and Labrador Seas, from where the global oceanic thermohaline circulation is driven. Improved monitoring systems are needed to provide consistent and long-term data on the ice-ocean circulation in the Arctic Ocean including the Fram Strait and Nordic Seas. Monitoring systems should have a central role in detection and verification of climate variability and trends. Monitoring and forecasting of the environmental conditions is also needed to support all types of marine operations to secure sustainable and safe development in high latitudes.

1.2 Rationale

The recent Arctic Climate Impact Assessment studies (ACIA, 2004) have identified a number of severe impacts of Arctic warming on society. Changes in air temperature, precipitation, river discharge, sea ice, permafrost, glaciers and sea level have been documented and further changes are expected over the next decades. The Arctic region is coming under increasing pressure from unsustainable development with pollution and other negative effects on the environment. The exploitation of resources, including sea transportation and offshore operations will be heavily affected by the climate variability and long-term changes at high latitudes. The northeast Atlantic, including Greenland and Icelandic waters, the Barents Sea and other Arctic ice edge regions provide 20% of the world's fish catch. Ocean temperature is one of the key variables that influence fisheries. For example, the temperature changes observed in the Kola section since the early 1900s show strong correlation with variability in spawning stock biomass of Norwegian spring-spawning herring (Thorsen and Østvedt, 2000), as shown in Figure 2. Monitoring the ocean environment is an important element in the management of fishery resources.

Tanker transportation of oil and gas in the Northern Sea Route between Russia and Western Europe is increasing, with associated risks for accidents and damage to the environment. The amounts of oil

transportation along the Norwegian coastline from Northwest Russia has increased considerably during recent years (Frantzen and Bambuliak, 2003), causing severe concerns that accidents like the Exxon Valdez in 1989 and the Prestige in 2002 can happen in European Arctic seas. Long-term

Difference in temperature after CO2 doubling   seasson: summer

Difference in temperature after CO2 doubling   seasson: winter

a)

b)

September

March
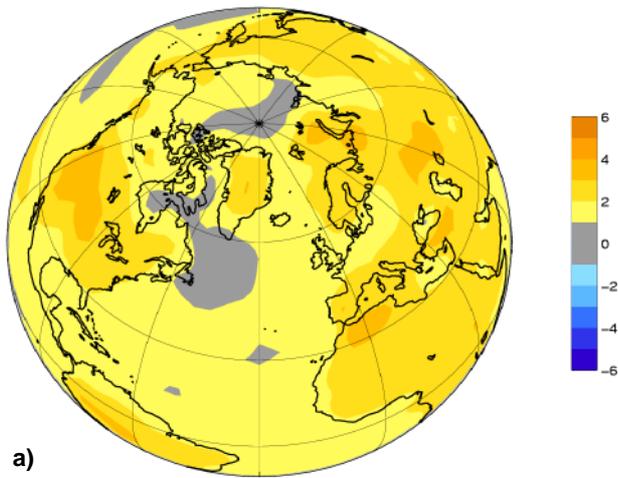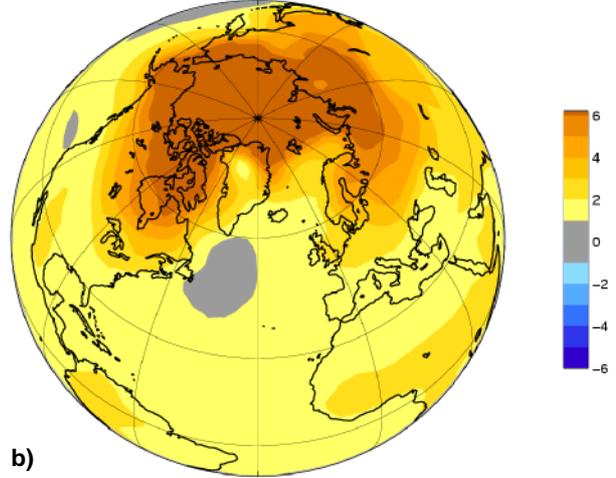
c)

d)

Figure 1 *Climate prediction scenario on doubling of CO_2 using the Bergen Climate Model (www.bcm.uib.no). Temperature change for the Arctic and sub-Arctic areas is shown for summer (a) and winter (b). Prediction of sea ice extent in 2070 is shown for September (c) and March (d) where the red area is the control run and the white area is the CO_2 doubling.*

a)

b)

Year
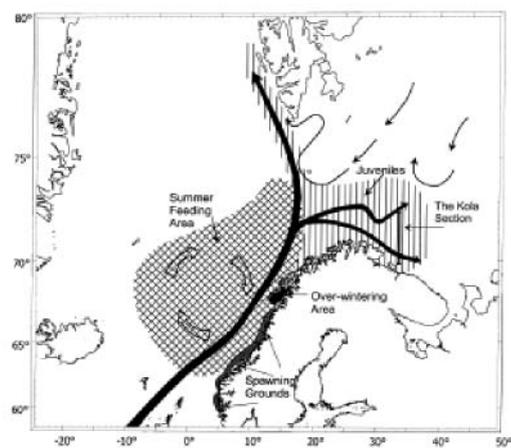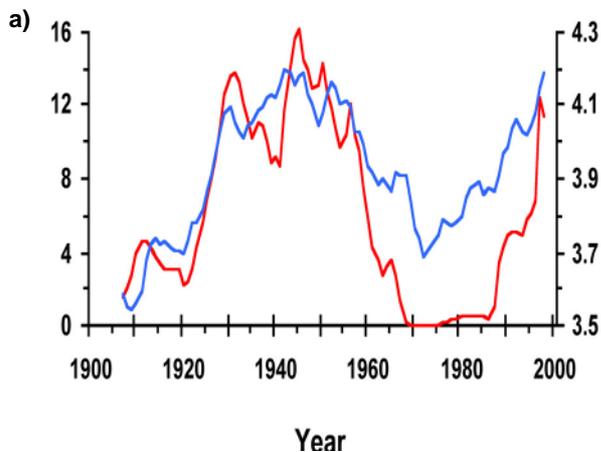
Figure 2 *(a) The red line shows fluctuations of spawning stock biomass (SSB) of Norwegian spring-spawning herring (unit: recruits 0-grp) and the blue line shows mean annual temperature in °C at the Kola section, (b) Distribution area of Norwegian spring-spawning herring in the north-east Atlantic region. Open arrows: migration route of herring during summer; thick arrows: main flow of Atlantic water; thin arrows: main flow of cold Arctic water (Thoresen and Østvedt, 2000).*

effects on the wildlife from the Exxon Valdez accident have recently been documented, showing unexpected persistence of toxic subsurface oil with chronic exposure to the Alaskan coastal ecosystem (Peterson *et al*., 2003). Various offshore operations in ice-covered waters will increase such as drilling, production, pipeline deployment in the seabed, and building of terminals in several locations along the Arctic coasts. All these activities will increase the risk of accidents and severe pollution of the fragile Arctic environment. The oil and gas resources in Arctic regions are huge and increased exploitation of these resources is expected in the future, with corresponding increase in tanker traffic and offshore operations. Northwest Russia and the Barents Sea has 25% of the world's unexploited petroleum resources (Figure 3), which will have an impact on global energy and transport policies.

Research expeditions and tourist traffic in Arctic waters are increasing. After the first icebreaker expedition to the North Pole with the Russian icebreaker Arctica in 1977, more than 50 vessels have visited the Pole during the summer periods. Over the last 10 years there have been several vessels to the Pole every year, most of them tourist expeditions.

Transit transportation between Europe and the East Asia and the west coast of North America through the Northern Sea Route can become economically attractive in the perspective of reduced sea ice cover. Transit expeditions with non-Russian vessels during summer started in 1991 with the L'Astrolabe voyage. Several demonstration voyages have taken place during the 1990s, and commercial transit traffic is expected to develop in a longer perspective (Johannessen *et al*., 2000).

The Arctic areas have rough weather and ice conditions which require improvement of operational monitoring and forecasting services in order to safeguard all types of marine and coastal operations. The operational services should also include long-term data archiving services to build up statistics of the environmental conditions. The International Maritime Organisation (IMO) develops the regulations and standards for legislation in countries with maritime activities. Guidelines for ships operating in Arctic ice-covered waters have recently been issued (IMO, 2002), specifying requirements for ship construction, machinery, equipment, crews, training and operational procedures. Furthermore, the guidelines have rules for environmental protection and damage control.

The Arctic Council is a key inter-governmental body focusing on protection of the Arctic environment and sustainable development as a means of improving economic, social and cultural well-being. The Arctic Council provides a mechanism to address the common concerns and challenges faced by the Arctic governments and the people of the Arctic. The Arctic Council runs several programmes, which need monitoring and data for assessment of the environment of the Arctic areas. One working group is PAME: Protection of the Arctic Marine Environment with responsibilities to take preventative and other measures, directly or through competent international organisations, regarding marine pollution in the Arctic, irrespective of origin. PAME has recently produced the Snap Shot Analysis of Maritime Activities in the Arctic (PAME, 2000) and Guidelines for Arctic Oil and Gas (PAME, 2002) activities to minimise negative impacts on the environment (Figure 4). The other working groups include AMAP (Arctic Monitoring and Assessment Programme), CAFF (Conservation of Arctic Flora and Fauna), EPPR (Emergency Prevention, Preparedness and Response) and SDWG (Sustainable Development).

The Commission on Oceanography and Marine Meteorology under WMO/IOC has issued a report on the need to establish improved observing systems for the polar regions (JCOMM, 2000). The Global Climate Observing System under WMO/IOC has produced an implementation plan in support of the United Nations Framework Convention on Global Change (GCOS, 2004) where global ocean and sea ice observations are on the list of essential climate variables.

The European Commission and the European Space Agency have jointly initiated GMES: Global Monitoring for Environment and Security, where the overall objective is to build up European capacity to provide operational monitoring services using spaceborne data as a key component (CEC, 2004). Services developed under GMES shall enable decision-makers in Europe to acquire the capacity for global as well as regional monitoring so as to effectively realise the EU's objectives in a wide variety of policy areas. Monitoring the Arctic is one of the thematic areas of the GMES services.

Operational services on met-ice-ocean conditions in the Arctic Ocean and the Nordic Seas are extremely important for safe and cost-effective industrial and transport activities as well as for protection of the vulnerable environment. In order to improve the operational services, it is necessary

to develop forecasting systems using numerical models and data assimilation techniques. Furthermore, availability of marine observations and development of information dissemination services are essential for improvement of services. The marine observations that form the basis for operational services are basically the same as those needed for climate research. It is therefore relevant that these two topics are considered simultaneously when planning an Arctic marine monitoring and forecasting system.
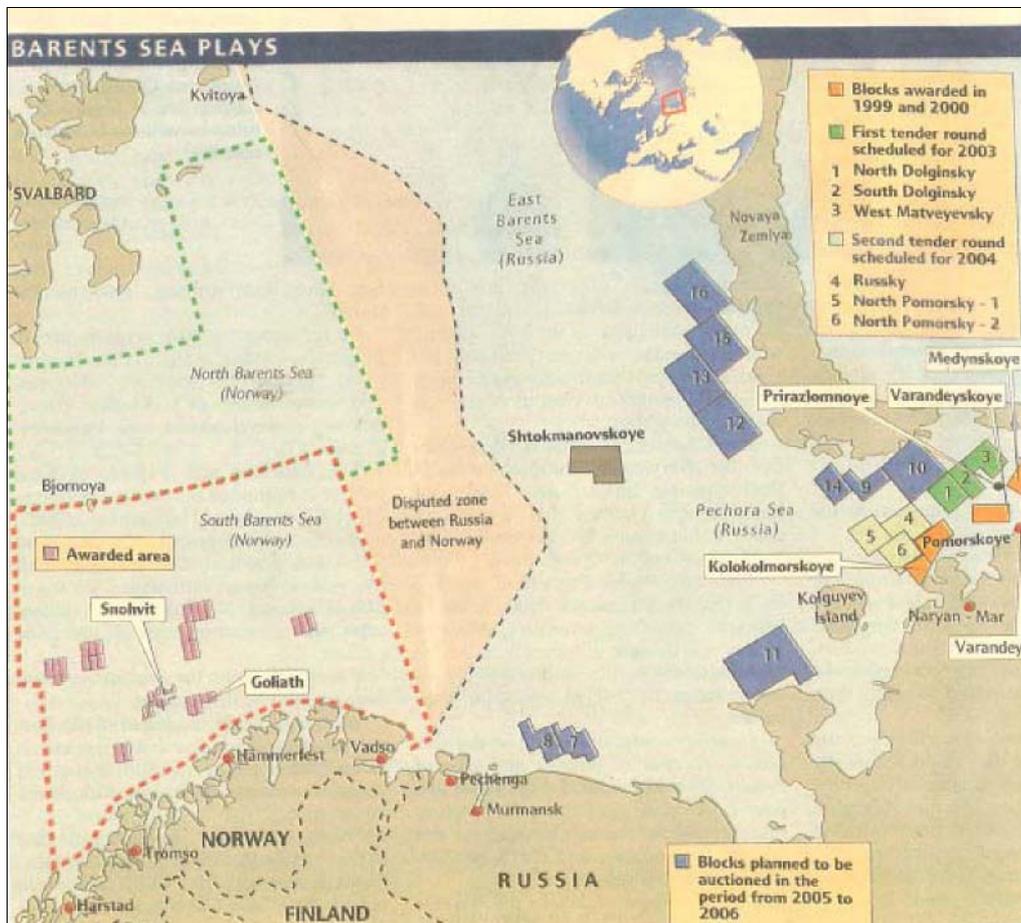

Figure 3 Map of the oil and gas fields in the Barents Sea and Pechora Sea. (Barlindhaug, 2004).

Figure 4 Concrete Island Drilling Structure (CIDS) in the Beaufort Sea, Alaska (PAME, 2002)

1.3 Objectives

The overall objective of the Arctic Task Team is to develop and implement optimal and sustainable monitoring and forecasting systems for operational applications in the Arctic Marine Region and adjacent seas using state-of-the-art remote sensing, *in situ* data, numerical modelling and data assimilation techniques.

In order to meet these objectives there is a need to

- Further develop the observing system network for operational monitoring and forecasting of sea ice and ocean parameters for shipping, fishing, pollution incidence and offshore industries

- Monitor the large- and mesoscale sea ice, hydrographic and current conditions in order to quantify climate change and variability

- Validate and improve existing models and data assimilation techniques and develop new models where needed

- Develop provider services to disseminate data and information products for the different users

- Monitor the direct and indirect impact of climate on recruitment, growth and distribution of commercial fish

- Assess the predictability of the fish stocks in relation to fishery management under varying climate conditions

- Establish quantitative relations between climate variability and plankton biomass and distribution.

1.4 Users of operational oceanography

1.4.1 Operational users who need near real time monitoring and forecasting services

Timely information on sea ice and other met-ocean conditions is essential for all types of marine operations in polar regions. Polar waters represent a significantly higher degree of risk to shipping than most other waters, by the presence of ice fields, wind and waves, icing of vessels and darkness in the winter. Human error is acknowledged to be a major factor in some 80% of all marine accidents in polar waters and the risk of errors is increased by the high demands placed on mariners. Another risk is the possibility of oil spill and other pollution which can cause severe damage to the environment. The presence of sea ice makes clean-up techniques normally employed in more temperate climates

useless in ice-covered areas. The safety and efficiency of sea transportation, off-shore operations, and fisheries and other marine activities have been the motivation for establishing operational sea ice monitoring and forecasting services in many countries in addition to the weather services. These services are usually limited to national areas of interest and leave large parts of the Arctic without daily monitoring and forecasting services.

1.4.2 Climate monitoring and modelling

One of the most significant aspects of climate change is the enhanced warming and the reduction of the sea ice cover in the Arctic. Better climatic data sets for the Arctic, including sea ice data, are required to validate and improve the climate model predictions for the high latitudes. Ice thickness and oceanographic variables are only observed in a few locations and occasionally by submarines and other ship-based methods. Ice volume budgets and fluxes are not observed due to lack of thickness data. Leads and polynyas, which are important for the vertical heat fluxes in the Arctic, are not well quantified due to the coarse resolution of the current ice maps. There is a significant lack of systematic long-term observations of the oceanographical variables in the Arctic Ocean.

1.4.3 Environmental monitoring and resource management

Human activities within the Arctic regions such as resource exploitation, transport, and tourism can have a severe impact on a vulnerable environment through pollution and other disturbance of the ecosystems. In addition, transported pollution from industrial areas at lower latitudes can have a significant impact on the Arctic environment, as shown in reports from the Arctic Monitoring and Assessment Programme (Figure 5). Issues for the marine environment include fisheries, ballast water from ships, oil discharge/emissions from ships, and effects of NO_x emissions over relatively remote oceanic areas with low background values. There is a lack of observations for most of the environmental variables in the Arctic Ocean. Observing systems are needed which includes physical as well as chemical and biological parameters.

1.5 Links to ongoing programmes and organisations

Implementation of operational oceanography in the high latitudes needs to build on existing programmes and organisations developing

observing and modelling systems for the Arctic Ocean and surrounding seas. The organisation of the EuroGOOS ATT will follow the functional structure of GOOS shown in Figure 6, where 'liaison and integration' will include links to Arctic Council Working Groups, GCOS, JCOMM, CliC, GMES, IABP, various EU-funded projects, and national monitoring programmes for the Arctic and Nordic Seas. Some programmes and projects deal with topics related to short-term operational services, while others deal with climate monitoring and research. GMES is a key programme in Europe to develop satellite monitoring systems, aiming to develop European operational services in support of public demand and policy-driven requirements

for information. Several programmes and projects relevant for the EuroGOOS ATT are listed in Table 1. The implementation of operational oceanography in the Arctic will build on the observing methods and modelling systems developed in these projects. Links also need to be established with activities in USA, Canada, Russia and other countries with interests in the Arctic.

1.6 Implementation Process

Initiatives have been taken to create an Arctic GOOS and the planning process has started. A number of parallel activities are ongoing which can make contributions to the development of opera-

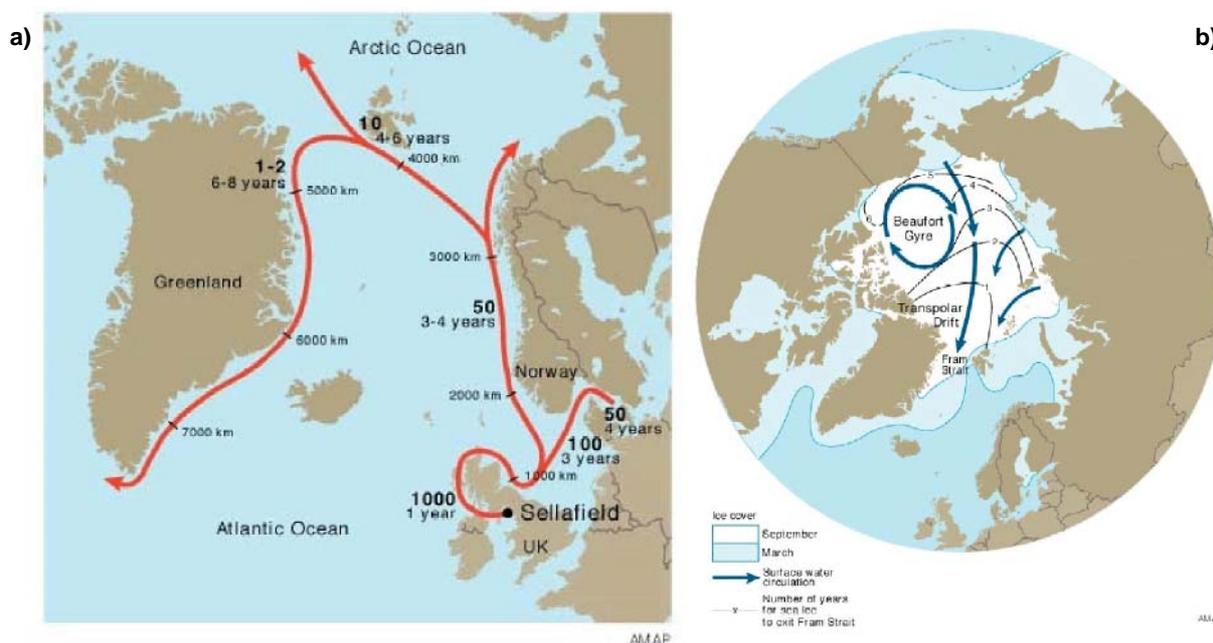**Figure 5** *Marine pathways of pollutants are illustrated by a) Radionuclides from storage and handling of spent nuclear fuel and waste, operation of nuclear power plants and vessels and military installations in Europe are transported by ocean currents; b) sea ice drift is also a potential mechanism for transport of pollutants over large areas. Copyright: AMAP*
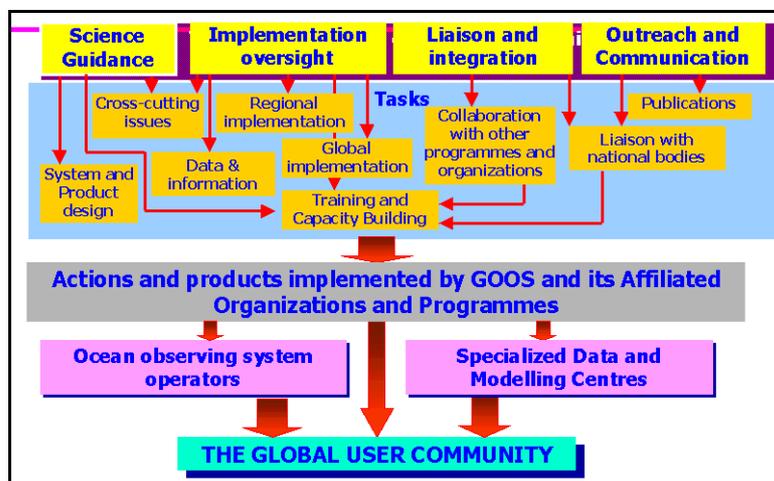

Figure 6 *The GOOS functional structure*

tional oceanography in the Arctic and surrounding seas. The Global Climate Observing System has produced an Implementation Plan which identifies a number of actions to be taken to establish observing systems, many of which are directly related to the polar regions (GCOS, 2004).

The GMES programme, initiated jointly by the EU and ESA, aims to develop and establish monitoring services by 2008. A number of GMES projects are funded to develop use of satellite Earth Observation (EO) in operational monitoring, including several Arctic projects (see Table 1). GMES is a mechanism to fund development and implementation of observing and modelling systems for the high latitudes where polar orbiting EO satellites are particularly useful.

The ESA GMES programme has defined several key service elements to be implemented against the background of user needs and ongoing developments in many applications of satellite data, including sea ice monitoring and other polar themes. The GMES includes satellite space segments and ground segments, data provision and distribution, service providers, research and development, and links to user groups who are the recipients of the data products. GMES builds links between research institutions and operational institutions and between climate monitoring and operational services (monitoring and forecasting). The Final Report form the GMES initial period 2001–2003 outlines a number of actions for the implementation of operational services within the next five years (GMES, 2004).

The ongoing Arctic/Subarctic Ocean Fluxes (ASOF) programme aims to measure and model the variability of fluxes between the Arctic Ocean and the Atlantic Ocean using arrays of current meter moorings in all the key straits as the main observing method. The European component of ASOF is funded for 2002–2005 by the EU Fifth Framework Programme.

The International Polar Year (IPY), which is planned for 2007–2008 under the leadership of the International Council for Science, will consist of internationally coordinated interdisciplinary scientific research and observations focused on the Earth's polar regions. IPY offers an opportunity to develop and implement new observing systems for the Arctic and perform intensive field campaigns and data collection. IPY 2007–2008 will thus provide a framework and impetus to undertake projects that normally could not be achieved by any single nation. The IPY Planning Group has developed a science plan and implementation strategy (IPY, 2004) available at www.ipy.org.

An EU-funded project "Climate of the Arctic and its Role for Europe (CARE)—a European component of the International Polar Year" will during 2005–2006 plan a number of climate-related studies as part of IPY (Johannessen *et al*., 2004b).

The proposed Arctic Ocean Observing System (AOOS) will deploy a number of observing platforms on ice floes and in the deep water underneath the sea ice cover. AOOS is part of the Arctic Ocean Science Board–CliC observing plan for the IPY (Dickson, 2004). AOOS addresses a number of technical challenges that will make a significant contribution to operational observing systems such as near real time data transmission from deep ocean platforms under the sea ice.

Monitoring of sea ice will be part of the Integrated Global Observing Strategy Cryosphere Theme (IGOS-Cryo), which was initiated in May 2004 when a concept paper was presented to the IGOS Partners (IGOS 2004). The concept paper was prepared by people from the World Climate Research Programme (WCRP) Climate and Cryosphere (CliC) project in collaboration with the Scientific Committee on Antarctic Research (SCAR), and in consultation with several IGOS partners. The response was favourable, and the IGOS Partners agreed that the cryosphere is very important for IGOS and encouraged the proposers to proceed. The next major step is to generate a theme report in 2005. The report will review the needs in observing data and products, analyse the current state and future of these observations, and propose feasible objectives for the development of the observations which represent a consensus between most important data users and data providers. On the basis of the consensus, the Theme team proposes a plan of actions and developments. These actions must have clearly specified objectives, implementing organisations, deadlines, an indication of resources needed and of readiness by the data providers to commit the resources. The IGOS Partners consider the report and decide whether it can go to the Implementation Phase.

Table 1 *Programmes and organisations with activities of relevance to the EuroGOOS ATT*

Programmes	Objective and Homepage
Global Climate Observing System (GCOS) 1992−	Programme under WMO and IOC to ensure that observations and information needed to address climate-related issues are obtained and made available to all potential users. http://www.wmo.ch/web/gcos/gcoshome.html
International Arctic Buoy Programme (IABP), 1979−	Operates a network of ice buoys in the Arctic Ocean to provide meteorological and oceanographic data for real-time monitoring. http://iabp.apl.washington.edu/
Arctic Climate Impact Assessment (ACIA), 2000−	Evaluates and synthesises knowledge on climate variability, climate change, and increased ultraviolet radiation and their consequences. http://www.acia.uaf.edu/
Climate Variability and Predictability (CliVar) 1995−	WCRP programme to study the natural climate variability and anthropogenic climate change. http://www.clivar.org/
Arctic Climate System Study (ACSYS), 1994−2003.	Completed WCRP programme to ascertain the role of the Arctic in global climate. http://acsys.npolar.no/
Climate and Cryosphere (CliC), 2003−	WCRP programme to assess and quantify the impacts of climate variability of all the cryospheric components on both hemispheres. http://clic.npolar.no
A Study of Environmental Arctic Change (SEARCH), 2003−	US programme to study the full scope of the changes going on in the Arctic psc.apl.washington.edu/search/
Arctic Monitoring and Assessment Programme (AMAP), 1991−	Programme under the Arctic Council to provide information on the status of, and threats to, the Arctic environment. http://www.amap.no
Protection of the Arctic Marine Environment (PAME), 1993−	Programme under the Arctic Council to address policy, non-emergency pollution prevention and control measures for protection of the Arctic marine environment http://www.pame.is
Arctic Subarctic Ocean Flux Array for European Climate (ASOF), 2003−2005.	Ongoing programme to measure and model the variability of fluxes between the Arctic Ocean and the Atlantic Ocean. The European component is co-funded by EU. http://asof.npolar.no/index.html
GMES projects under ESA's GSE programme (2003−2008)	ESA Earthwatch GMES Service Element (GSE) is a 5 year programme dedicated to GMES. http://earth.esa.int/gmes/index.html. Sea ice monitoring project: see http://www.icemon.org
Arctic Operational Platform (ARCOP), 2002−2005.	EU-funded project on technological, environmental, economic and legislative aspects of Arctic shipping and oil exploitation. http://www.arcop.fi/main.htm
Ice Ridging Information for Decision Making in Shipping Operations (IRIS), 2003−2005.	EU-funded project to develop operational ice services by improving information on ice ridges and to develop route selection methods for ships. http://www.hut.fi/Units/Ship/Research/Iris/Public/
Integrated Observing and modelling of Arctic sea ice (IOMASA), 2002−2005	EU-funded project to develop earth observation for Arctic sea ice & atmosphere. http://www.iup.physik.uni-bremen.de/iuppage/psa/2001/14iomasa.html
Arctic Ice Cover Simulation Experiment (AICSEX), 2001−2003.	EU-funded project to study the natural variability and trends for climate-sensitive variables, the performance and prediction capabilities of climate models in the Arctic. http://www.nersc.no/AICSEX/
Marine EnviRonment and Security for the European Area (MERSEA), 2002−2008.	EU-funded Integrated Project to develop operational oceanography using spaceborne data, *in situ* monitoring networks, ocean modelling and data assimilation systems. http://www.mersea.eu.org
International Polar Year 2007 (IPY− 2007).	http://www.ipy.org

2 Natural Conditions

2.1 Ice-covered and ice-free areas

The EuroGOOS ATT will cover the Arctic Ocean including the Nordic Seas, the Barents Sea and the Russian shelf areas due to the importance of these regions for climate, environment and economic activities. According to different sea ice conditions, the areas can be divided into three domains (Figure 7).

A. Ice-free areas. The Norwegian Sea and parts of the Barents Sea and the Greenland Sea are always ice-free. These areas have considerable ship traffic, fisheries and growing offshore activities off the coast of Mid- and North Norway. In these areas observation systems similar to other open ocean areas can be implemented.

B. Seasonal ice areas. The Arctic Ocean and the adjacent shelf seas including the Greenland coastal areas have seasonal ice cover making the areas accessible by vessels in summer and autumn. Observational systems can be deployed on subsurface moorings from ships during this period and operate for a year including the winter season when the areas can be fully ice-covered. Deployment and recovery requires ice-strengthened vessels. Important activities in these areas include fisheries, offshore operations in the Pechora Sea and sea transportation in Greenland area, Svalbard and in the Northern Sea Route. In recent years the size of the seasonal ice areas has increased because the summer ice extent has been reduced.

C. Perennial ice areas. The area of perennial ice cover, which mainly consists of the deep Arctic Basin, can only be reached by strong icebreakers, submarines or aeroplanes. These areas are the least observed of all oceans, and *in situ* measurements are only available from occasional expeditions. Ice buoys from the International Arctic Buoy Programme provide air pressure, temperature and ice motion, but no sub-surface measurements. Ocean observations in these areas require autonomous systems that can operate under the ice.
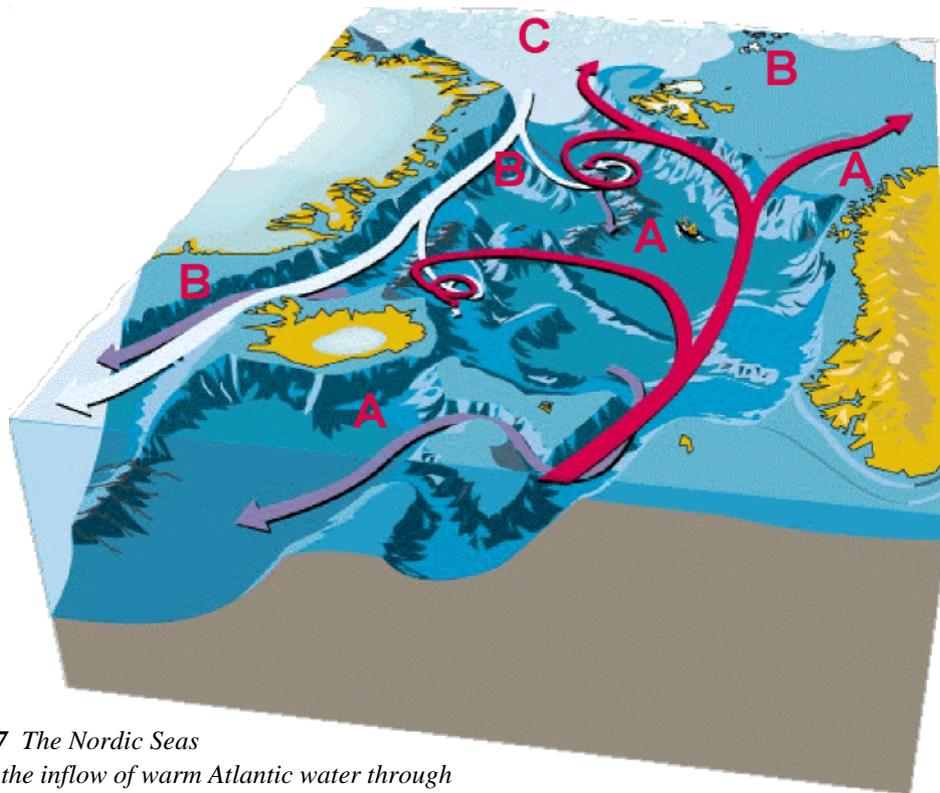
Figure 7 The Nordic Seas showing the inflow of warm Atlantic water through the Faroe−Shetland Channel (red arrows) keeping the Norwegian Sea and part of the Greenland and Barents Sea ice-free throughout the year (Area A). The outflow of sea ice and polar water through the Fram Strait and the Denmark Strait is shown by white arrows, and deep water outflow to the North Atlantic is shown by blue arrows. Area B indicates the seasonal ice zone, whereas C is the perennial ice region extending across the deep Arctic Basin.

2.2 Description of the Arctic Ocean and the adjacent seas

The Arctic Mediterranean includes the Arctic Ocean with the adjacent shelf seas and the Nordic Seas. It consists of a series of ocean basins which are separated by ridges. The basin structure determines to a large extent the internal circulation which controls the water mass modifications (Figure 8). Relatively warm and saline water enters into the Nordic Seas from the Atlantic Ocean and is advected through the Fram Strait and the Barents Sea into the Arctic Ocean. Water of relatively low salinity is supplied through the Bering Strait from the Pacific. River run-off from the continents adds a significant amount of fresh water. The water of Atlantic origin circulates within the Arctic Mediterranean on different paths where it undergoes intensive modifications. The waters exiting the Arctic Mediterranean supply the source waters for the formation of North Atlantic Deep Water which plays a significant role in the global thermohaline overturning circulation. Shallow water masses leave the Arctic Ocean through the Canadian Archipelago into the Labrador Sea. The Fram Strait represents the only deep water connection between the Arctic Ocean and the Nordic Seas. This strait is characterised by a northward flow of deep waters
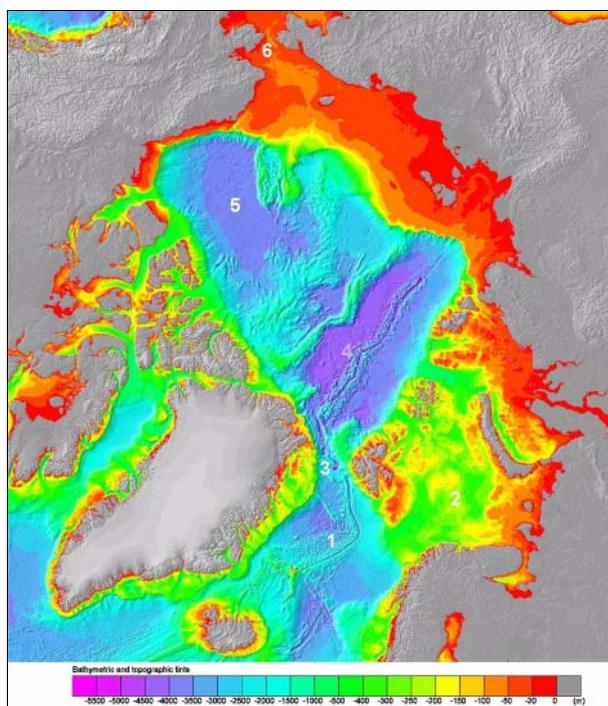

Figure 8 *Bathymetry of the Arctic Ocean and surrounding seas. 1: Nordic Seas, 2: Barents Sea, 3: Fram Strait, 4: Eurasian Basin, 5: Canadian Basin, 6: Bering Strait.*
(IBCAO, http://www.ngdc.noaa.gov/mgg/bathymetry/ arctic/arctic.html)

from the Greenland and the Norwegian Seas entering the Arctic Ocean, and deep waters from the Arctic basins flowing southward to the Nordic Seas. The source waters for the North Atlantic Deep Water formation leave the Nordic Seas as overflows between Greenland and Scotland.

The Nordic Seas comprise the Icelandic, the Norwegian and the Greenland Sea. To the south they are separated from the North Atlantic proper by a system of sills between Greenland and Scotland (Hansen and Österhus, 2000). In the east warm and saline Atlantic water penetrates across the sills into the Nordic Seas. Cold and dense water crosses the sills to the south and forms the overflow which, together with the water masses from the Labrador Sea, determines the properties of the North Atlantic Deep Water. Within the Nordic Seas the Norwegian Current leads the Atlantic Water at the eastern side to the north where it reaches the Arctic Ocean through the Barents Sea and Fram Strait. On the western side, the East Greenland Current transports cold and low saline Polar Water from the Arctic Ocean to the south. The two major meridional current systems are connected by cyclonic gyre flows which form several circulation branches. They are to some extend steered by bottom topography and lead water of Atlantic origin to the west where it is incorporated into the southward flow as Atlantic Return Water, while water from the East Greenland Current is led to the east. In the interior of the gyre, water mass modifications occur affecting the properties of the recirculations and forming the Greenland Sea Deep Water which leaks into the deep Norwegian Sea. The overflow water to the North Atlantic consists mainly of waters from intermediate depths and comprises a variety of products of water mass modifications (Rudels *et al.*, 2002).

The oceanic circulation in the Arctic Ocean is driven by a combination of wind and thermohaline forcing. The air pressure distribution is basically determined by a high pressure system over the Beaufort Sea and low pressure over the Nordic Seas leading to an anticyclonic circulation pattern. However, it is strongly modified by the topographical structure of the basins which gives rise to internal circulation cells.

The Arctic Mediterranean is covered by a seasonally varying ice cover which moves by wind forcing and ocean currents. The anticyclonic circulation in the Beaufort Gyre, often called the Beaufort High, and a less well established cyclonic counterpart over the European Arctic feed into the Transpolar Drift. The latter provides the major

export of sea ice through the Fram Strait into the Nordic Seas where most of it melts and affects the stability of the water column. Due to the large scale sea level inclination there is a net flow from the Pacific Ocean into the Atlantic. In spite of a relatively small mass transport, this flow represents a major control of the global fresh water cycle due to its low salinity, maintaining the balance between the relative saline Atlantic and the fresher Pacific water.

A major shift in the atmospheric pressure system and the ice drift pattern has been observed during the 1980s and 1990s as shown in Figure 9 (Steele and Boyd, 1998). The most pronounced changes are:

1. the Beaufort High has decreased and shifted towards the east

2. the Transpolar Drift shifted axis anti-clockwise producing more cyclonic motion in the 1990s

3. the ice extent and thickness have decreased.

Furthermore, the properties of the water masses have changed during the same period. A comparison of observations during the 1990s with earlier data shows that the Atlantic Water layer was significantly warmer than during earlier decades and the freshwater layer was significantly saltier (Figure 10). A frontal shift towards the east has also been observed between Atlantic and Pacific waters in the Eurasian Basin (Morison *et al.*, 2000). These changes can have severe impacts on the heat fluxes, ice formation and melting rates and other climate related processes. Observing and quantifying the changes in the Arctic water masses more systematically is an important task to be included in future monitoring systems.
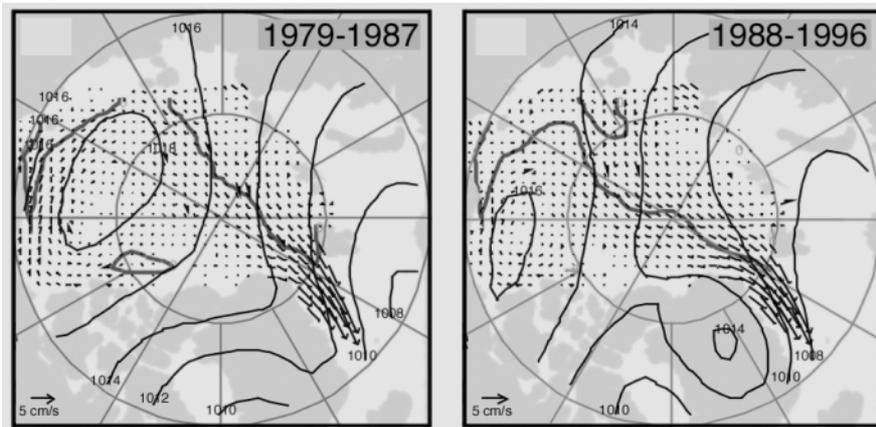

Figure 9 *Average atmospheric surface pressure fields and sea ice drift fields for the periods 1979–1987 and 1988–1996 respectively (Steele and Boyd, 1998).*
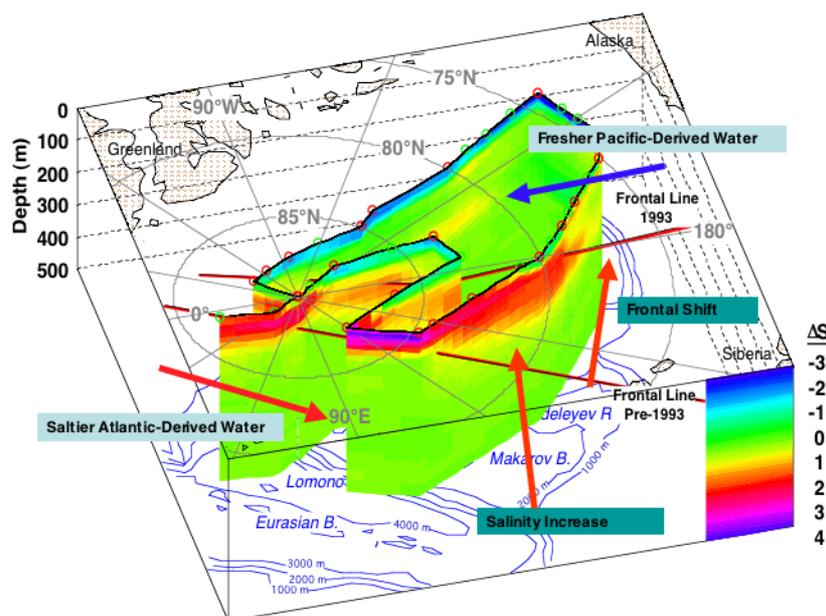

Figure 10 *Observed changes in water masses and fronts in the Arctic Ocean during the 1990s (Morison et al., 2000).*

3 Variables and Observing Strategies

Data collection in the Arctic Ocean and the Nordic seas will serve two purposes: real-time data to be delivered to the users soon after acquisition and long-term climate data which do not necessarily need to be delivered in real-time. Both modes of data collection are highly demanding regarding observational equipment, data communication, data quality and reliability of the systems. The two systems are characterised as

- **Real-time data collection** to provide data for a near real-time description of the ocean state of the Arctic (wind, waves, temperature, salinity, currents sea ice, etc.) as well as generating initial fields and assimilation data for ocean forecasting modelling.
- **Climate monitoring** to generate data for climate research projects and process studies as well as for the generation of time series of essential ocean parameters in strategic areas.

The real-time ocean monitoring requires robust operational systems capable of delivering data continuously or at intervals when subsurface buoys pop up to the surface and transmit data via satellites such as the ARGO system (Gould *et al.*, 2004). The requirements on the data quality are however not as strong as in oceanographic research campaigns, although it has to be taken into account that the Arctic area is very dynamic where a large number of water masses with minor T/S differences enter and form. Climate monitoring, on the other hand, requires more strict data quality because it is important to detect trends with low signal-to-noise ratio.

The particular conditions in the Arctic Ocean restrict the maintenance of an ocean-wide observational system with quasi-continuous data. Therefore special efforts are required where different types of measurements are combined, using both remote sensing and *in situ* systems. Furthermore, data assimilation will be used to fill gaps in the observation network. *In situ* measurements will be focused on observation of fluxes through the boundaries, supplemented by some interior control areas to constrain model calculations. Only a part of the data will be available in real time, but new technologies will be used to transmit data from subsurface platforms when this is a feasible solution.

Sea ice represents a barrier as well as opportunities for deployment of observing platforms. Therefore, development of new *in situ* observing systems which can be used operationally will have high priority in the Arctic regions. These systems can be divided into four categories:

- Ship-borne measurements
- Measurements from moored systems
- Measurements from ice buoys
- Measurements from subsurface free drifting or propelled autonomous systems

3.1 Sea ice

The presence of sea ice together with harsh climate and weather conditions in the Arctic imposes strong limitations on maritime activities in these areas. Monitoring and forecasting of sea ice, weather and ocean variables are therefore of high priority to support safe and cost-effective maritime operations in ice-covered areas (Figure 11). Ships and platforms need to have ice class certification depending on the severity of the ice conditions where operations take place. Weather and some ocean forecasts (mainly storm surge and waves) are available on a routine basis, while operational forecasting of ocean currents, hydrographical conditions and sea ice parameters still have to be implemented.

Sea ice has a dramatic effect on the physical characteristics of the ocean surface. It modifies the

Figure 11 Photograph of R/V Polarstern during the research expedition ARK XIX/1 in the sea ice region north of Svalbard in April 2003. Courtesy Alfred Wegener Institute for Polar and Marine Research.

surface radiation balance due to its high albedo, and it influences the exchange of momentum, heat, and matter between atmosphere and ocean. It also results in much lower surface air temperatures over the ice-covered areas in winter than are maintained by the ocean immediately underneath. Freezing of sea ice expels brine which deepens the surface mixed layer and can, through convection, influence the formation of deep and bottom water in both hemispheres. Melting, in contrast, produces relatively fresh water that stratifies the oceanic surface layers (i.e. the mixed layer retreats to shallower depths). In contrast to low latitudes, the mixed layer evolution in Polar Regions is dominated by surface fluxes of salt or fresh water (positive or negative freezing rates). In the Nordic Seas added freshwater may be critical for the formation of deep- and intermediate water masses.

Through these effects, sea ice plays a key role in the global heat balance and the global thermohaline circulation. A retreat of sea ice associated with climate warming can therefore have global consequences and contributes, through various feedback processes, to enhanced climate change, particularly at high latitudes.

Sea ice observation and mapping is today based mostly on satellite remote sensing, supplemented by observations from ships, aircraft and coastal stations. Remote sensing techniques provide good spatial data coverage and repeated observations which are needed for operational monitoring. Operational monitoring uses different remote sensing sensors which provide variable data coverage, while *in situ* observations are used for validation and quality control of the remote sensing data. An overview of the most important satellite sensors and operational monitoring methods is presented in Table 2 and 3.

3.1.1 Ice concentration/extent and navigational ice charts

Global sea ice monitoring, which is one of the main elements in climate change detection, is only possible with use of satellite data. Starting with NASA's Nimbus–7 in 1978, passive microwave observations of the global ice areas have been regularly available for more than two decades, providing a unique data set to study seasonal, inter-annual and long-term variability of sea ice extent. Complete coverage of the polar regions of the Earth is available every day (1987–) and every other day (1978–1987). Monthly mean areas of total and multiyear ice have been produced by the Nansen Environmental and Remote Sensing Center to study the trends in the ice area in the Arctic since 1978. The time series of passive microwave data shows that the total ice area has been reduced by 3–4% per decade, while the multiyear ice areas has been reduced by 7% per decade (Johannessen *et al*., 1999, 2004) Maps of ice concentration and extent are produced by several service providers such as the EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI–SAF) (http://saf.met.no), the Institute of Environmental Physics, University of Bremen (http://www.seaice.de) and the Danish Centre for Remote Sensing at the Technical University of Denmark (http://www.seaice.dk). Examples of large scale ice maps and time series from passive microwave data are shown in Figure 12–Figure 14.

Table 2 Satellite sensors and the geophysical variables which can be observed

Satellite sensor	Geophysical variables
Optical imager	Ocean colour features, sea ice area, leads, polynyas, floes
Scatterometer	Ice area, ice motion, surface wind vectors
Passive microwave radiometer	Sea ice extent and concentration, sea ice motion, surface wind speed, waves
Synthetic Aperture Radar (SAR)	Ice types, ice features, ice drift, leads, polynyas, surface wind, ocean features, waves
Infrared radiometer	Sea surface temperature, ice area, leads, polynyas
Radar altimeter	Sea level, ocean currents, sea ice freeboard and thickness
Laser altimeter	Sea level, sea ice freeboard and thickness
Gravimeter	Improved geoid for determination of sea level and ocean currents

Table 3 *Satellite data used in operational ice monitoring*

|	Satellite Sensors	Start	Comments	Operational use
Optical/ IR	NOAA AVHRR DMSP OLS	1978– 1987–	Traditionally the most commonly used satellite data for ice monitoring. Repeated coverage every day	Use by most ice centres, but limited by clouds
	SeaWiFS, MODIS	1999	Used for ocean colour mapping, MODIS is also useful for ice mapping	Used occasionally in high latitudes due to frequent cloud cover
	ENVISAT AATSR & MERIS		Several similar sensors are available on other satellites	Not used regularly
Active Microwave	ERS−1/2 SAR	1995–	ERS−1 was the first satellite to provide extensive SAR coverage in 100km swath over ice. ERS−2 followed ERS−1 in 1996.	Used in pre-operational demonstrations since 1991
	Okean SLR	1983–	Real-aperture radar with 1.5 km resolution, Swath width 450 km	Used by Russian ice services
	RADARSAT	1996–	Most commonly used satellite data in regional ice monitoring. The first SAR satellite providing wideswath images for operational ice monitoring	Used by the ice services in Canada, USA, Denmark, Finland, Sweden and Norway
	ENVISAT ASAR	2002	First SAR satellite providing wideswath and dual polarisation images for operational ice monitoring	Data delivery started in 2003, used as supplement to RADARSAT
	Quikscat Scatterometer	1999	Repeated coverage every day of all ice areas. Resolution of 25 km	Used in EUMETSAT OSI−SAF products
Passive Microwave	DMSP SSM/I	1987–	Repeated coverage every day of all ice areas. Useful in climatology studies as well as near real time large scale monitoring. Resolution 10−30 km	Time series of ice area since 1978. Used in EUMETSAT OSI−SAF products
	NASDA & NASA AMSR	2003–	Next generation passive microwave instrument. Improved spatial resolution, better spectral coverage: 6−10 km	Supplement to the SSM/I data
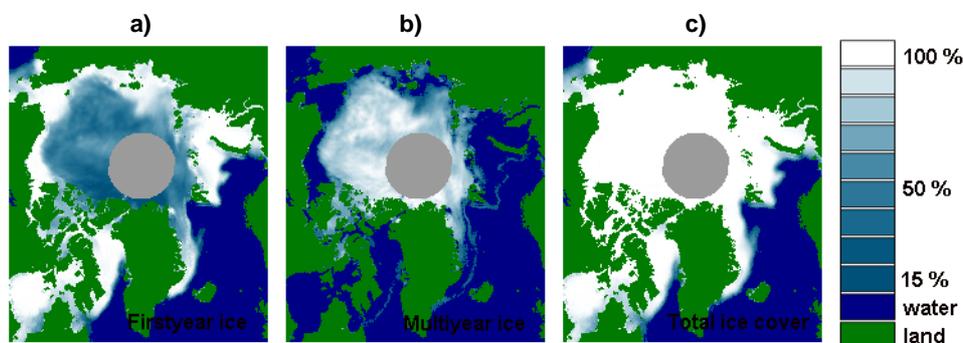
Figure 12 *Example showing Arctic ice area maps produced from passive microwave satellite data (SSMI), showing a) firstyear fraction of ice concentration, b) multiyear fraction of ice concentration, and c) total ice concentration.*
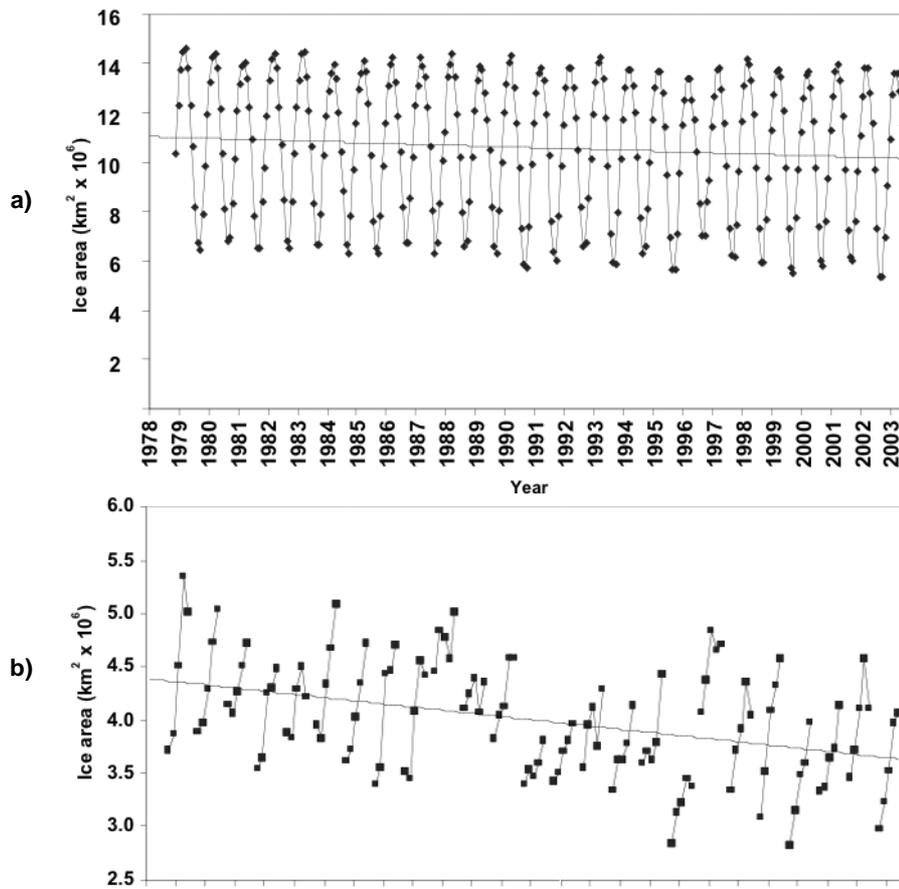
Figure 13 *Time series of a) monthly mean total ice area and b) monthly mean.multiyear ice area in the Arctic from passive microwave satellite data (SSMI) from 1978 to 2003. In addition to the seasonal cycle, the trend line is shown indicating a reduction of about 3% per decade of the total ice area and about 7% per decade for the multiyear ice. Note that the multiyear ice is only calculated for the winter months.*
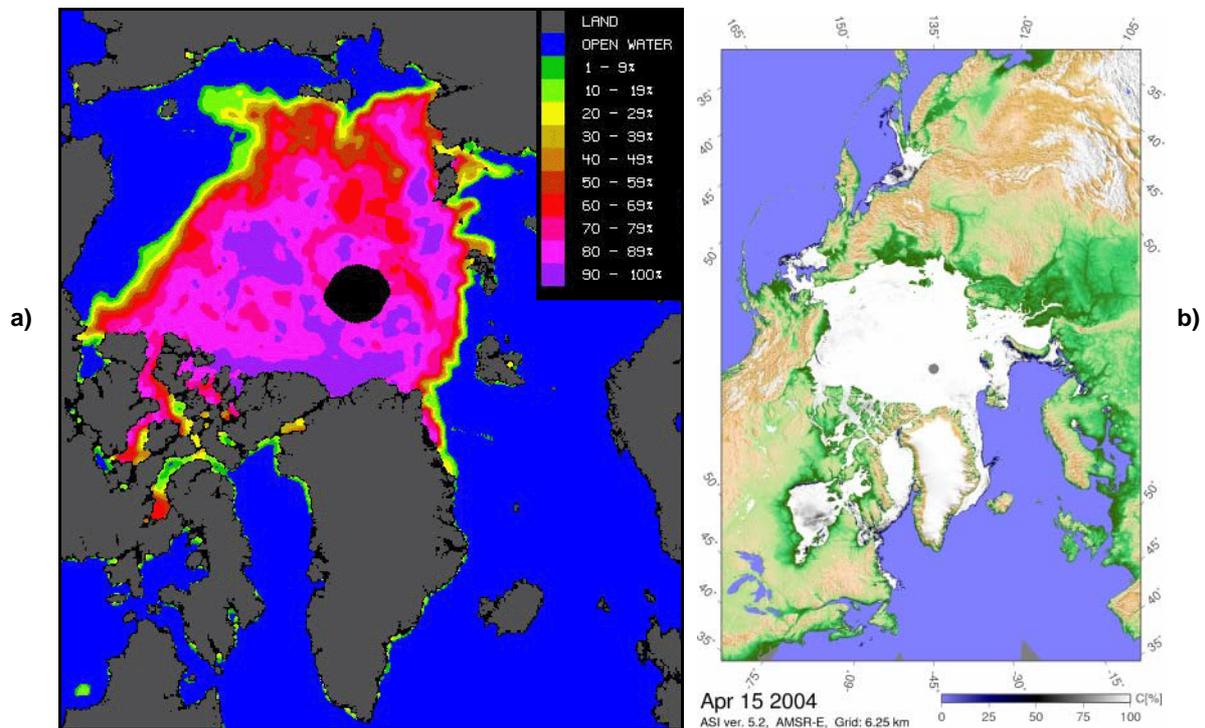

Figure 14 *a) Example of ice chart produced by EUMETSAT's Ocean and Sea Ice Satellite Application Facility (OSI SAF) obtained in October 2004 based on SSMI; b) example of ice concentration map produced by Institute of Environmental Physics, University of Bremen based on AMSR–E data, providing higher resolution than the SSMI data.*

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In addition to large scale ice maps, operational monitoring also provides high-resolution ice charts for navigation purposes. For this purpose wideswath SAR data from the RADARSAT and ENVISAT satellites have been implemented in ice services in USA, Canada, Greenland, Svalbard area, and the Baltic Sea (Sandven *et al*., 1999). SAR sea ice mapping started with the ERS programme and continued with RADARSAT providing ScanSAR images from 1996. ENVISAT has provided wideswath SAR images since 2003. In the Northern Sea Route (NSR), which is the sailing route along the Northern coast of Russia from the Barents Sea to the Bering Strait, SAR ice monitoring has been demonstrated on several occasions since 1991 (Johannessen *et al*., 2000). In August–September 1997, the first demonstration of RADARSAT data for ice observation and navigation support in the eastern Kara Sea and Laptev Sea during summer was performed by the Nansen Center in cooperation with the Murmansk Shipping Company's nuclear icebreaker (N/I) Sovetsky Soyuz (Sandven *et al*., 2001). In the late winter of 1998, a mosaic of ScanSAR images was produced in the western part of the NSR (Figure 15) as part of the ARCDEV project where the feasibility of navigating an ice-going tanker from Ob Bay to Murmansk during severe ice conditions was demonstrated (Petterson *et al*., 1999; Alexandrov *et al*., 2000). Since then, several Arctic expeditions have used wideswath SAR data delivered to the ships in near real time to support ice navigation.

3.1.2 Ice thickness

In order to assess changes in the Arctic ice volume, the thickness of the ice needs to be measured as well as the concentration and area. An ice thickness observation system should provide long term measurements as well as a sound data base to improve the representation of processes in numerical models. Thus, thickness observations on different spatial and temporal scales are necessary. The overall changes of the Arctic Ocean's ice volume can only be estimated from basin-wide observations, as there is likely to be much redistribution of ice within the basin.

Most of the ice thickness data have been gathered by upward-looking sonar (ULS) measurements from military nuclear submarines (Rothrock *et al*., 1999; Wadhams, 1994) and from oceanographic moorings equipped with ULS (Vinje *et al*., 1998). However, for ice thickness there is severe lack of synoptic observations across the Arctic Ocean. Satellite radar altimeter data can provide an important contribution to ice thickness observations in the Arctic (Laxon, 2003). The methodology is based on the separation of radar altimeter echoes from ice and water, allowing direct measurement of
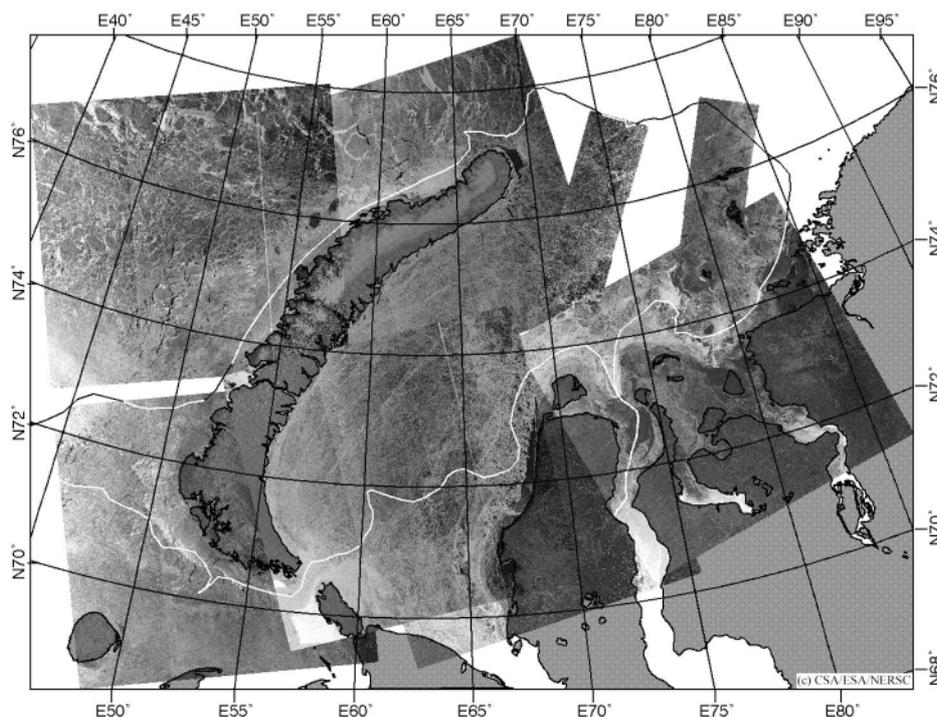

Figure 15 *Mosaic of RADARSAT ScanSAR images with 500 km swath width obtained during the period 25–30 April 1998, during the ARCDEV expedition (Pettersson et al., 1999). The mosaic also includes some ERS SAR stripes which are 100 km wide. The line shows the track of the icebreakers escorting M/T Uikku to the Ob Bay.*

sea ice freeboard and hence retrieval of ice thickness (Figure 16). CRYOSAT, an ESA mission dedicated to profiling of sea-ice thickness, is scheduled for launch in 2005 and is designed to operate for three years.

Recently, electromagnetic (EM) sounding from helicopter flights has become a well-established technique for measuring ice thickness on local and regional scale. Large data sets representative for regional ice regimes can be gathered for determination of the of ice thickness distribution as shown in Figure 17 (Haas and Eicken, 2001). EM technology is under further development and will allow repeated systematic surveys in regions where helicopters can operate. These data will also be important for validation of CryoSat ice thickness data.

3.1.3 Ice drift

A well-established autonomous system to measure ice drift consists of buoys deployed on sea ice by the International Arctic Buoy programme (IABP). They are normally expendable and airdropped and transmit location and meteorological parameters such as surface pressure and temperature via ARGOS. The positions of the buoys (Figure 18a) are used to estimate ice drift in the areas where the buoys are located. Synoptic ice drift is derived from scatterometer and passive microwave data, providing a valuable supplement to the drifting buoy measurements (Figure 18b). Ice drift is also observed in areas such as in the Fram Strait from moorings equipped with ADCP and ULS, providing time series over several years.
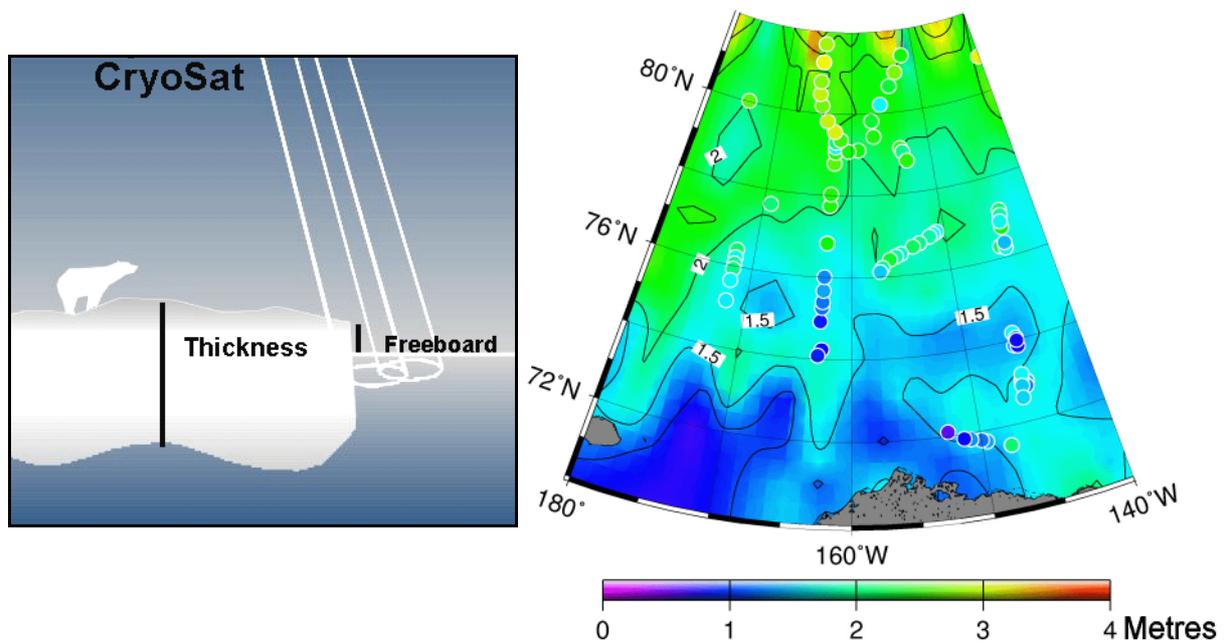

Figure 16 a) Concept of ice thickness measurements from space using radar altimeter (courtesy ESA),
b) example of ice thickness map in the Beaufort Sea based on ERS radar altimeter (courtesy S. Laxon).
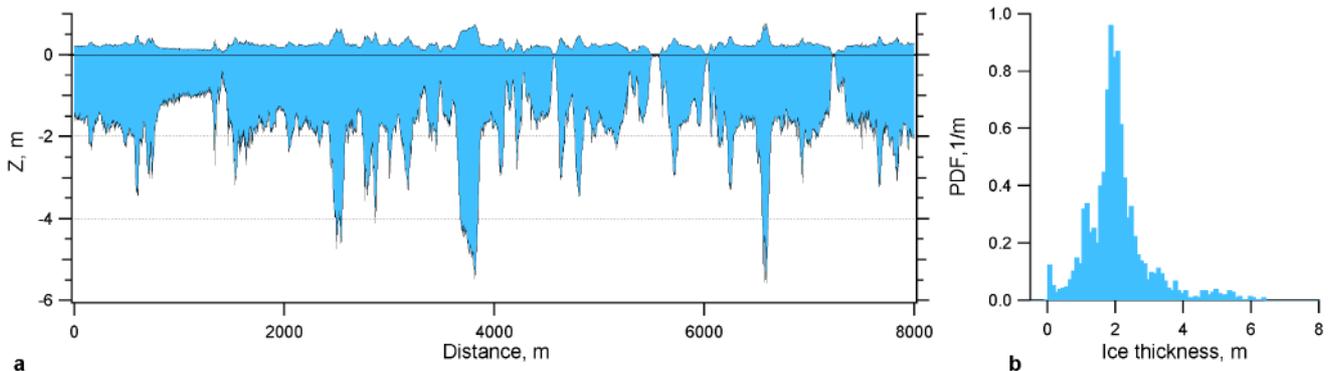

Figure 17 a) Example of profile of ice thickness and ice surface derived from electromagnetic induction measurements from helicopter flights, b) ice thickness distribution function estimated from the profile data (courtesy C. Haas).

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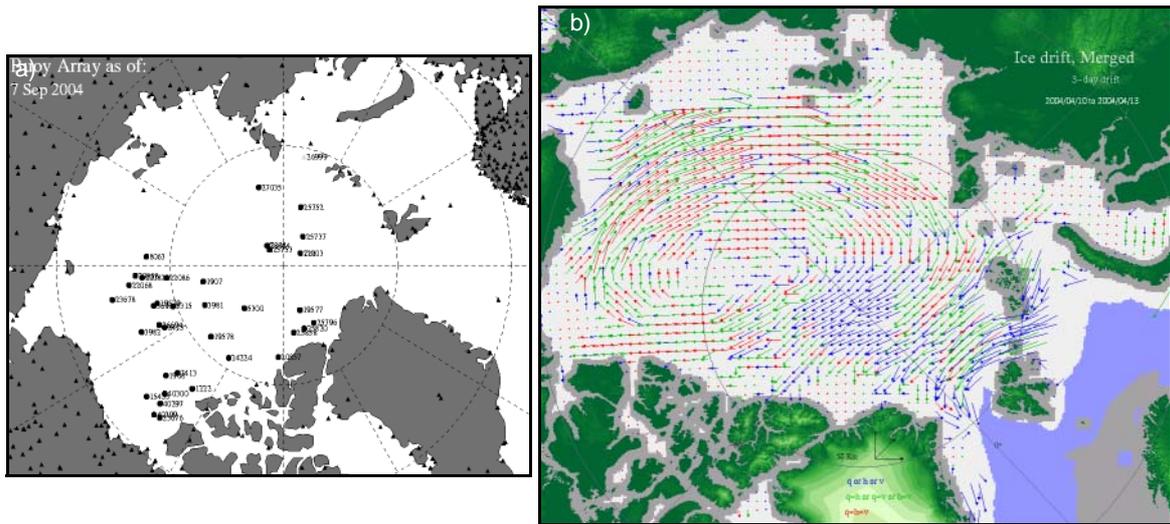
Figure 18 *a) Example of IABP data which can be obtained from http://iabp.apl.washington.edu, b) ice drift from satellite data produced by Ifremer (courtesy R. Ezraty, Ifremer).*
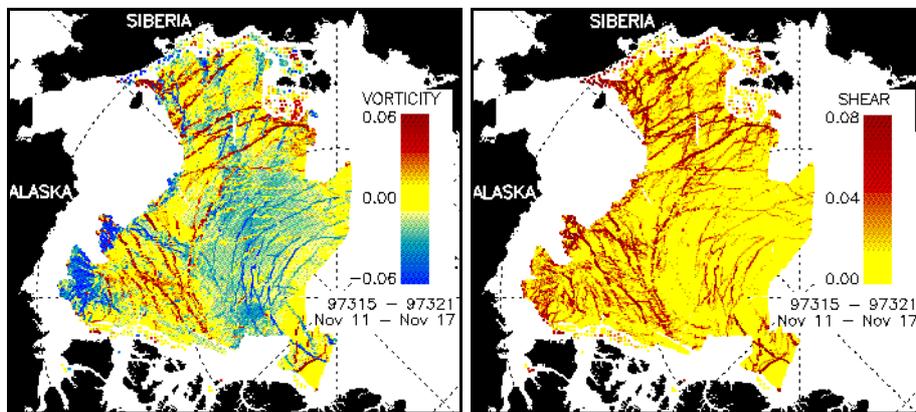
Figure 19 *Example of derived vorticity and shear derived from high resolution ice drift measurements carried out by the RADARSAT Geophysical Processor Team at NASA/JPL. (Courtesy R. Kwok).*

Figure 20 *a) Map of the main iceberg-producing areas in the European Arctic and the major drift paths for icebergs, b) photograph of a characteristic tabular iceberg in the Barents Sea, with horizontal scale of about 100 m and freeboard height of 6−8 m.*

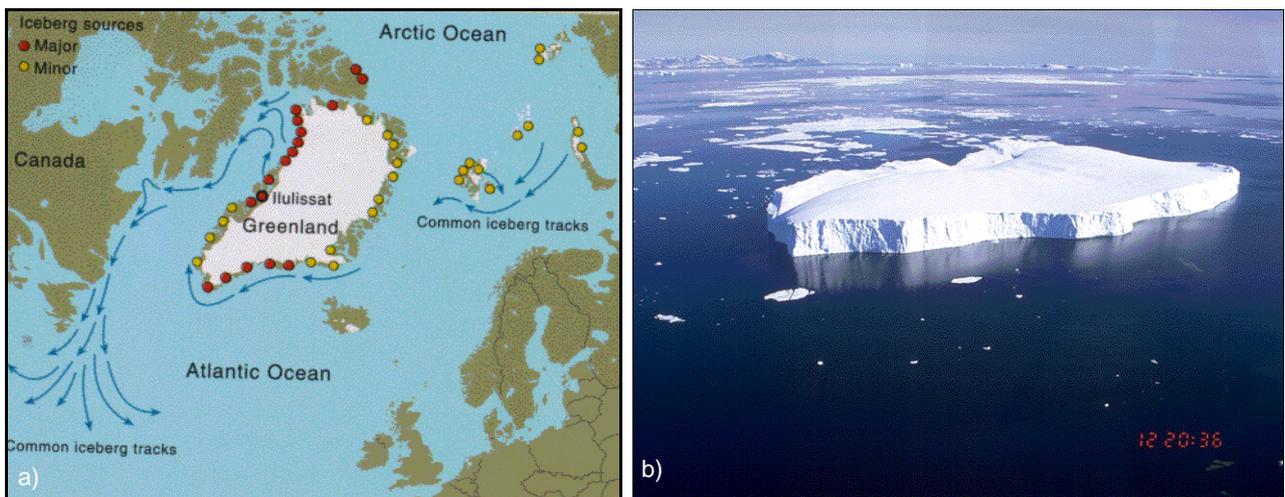Ice drift measurements from subsequent SAR images covering the main part of the Arctic are produced by NASA's RADARSAT Geophysical Processor System (RGPS) allow derivation of deformation fields and derivatives such as vorticity and shear (Kwok, 1998). Maps of vorticity and shear show long, narrow features which can open water, new ice, nilas, young ice, first year ice, rafted ice or ridged ice (Figure 19). Locally, they can be created by divergence, convergence, shear, or a combination of these.   Further examples of RGPS products can be found at http://www-radar.jpl.nasa.gov/rgps/radarsat.html.

3.1.4 Icebergs

Icebergs — ice originating from glaciers — are commonly found off eastern Canada, around Greenland, in the Barents Sea and several places in the Russian Arctic (Figure 20). They can be very dangerous for ships and oil rigs because most of the ice mass is below the surface. Smaller icebergs, with a horizontal scale of around 100 m, can be difficult to detect. Observations of sea ice and icebergs are obtained by several methods: aircraft/helicopter surveys, ship observations, reports from coastal and meteorological stations, data from drifting buoys and satellite data. The International Ice Patrol is responsible for observing and reporting icebergs in the Northwestern Atlantic (http://www.uscg.mil/lantarea/iip/home.html).   In the European Arctic there is a need to establish a monitoring system for icebergs to support the offshore oil and gas exploration.

3.2 Temperature, salinity and currents

Ocean temperature and salinity are the fundamental hydrographical parameters that need to be observed in the Arctic Ocean and surrounding seas. In combination with current measurements, hydrographical data are used to quantify water masses, their fluxes and variability. The present hydrographical and current measurement network is sustained through complementary satellite and *in situ* measurement systems. A continuation and strengthening of this network with increased focus on the quality and accuracy of the long-term record and on improved integration of available remotely sensed data for high-resolution products is strongly recommended.

In situ observations from ships and drifting surface buoys are scarce in most locations and must be strengthened. ARGO floats can operate in the Norwegian Sea, but not in ice-covered areas. Time series of current measurements, temperature and salinity from moored instruments are used in several key locations in ice-free areas. Other subsurface observing systems are needed for operation in ice areas.

Satellite-based observations of surface temperature, salinity and ocean current patterns represent an important supplement to *in situ* data, because satellites can provide synoptic measurements over large areas where few other data exist.

3.2.1 Satellite observations of sea surface temperature and ocean colour

For the ice-free areas of the Arctic and Nordic Seas, sea surface temperature (SST) from thermal infrared sensors is currently available from several satellite systems, where the NOAA AVHRR data are most commonly used. There are several service providers for SST products. In Europe CLS has developed a processing system for AVHRR data from the NOAA satellites and other infrared radiometer data to generate global sea surface temperature maps. Ocean colour data for monitoring of chlorophyll and algal blooms are available from many different satellite sensors where SeaWiFS, MODIS and MERIS are most commonly used (see http://www.ioccg.org for details on sensors). Frequent cloud cover in the Nordic Seas and darkness in the winter months limit the usefulness of temperature and ocean colour measurements from infrared and optical sensors in daily, operational monitoring. Sea surface temperature from passive microwave sensors can be provided in 25 km grid cells independent of cloud and light conditions, as shown in Figure 21. These data are useful for near real time as well seasonal and long-term monitoring. Sea surface salinity observation from space is under development. ESA's SMOS mission, scheduled in 2006, will deliver global data for sea surface salinity with an accuracy of 0.1 for a 10–30 day average in 200×200 km grid cells (http://www.esa.int/export/esaLP/smos.html).

3.2.2 Ship observations

Hydrographical observations from the water column obtained regularly from ships represent the baseline observing system in the Nordic Seas. Hydrographical data including Russian observations have been collected for more than a century in the ice-free areas (Figure 22), but in the ice-covered areas the amount of data is much less and are only obtained occasionally during expeditions. To detect

long period variations, transarctic repeat sections with high accuracy of WOCE standards (0.002 K for temperature and 0.003 for salinity) are needed with full-depth profiles. The repeat has to occur in a time period of a few years (less than 5). An annual repeat would be preferable, but seems to be outside the range of logistic feasibility. Tracers are of significant need to identify processes responsible for observed changes.

Expendable Bathythermographs (XBTs) are launched from moving vessels. They provide reduced accuracy (0.01 K for temperature) and only restricted depths of 750 m or 1500 m. XCTDs are

available, but at considerable cost. XBTs are connected to the ship by a thin wire during deployment. The wire might be damaged when ice is present. Consequently XBTs can only be successfully used in open water.

Towed undulating systems are used from moving ships to obtain data with high horizontal resolution to a depth of several hundred metres. Penetration depths depend on the system and the ship's speed. For deep diving tows the ship's speed has to be reduced considerably. Towing is not possible if there is significant sea ice cover.
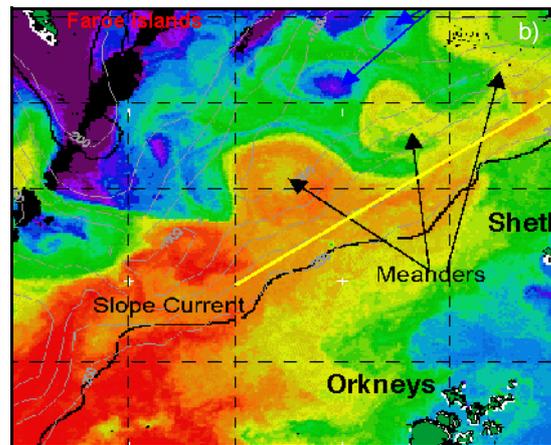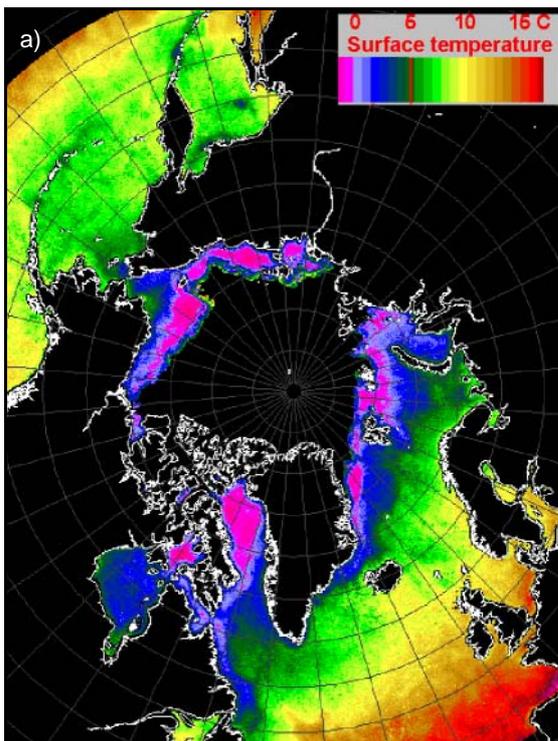
Figure 21 *Examples of sea surface observations from satellites: a) AMSR–E 7-day mean sea surface temperature image for the whole Arctic region and surrounding seas, provided by Technical University of Denmark. Note that sea ice cover is masked in black;*
b) instantaneous surface temperature from NOAA AVHRR showing the relatively warm Atlantic water flowing northwards between Faroe islands and Shetlands.

Figure 22 *a) Distribution of hydrographical stations in the Nordic Seas;*
b) histogram of Russian hydrographical data in the 20th century (Alekseev et al., 2000).

A significant contribution to hydrographic measurements in the deep Arctic Ocean came from submarines under the US SCICEX program from 1993–1999 (Morison *et al*., 1998, 2000). However, submarine measurements are limited by military restrictions and there is a question of how much submarine data will be available from th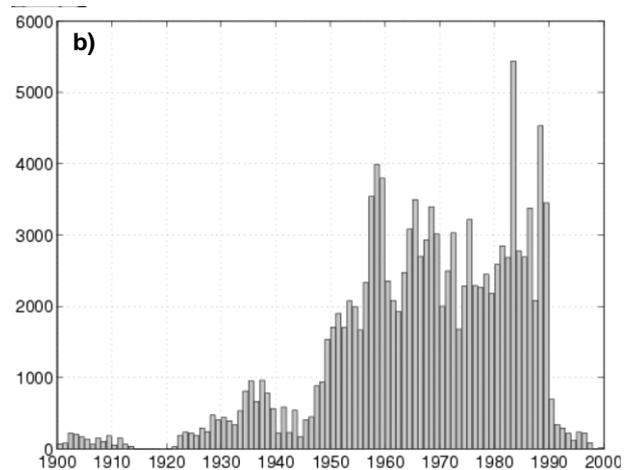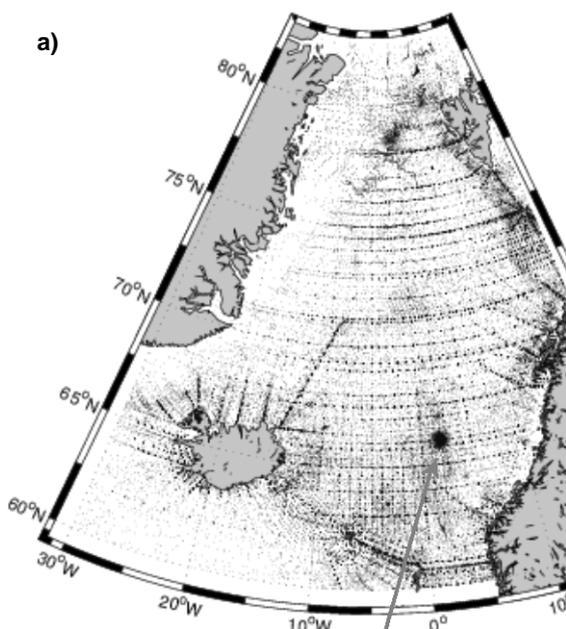e Arctic in the future. To improve the frequency and coverage of large scale sections in the Arctic Ocean it will be of primary importance to use powerful research icebreakers.

Ships of opportunity are widely used in other ocean areas where merchant ships provide the basis of frequent repeats along the same lines. They can be used to deploy XBTs or to measure near surface temperature and salinity by thermosalingraphs, or upper ocean currents by ADCPs. One section between Greenland and Denmark has been occupied monthly since 1999 by the vessel Nuka Arctica, measuring temperature, salinity and current profiles by ADCP (Figure 23). Similar data should be collected by other ships operating regularly in the Nordic Seas.

3.2.3 Measurements from moored systems

Measurements of hydrography and currents by moored systems provide quasi-continuous time series in selected control areas, supplementing ship-borne surveys which only occur at intervals. It is common to use subsurface moorings which avoid the rapid movements of surface waves. Data can only be obtained after the recovery of the moorings.
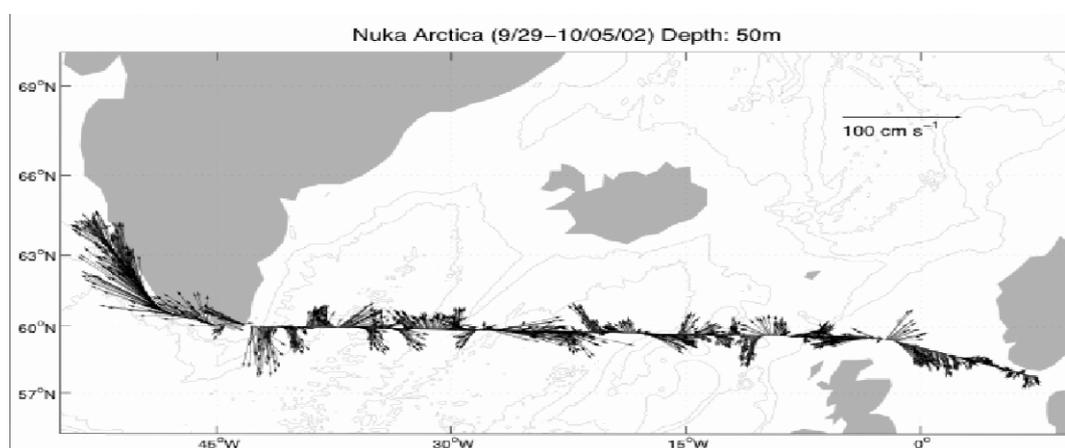
Figure 23 *Example of ADCP measurements at 50 m depth obtained by Nuka Arctica on one the trips between Denmark and Greenland (Courtesy H. Svendsen and S. Østerhus, University of Bergen).*
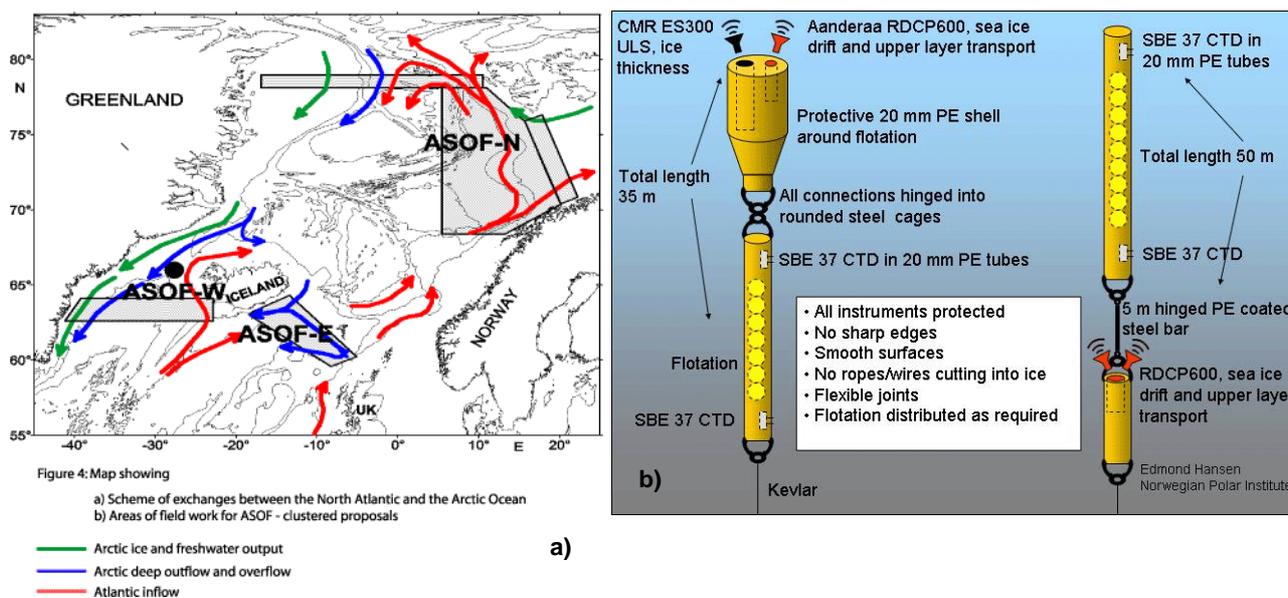
Figure 24 *a) Map of the ASOF monitoring areas in the Nordic Seas, showing the main flow patterns of Atlantic inflow (red arrows), Arctic ice and freshwater flows (green arrows) and Arctic deep outflow and overflow (blue arrows); b) diagram of Fram Strait mooring with upward looking sonar (ULS) for ice thickness measurements (ES300) and acoustic doppler current profiler (RDCP) for sea ice drift and upper ocean transport. Furthermore, there is a 50 m long CTD embedded in a 20mm tube on top of the RDCP for measurement of temperature and salinity profiles*

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However systems are under development that transmit the data from deep instruments to a near-surface controller which then transfers the data via satellite. Sensors in the moorings can be on fixed levels or as profilers. Moorings can be used to install arrays for acoustic thermometry which can supply integral information of temperature variations over large ocean volumes.

Moored instruments are most commonly used in open water of the Nordic Seas, but moorings are also used in ice-covered areas, where deployment and recovery must take place during light ice conditions. Due to the high costs, moorings are only used in selected key areas for monitoring heat and mass fluxes, deep water formation or other process studies. Examples of key areas are the Fram Strait, the central Greenland Sea and Ocean Weather Station "Mike" in the Norwegian Sea.

The Arctic and Subarctic Ocean Flux (ASOF) programme (http://asof.npolar.no), which is currently running, aims to monitor and understand the oceanic fluxes of heat, salt and freshwater at high northern latitudes. The programme will determine the flows of water into and out of the Arctic Ocean and Nordic Seas. The key observing areas are shown in Figure 24. In the Fram Strait current measurements have been done with an array of 14 moorings since 1997 in order to quantify the heat and freshwater fluxes in through the strait. The new moorings includes ULS for ice thickness and ADCPs for sea ice drift and upper layer transport built into the same unit on top of the mooring (blue square). Tube moorings measure the upper layer properties on the shelf (black rectangles).

In the Arctic the deployment and recovery of moorings is complicated by sea ice, prohibiting measurements in the near surface layers and real time transmission of data. Therefore the development of surface reaching instruments which are able to use open areas to approach the surface to measure and to transmit data are a basic requirement. Flexible data storage in self-recording instruments and transmission can be controlled optimally by a bidirectional communication.

### 3.2.4 Measurements from free drifting or propelled autonomous systems

Drifting buoys at the sea surface can be deployed by ships or aeroplanes. They are normally expendable and transmit location and meteorological parameters as surface pressure and temperature by satellites. Surface buoys can be equipped with sensor cables or profiling instruments which transmit data of the upper to intermediate ocean layer in real time by satellite. They can be deployed in the open ocean and on sea ice.

Autonomous systems for the subsurface levels of the open ocean can consist of freely drifting floats which stay at a certain depth or density level or profiling floats which drift at a prescribed depth level and leave it at certain time intervals to measure CTD-profiles and to transmit the data via satellites. The Argo programme of profiling floats represents the backbone of the global ocean observing system (Gould *et al*., 2004). Presently, about 1500 floats are in operations world wide and a total of 3000 floats are planned to be in operation in the next few years. A few Argo floats are operated in the Norwegian Sea. The depth level of the floats is 2000 m with a repeat cycle of 10 days to rise to the surface for data transmission. An example of Argo data is shown in Figure 25.

Another autonomous system that can stay in certain areas or follow prescribed tracks is the SEAGLIDER float. This self-propelled float can drift at a horizontal speed of 20 cm/s with a glide

Figure 25 *a) Photograph of Argo float deployment from a research ship, b) example of temperature and salinity profiles from an Argo float in the North Pacific (20.25 N, 121.4 W, May 15 2004), retrieved from* *http://www.argo.ucsd.edu/.*
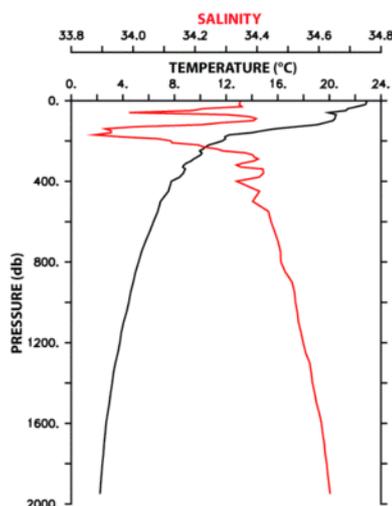
angle of 1:3 to 1:5. The mission duration can be 6 months and the net horizontal distance covered up to 3000 km. Other systems with more efficient controls are Autonomous Underwater Vehicles (AUV) as AUTOSUB. They can carry out survey patterns with a higher degree of freedom. Operation in ice-covered areas is being tested.

3.2.5 Planned systems for under-ice monitoring

The establishment of an observation system of water mass properties and currents in the deep Arctic Ocean requires the combination of different technologies, surface drifters on the ice, profiling subsurface floats and moored stations. A proposed system for under-ice operations is the HAFOS system, illustrated in Figure 26. Navigation under the ice is presently only possible by acoustic means. Data transmission by sound is only possible in small quantities over limited distances. The range of detectable sound transmission together with energy consumption are limiting factors of these systems. The drifters can receive information on the ice situation by satellite from a land station and transmit it to the floats and moorings. When they are in open water the floats and the transmitters from the moorings can ascend to the surface and transmit the full data sets by satellite to shore. The moorings should be simultaneously used as strategic moorings to monitor full depth water mass properties. Therefore they should be equipped with current meters and CTD sensors which provide data for the full water column. This is needed because profiling floats can not covered the full depth. Furthermore the moorings can serve as fixed location reference stations which are necessary to

separate spatial and time variability which both affect the float data. The moorings need to be exchanged every second year.

A similar concept for under-ice observations has been proposed as part of an Arctic Ocean Observing System (AOOS) for the International Polar Year (Dickson, 2004). It consists of ice-tethered platforms (ITF), floats and gliders (Figure 27). The main components are:

- Neutrally buoyant drifting floats (yellow) equipped with Ice Profiling Sonar (IPS)
- Vertically profiling floats equipped with SOFAR long-range navigation
- Gliders equipped with CTD and SOFAR acoustics for long-range navigation and acoustic modems for shuttling data between floats and transponders
- Transponders (GPS geolocated) equipped with SOFAR long-range acoustics for floats and gliders navigation.

Floats and gliders will be linked to surface ice tethered platforms only by acoustics for long-range navigation purposes (Sound Fixing and Ranging SOFAR) and also for transferring large data files (HF acoustic modem). Both floats and gliders will use the same system for controlling buoyancy. Floats will either remain at constant pressure when measuring sea-ice drift or change buoyancy to move up and down in order to take vertical profiles of temperature and salinity. Gliders will move both vertically (like floats) and horizontally across the fluid and will take vertical sections of temperature and salinity. The vertically profiling floats will
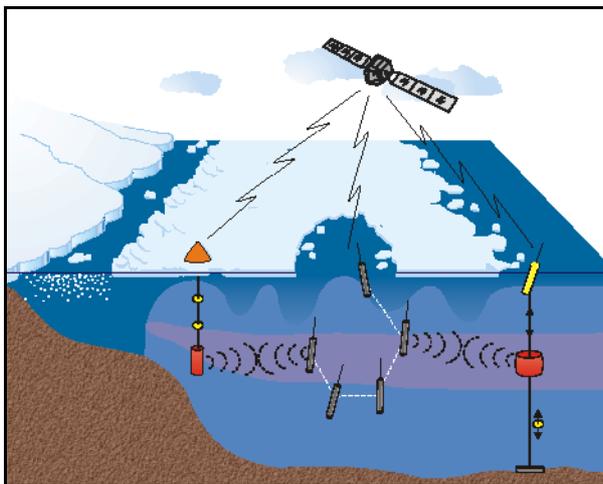

Figure 26 The concept of Hybrid Arctic Float Observing System (HAFOS) which combines moored and drifting instruments with satellite and acoustic communication.
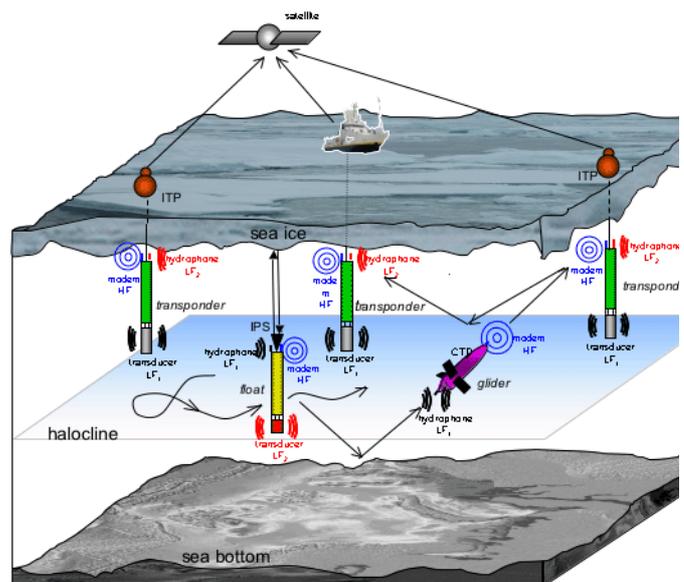

Figure 27 Schematic illustration of the underwater components of the Arctic Ocean Observing System (Courtesy Jean-Claude Casgard).

enhance the horizontal network of the ice tethered profilers in the upper 800m to an ARGO-similar spatial resolution and extend the network in the vertical to 2000m to survey the transition to the deep ocean. The parking depth of the profiling floats will be in the level of the Atlantic Water. The main tasks for the floats will be to measure:

a) sea-ice thickness distribution
b) deep vertical profiles of temperature and salinity across the surface mixed layer and the cold halocline down to the deep Atlantic layer
c) lagrangian currents. There will be a need for accurate measurements of sea-ice drifts relative to float displacements to infer sea-ice thickness distribution from sea-ice drafts measured by ULS installed on isobaric floats.

3.3 Sea level, surface topography and wave forecasting

3.3.1 Tide gauge measurements

Measurements of sea level is a vital component of an oceanographic observation programme for many reasons ranging from operational requirements including storm surge to long-term monitoring and prediction of global sea level changes due to climate variations. European waters are well covered with sea level measuring sites of which the most strategically placed stations constitute an integral part of the global network operated by the Global Sea Level Observing System (GLOSS), under the Intergovernmental Oceanographic Commission (http://www.pol.ac.uk/psmsl/ programmes/gloss.info.html).

The Arctic region is however an exception from this statement due to the practical problems and the resources needed to operate tide gauges in the harsh Arctic climate. It will therefore be an important task to secure a sufficient number of tide gauges in the Arctic region, as an important component of the GLOSS observing network.

There are two basic parameters which may be monitored, having both scientific as well as instrumental advantages:

• the surface level itself
• the pressure at some fixed point on the seabed

Traditionally, the sea surface has been measured by means of a float arrangement mounted above a well which damps out short-period wave motions. This procedure is simple, well proven and has no inherent drift. However, there are problems of non-

linear responses of stilling wells to waves and currents (Bernoulli effect), which can produce errors in the measurement of the water level, and the method is far from well suited for the climatic conditions found in the Arctic.

The best alternative is to measure near-shore seabed pressure and to convert this to sea level by means of the hydrostatic relationship between pressure, water density and gravitational acceleration. Seabed pressure includes atmospheric pressure, which must be corrected for, either by separate measurement or by differential transducers vented to the atmosphere as in some bubbler gauges. With pressure systems, care must be taken to ensure that the datum level remains constant and sea water density variations must be monitored at suitable intervals for the best accuracy.

In the future the use of remotely sensed data from various satellite missions will play a substantial role in monitoring of the sea level. ESA's GOCE mission (Gravity Field and Steady-State Ocean Circulation Explorer), scheduled for launch in 2006, is designed to measure the Earth's gravity field and model the geoid with an accuracy of 1–2cm on a 100km scale and to 0.1cm on a 1000km scale (Johannessen *et al.*, 2003). Precise modelling of the Earth's geoid is important for many applications:

• Improved recovery of ocean tides, i.e. monitoring of sea level in open ocean areas.
• Improved analysis of seasonal sea level changes
• Improved sea level forecasting and storm surge warning

In order to be operational, tide gauges must record automatically in computer-format and data must be transmitted to a regional database in real time. Sampling of sea level averaged over a few minutes (to avoid aliasing), at intervals of 15 minutes is recommended.

3.3.2 Sea surface topography from altimetry

Sea level anomaly (SLA) data from several satellites (GeoSat, ERS 1/2, TOPEX/Poseidon, Envisat, GFO, Jason–1) have been used for more than a decade to map open ocean dynamics. Both near real time data and archived data are provided on a global scale by CLS (http://www.cls.fr/html/oceano/welcome_en.html). Maps of geostrophic currents are deduced from the SLA data. These maps show the strength of oceanic eddies and the propagation of eddies in time sequences of such maps. At latitudes above 66 N,

the data coverage is not sufficient to resolve small scale eddies, but the main patterns of variability can be identified, as shown in Figure 28. Measurements of ocean surface topography in the Arctic from space will be significantly improved when precise geoid can be determined by the GOCE mission. With a precise geoid it will be possible to determine the absolute sea level and its spatial and temporal variability. The altimeter-derived data must be supplemented with a network of *in situ* measurements to calibrate the satellites and to produce accurate global determinations of sea level change.

3.3.3 Wave forecasting

Wave forecasting in the Nordic Seas is run by national meteorological services in connection with weather forecasting. The Norwegian Meteorological Institute uses the HIRLAM model for local-area forecasts up to +60 hours; it is run 4 times daily on a 20km polar-stereographic grid and uses lateral forcing data from the European Centre for Medium-Range Weather Forecasts (ECMWF). For longer weather forecasts—up to +10 days—data from the ECMWF are accessed directly. Wave forecasts for the ice-free areas of the Arctic are generated using the WAM model, run on a 0.45° rotated geographic grid. WAM calculates the directional wave spectrum, including standard parameters such as significant wave height and peak period. Forecasts up to +60 hours are forced by HIRLAM data, while ECMWF data are applied to generate forecasts up to +10 days. Altimeter observations of significant wave height are assimilated using a modified successive corrections scheme (Bratseth, 1986, Breivik and Reistad, 1994).

3.4 Boundary conditions

3.4.1 Meteorology

Observations on the Arctic marine atmosphere are needed to provide boundary conditions for marine
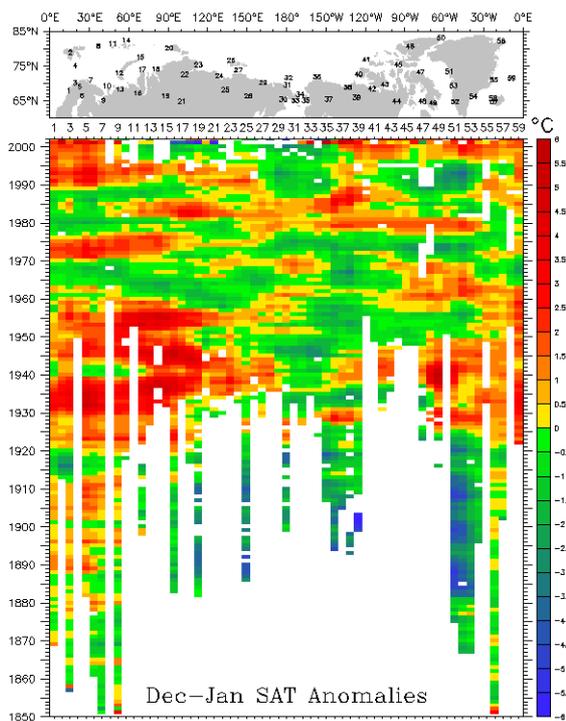
Figure 29 Surface air temperature anomalies for the network of observing stations around the Arctic Ocean (Courtesy: J. Overland)

models both for climate-scale and short-term operational applications which need

1. regular surface observations and rawinsonde soundings from coastal and island stations, and

2. buoy observations of the International Arctic Buoy Program (IABP).

The IABP buoys have typically been equipped with atmospheric pressure and air temperature sensors, and sometimes with wind anemometers. For long-term climate observations, several coastal and island stations have operated for many decades, providing important evidence for climate variability in the last century. An example of surface air temperature anomalies in various parts of the Arctic is shown in Figure 29. For long-term monitoring, it is a problem that the number of operating stations

Figure 28 Sea level anomaly map for the Nordic seas produced by CLS based on weekly averaged data from TOPEX/Poseidon, ERS and GEOSAT-Follow-On centred on 1 May 2002. The unit is sea level height in cm.

Variables and Observing Strategies

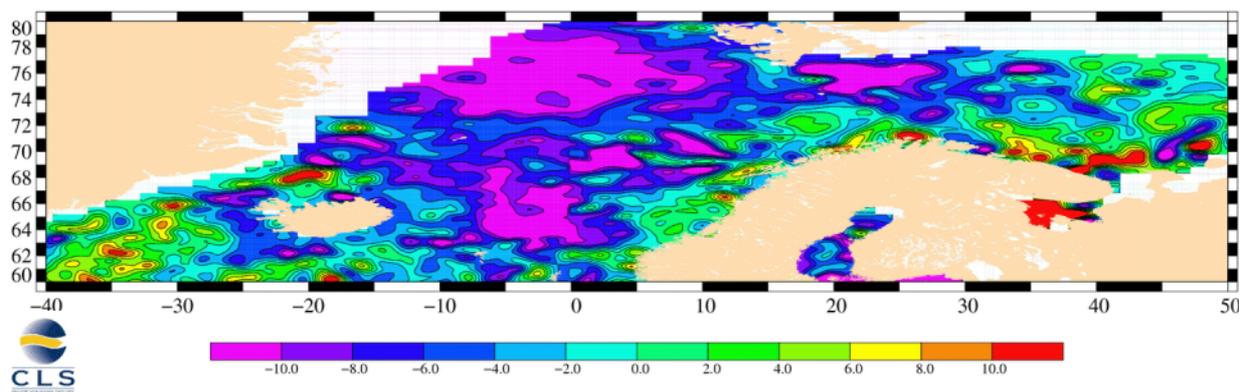has declined over the last decades. It is also a problem that the Arctic Ocean is heavily under-sampled because very few manned ice stations have been in operation over several decades. The IABP network, however, has improved data collection in the Arctic Ocean in the last two decades, but only for air pressure and temperature.

The present observation network is inadequate for detecting intensive mesoscale disturbances, such as polar lows, which can occur in the ice edge regions. There are also major problems in the analyses and forecasts of clouds, radiative transfer, surface exchange processes, and the structure of the atmospheric boundary layer (ABL). For cloud cover, less than half of the 19 global climate models (GCM) involved in the atmospheric model inter-comparison study produced results qualitatively similar to observations (Tao *et al.*, 1996). These problems are partly related to the sparse observations and partly to the complexity of modelling the physical processes active in the Arctic ABL.

The Arctic ABL is generally stably stratified, but due to the presence of leads and thin ice the surface can be extremely heterogeneous with respect to temperature and albedo. The surface conditions (sea ice concentration and thickness distribution, surface temperature and albedo) are closely coupled with the state of the Arctic atmosphere. The net radiation is usually the most important factor in determining the surface temperature over Arctic sea ice, and the net radiation strongly depends on the cloud cover and on the presence of "clear-sky" ice crystals in the air. The near-surface air temperature is affected by several processes: lateral advection, turbulent exchange with the surface, turbulent exchange with and through the

inversion layer, as well as the radiative cooling of the air. Under very stable stratification, the near-surface air temperature and wind are inaccurately represented in atmospheric models.

To improve the forcing of sea ice and ocean models, more meteorological observations are needed. An Arctic ocean observation programme must therefore include observations of basic meteorological parameters such as wind speed and direction, air temperature and humidity, sea surface pressure, cloud cover, and precipitation. In addition to increased spatial resolution of the near-surface observations, it is essential to collect more data on the vertical profiles of wind, temperature, and humidity. The number of rawinsonde sounding stations is not expected to increase in the near future, but development of remote sensing techniques can help to improve observations of several atmospheric processes in the Arctic.

3.4.2 River runoff

An essential part of the ocean dynamics of the Arctic is the fresh water balance. The river runoff into the Arctic Ocean has increased by about 7% between 1936 and 1999 (Peterson *et al.*, 2002). In the last two–three decades the increase has been more significant, as shown by Shiklomanov *et al.* (2000) in Figure 30. This result is based on synthesis of river monitoring data of six largest Eurasian rivers to the Arctic Ocean. The ACIA climate model predictions suggest that precipitation and river runoff will continue to increase in this century (ACIA, 2004). It is therefore important in an Arctic observation programme to monitor the fresh water supply of the major rivers entering the Arctic domain. River runoff data are taken by many
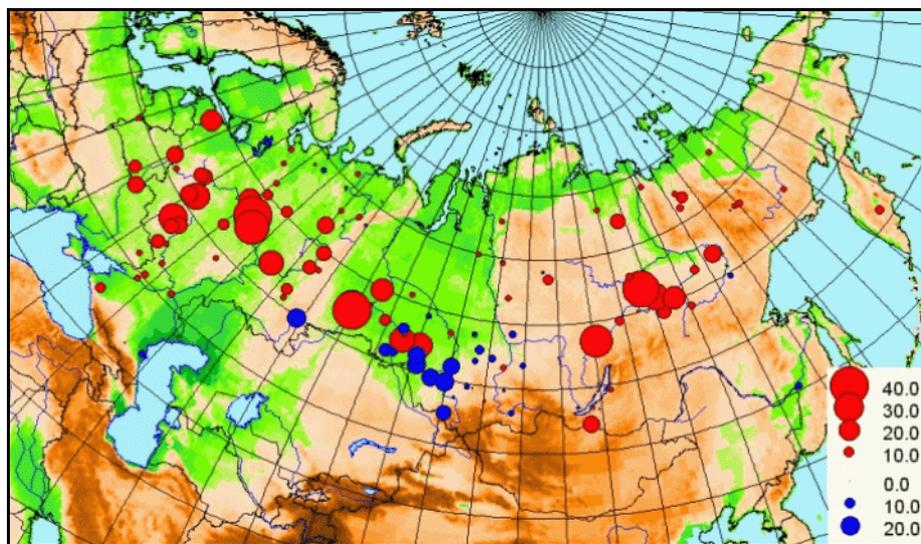

Figure 30 *Percentage increase (red circles) and decrease (blue circles) of river discharge in the main Russian rivers in the last 20–30 years (Shiklomanov et al., 2000).*

national hydrological institutes and agencies and timely reporting in an operational context is problematic. The World Climate Research Programme Arctic Climate System Study (WCRP ACSYS) has, in cooperation with the Global Runoff Data Center (GRDC), established an Arctic Runoff Data Base (ARDB) which can provide climatological data for validation of global and regional climate models and input into operational models. This effort is continuing under WCRP's Climate and Cryosphere (CliC) Project. The ARDB currently keeps river discharge time series data from a total of 2110 runoff gauging stations in the Arctic hydrological region. Further information on the ARDB, including information on how to access the data can be found at: grdc.bafg.de/html/internat/grdc/acsys/acsys.htm.

3.5 Tracers

A variety of natural and anthropogenic tracers have been used, either singly or in combination, to study pathways, residence times and ventilation rates in the Nordic Seas and the Arctic Basin; to provide seatruth for model simulations (e.g. Heinze, 1998); and, in relation to the fate of contaminants (e.g. Schlosser *et al*., 1995). The main groups of tracers are described in the following sections.

Tritium/3H, which decays to 3He, is produced continually in the atmosphere by the action of cosmic rays on oxygen and nitrogen. However, the contribution due to nuclear weapons testing, mainly in the late 1950s and early 1960s, provided a much larger signal which has been used extensively for ventilation studies. Equilibrium of 3H/3He in the atmosphere provides a marker for surface waters, and the observed 3H/3He ratio at depth gives an indication of 'age' in the top few hundred metres (Jenkins, 1988; Schlosser *et al*.,1999).

Cosmogenic nuclides have been used as tracers of ocean processes (Lal, 1999). These are formed by interaction of cosmic rays with O, N and Ar in the atmosphere. Like 3H, 14C has had an additional source due to weapons testing and this additional fraction represents a transient tracer. It has been used extensively in studies of carbon cycling and ocean mixing, and formed an important component of WOCE (http://www.soc.soton.ac.uk/OTHERS/woceipo/ipo.html). In addition 32Si and 32P have been used to study nutrient cycling and 10Be for particle dynamics.

Stable isotopes. The ratio 18O/16O has been used to trace the distribution and influence of freshwater in the Arctic (Schlosser *et al*., 1999). Fractionation

of these stable isotopes occurs during evaporation and condensation, producing a trend of decreasing δ18O with latitude. Rivers discharging into the Arctic have δ18O values of about –16 to –21‰, compared with 0.3‰ in inflowing Atlantic Water (Östlund and Hut, 1984). This has the potential to trace interannual variations in the transport pathways of river runoff across the Siberian shelf.

CFCs. Production of chlorofluorocarbons for a variety of industrial applications (e.g. refrigerators) since the 1930s, has provided well-defined source terms which increased steadily until the early 1990s. CFC-11 and CFC-12 concentrations and ratios (time-varying production rates) have been used to derive mean residence times in the Greenland and Norwegian Seas (Rhein, 1991). More recently, the tracers F-113 and CCl4 have extended the time scales which can be addressed (Haine *et al*., 1995; Lal, 1999). CFCs, in combination with 3H/3He, have been used to estimate the residence times for surface and intermediate waters in the Eurasian Basin (Franke *et al*., 1998), the Greenland Sea (Bönisch *et al*., 1997) and the Makarov and Canada Basins (Smethie, 2000).

SF6. Sulphur hexafluoride is an inert compound which has been used increasingly in the past decade in purposeful tracer release experiments. These have included studies of mixing across the pycnocline (Ledwell *et al*., 1993), nutrient mixing within an eddy at 60ºN in the North Atlantic (Law *et al*., 2001) and the mode and rate of deep ventilation in the Greenland Sea (Watson *et al*., 1999; Gascard *et al*., 2002). The release method allows injection along particular density surfaces, and the very low detection limits means experiments can continue for several years over distances of thousands of kilometres (Figure 31).

Artificial radionuclides released from nuclear reprocessing facilities in the UK (Sellafield) and France (La Hague) have provided a useful set of tracers to study circulation in the Nordic Seas and the Arctic Ocean for several decades (Figure 32). The most widely used have been 90Sr, 99Tc, 129I, 134Cs, 137Cs, and isotopes of Pu (Kershaw and Baxter, 1995 and references therein). Recent substantial decreases in the direct discharge of most nuclides have reduced the quantity of tracer in water entering the Nordic Seas. However, the discharges of 129I and 99Tc have increased. Both are relatively conservative and have been used to demonstrate transport pathways and mixing processes. The use of AMS (Accelerator Mass Spectrometry) has allowed 129I analysis on small samples (i.e. <1 litre), permitting shared use of
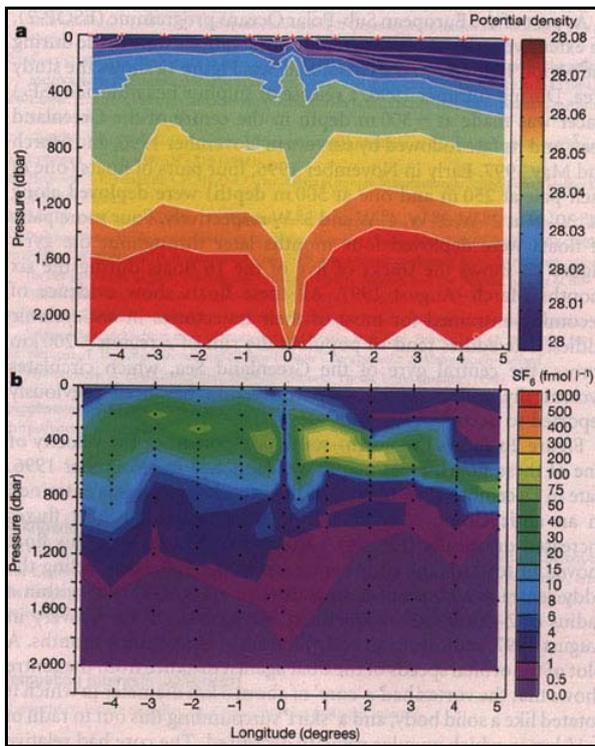
Figure 31 Vertical sections taken along 75°N in May 1997 in the central Greenland Sea (Gascard et al,. 2002), showing a) potential density (st), b) SF6 concentration (fmoll^{-1})

conventional water samplers (CTD rosette array) and submarines (SCICEX 1995 and1996). Smith *et al*. (1999) demonstrated the boundary between Pacific and Atlantic water masses over the Mendeleyev Ridge, and the flow of Atlantic Water along the Lomonosov ridge on the basis of 129I distributions.
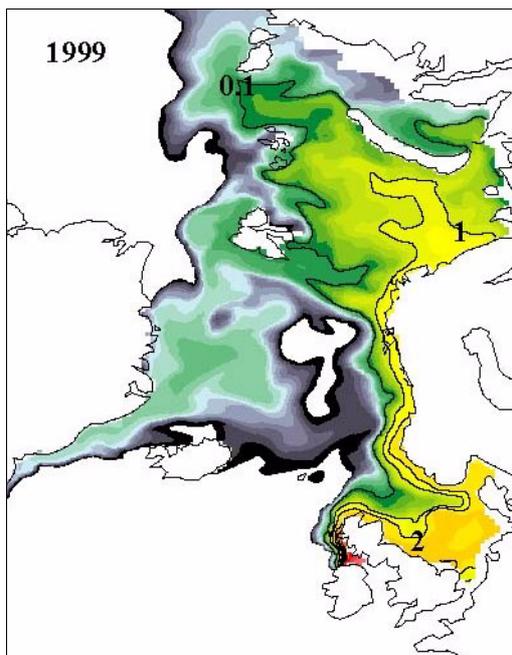

Figure 32 Simulation of distribution of 99Tc in the Nordic Seas, 1996–1999 which has been compared with observed distribution (Karcher et al., 2002).

Uranium- and theorem-series radionuclides. These series provide tracers with varying half-lives and chemical properties, with well-defined source terms, and they have many applications. For example, they have been used to study particle dynamics in the Canadian Basin (Smith and Ellis, 1995—210Pb, 210Po, 226Ra), the scavenging rates and circulation timescales in the Nansen Basin (Cochran *et al*., 1995), and particulate organic carbon export in the central Arctic (Moran *et al*., 1997).

Barium. The principal external sources of barium are from river inputs and hydrothermal venting. It is involved in biological cycling and has been investigated as a potential tracer for fluvial discharges in the Arctic, for distinguishing North American and Eurasian sources and for investigating features of the Arctic halocline (Guay and Falkner, 1997).

A feature of these tracer applications is the need to collect discrete water samples for later analysis, either on-board (e.g. SF6) or ashore (e.g. 99Tc). Analytical advances have minimised the sample volume required for some tracers (e.g. AMS for 129I <1 litre), whilst for others this still remains significant (e.g. 99Tc requires 100–200 litres). This has implications for the techniques required to retrieve samples. The tracers described here have many applications in high latitude process studies, in combination with more conventional oceanographic observations and to provide sea-truth observations with which to compare model simulations. In addition, they can complement observations of direct relevance to ocean-climate interactions, such as loss rates of atmospheric CO_2 (Murata and Takizawa, 2003).

3.6 Oil spills and other pollutants

Pollution of the Arctic has been of increasing concern in recent decades. A number of phenomena have reinforced this concern, for example the Exxon Valdez oil spill accident in Alaska in 1989 (www.pws-osri.org). Another example is the realisation that Arctic haze was due to aerosols of soot and sulphate from industrialised regions further south. Furthermore, unexpectedly high levels of toxic organic compounds have been found in polar bears living in 'pristine' environments, and high levels of PCBs have been documented in the diets of indigenous peoples due to long-distance transport processes. A combination of the cold climate and geographical characteristics means that the Arctic has become a sink for many pollutants

generated in industrialised regions. As well as long distance sources, there are regional and local concerns particularly in relation to the oil and gas development and the transport routes in Arctic coastal waters. Prevention and combat of oil spills in ice-covered seas (Figure 33) is a major issue related to exploitation and transport of oil in the Arctic (Dickins Ass., 2004).

A Finnish-led initiative in 1989 led to the creation of the Arctic Environmental Protection Strategy in 1991, supported by the 8 circumpolar countries and representatives of the indigenous peoples. The Arctic Monitoring and Assessment Programme (AMAP), which is one of five working groups under the Arctic Council, has established a coordination mechanism for production of comprehensive assessments "… to provide a baseline for understanding the status of contaminants in the Arctic: it provides the fundamental information needed to structure and conduct formal risk assessments related to human health and ecosystem damage in future work" (AMAP, 2002). The AMAP assess-

ments included oil and gas, persistent organic pollutants, heavy metals, radioactivity, human health, pathways, acidification and climate change. Pollutant behaviour and redistribution at high latitude is greatly influenced by wet and dry deposition, seasonal river flows and ice formation and transport. The most recent reports are from the Arctic Climate Impact Assessment (ACIA, 2004). Documents from AMAP are available at http://www.amap.no. Another working group under the Arctic Council is PAME—Protection of the Arctic Marine Environment, with the mandate to address policy and non-emergency pollution prevention and control measures related to the protection of the Arctic marine environment from both land and sea-based activities. These include coordinated action programmes and guidelines complementing existing legal arrangements (PAME, 2000, 2002). Production and distribution of improved data on marine pollution is part of these guidelines (http://www.pame.is).
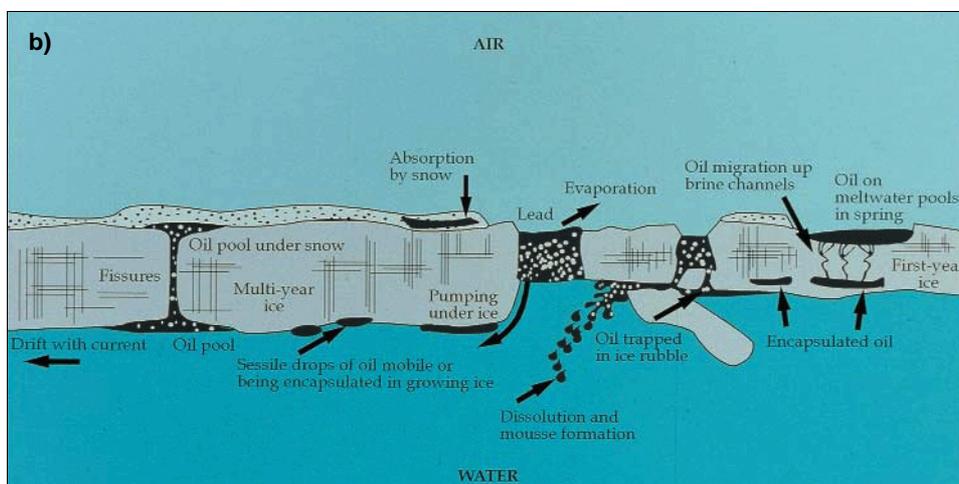

Figure 33 a) Oil in slush ice off the Canadian East Coast in 1986, b) a schematic composite displaying a number of possible configurations of oil in ice (Dickins Ass. 2004).

4 Modelling and Forecasting

Running various ice-ocean models as well as process-oriented models will be an important component of operational oceanography in Arctic regions. Three categories of ice-ocean models are envisaged:

1. global climate models with full coupling between atmosphere and ocean for simulations of decadal, interannual and seasonal variability

2. operational nowcasting and forecasting ice-ocean models driven by atmospheric forcing fields provided by ECMWF

3. regional scale forecasting models with higher resolution and nesting into a large-scale model.

The climate models typically have a resolution of 50–100km, the operational forecasting system 20km resolution, and the regional systems less than 5km resolution. The sea ice fields (concentration, drift and thickness) will be used for assimilation in the operational system.

4.1 Example of climate models: The Bergen climate model

Simulation and forecasting of seasonal and inter-annual variability is of particular importance in the Arctic Ocean and surrounding seas because of the strong climate change signals observed in the recent decades (ACIA, 2004). The Bergen Climate Model (BCM) is an example of a modelling system which can be used for this purpose. The system consists of a global version of MICOM which is

fully coupled to a dynamic and thermodynamic sea ice module. The model is configured with a local horizontal orthogonal grid system with one pole over North America and the other pole over central Europe. The horizontal grid resolution in the North Atlantic/Nordic Seas region is about 40km. There are 26 vertical layers, of which the uppermost mixed layer has a temporal and spatial varying density. The specified potential densities of the subsurface layers are chosen to ensure a proper representation of the major water masses in the North Atlantic/Nordic Seas region. Model simulations with daily NCEP reanalysis forcing fields since 1948 have been performed, showing that the model can reproduce realistic seasonal variability of ice extent as compared to satellite data. Examples of model ice output are shown in Figure 34. The BCM is currently run as a fully coupled atmospheric-ocean system, producing century scale simulations.

4.2 Example of operational forecasting: The TOPAZ system

The TOPAZ model system is an operational real time ocean monitoring and forecasting system covering the Atlantic and Arctic Oceans with a resolution varying from 18 to 35 km (Bertino *et al.*, 2004). The model system consists of an ocean circulation model, the HYCOM model (Bleck, 2002), coupled to an ice model based on the Elastic Visco Plastic (EVP) rheology by Hunke and
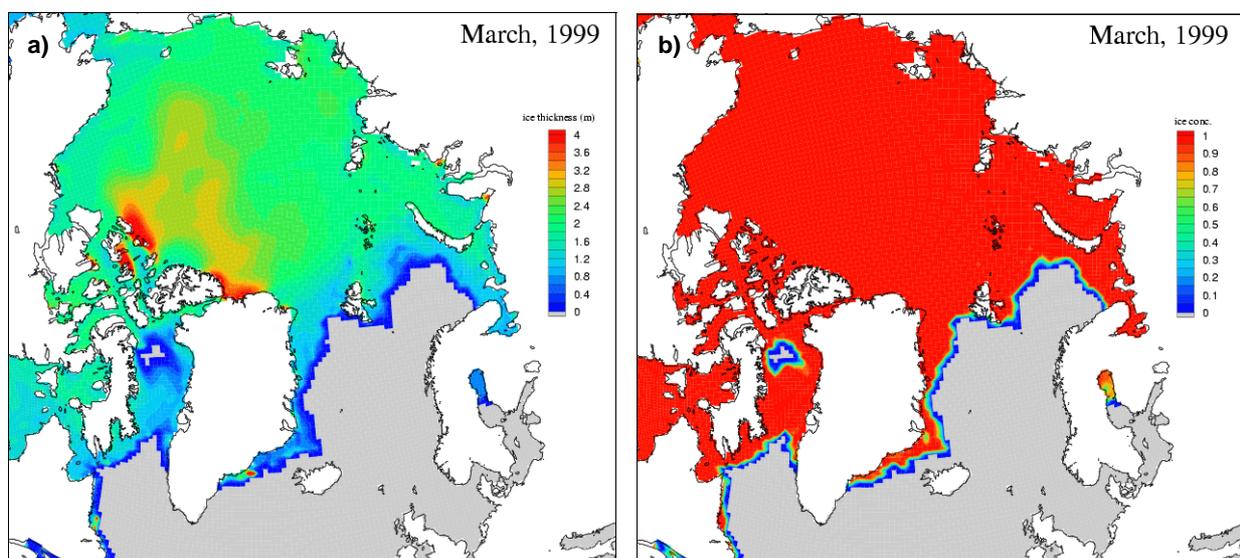

Figure 34 Bergen Climate Model simulations for March 1999: a) Ice thickness, b) Ice concentration.

Dukowicz (1997) for the dynamic part. Thermodynamics is computed using a simple parametrisation with a single ice thickness class (Drange and Simonsen, 1994). The ocean model is forced by atmospheric data, both nowcast and 10–day forecast with a resolution of 0.5×0.5 degrees, available from the European Center for Medium range Weather Forecasting (ECMWF). The TOPAZ system assimilates weekly fields of sea level anomalies (SLA) from four satellite altimeters (GFO, ENVISAT, TOPEX–Poséidon, and Jason–2), sea surface temperature (SST) from AVHRR, and sea ice concentrations from SSM/I data. The data assimilation method is the Ensemble Kalman Filter (EnKF, Evensen 1994, 2003). Assimilation of ocean surface parameters controls the ocean surface dynamics, as shown by Brusdal *et al*. (2003) and assimilation of sea ice concentrations has been developed by Lisæter *et al*. (2003). This enables the model to represent the general circulation, such as the Atlantic inflow to the Arctic, so it is well represented in the TOPAZ model. The next steps are to assimilate ice drift derived from satellite data and drifting ice buoys. Zhang *et al*. (2003) showed that the assimilation of ice motion data from SSM/I and buoys improved the ice motion and, through changes in ice motion, the ice thickness fields. Every week the TOPAZ system produces analysed maps of current ice-ocean state, and 10 day forecasts for the whole Arctic region at a resolution of 20–25 km. The sea ice forecast products consist of maps of ice concentration, ice drift and ice thickness (Figure 35). Results from the model systems are provided in several formats,

including presentations on the web (http://www.topaz.nersc.no).

4.3 Ocean Forecasting by the MI–POM model system

The ocean forecasting system at the Norwegian Meteorological Institute uses the ocean model MI–POM (Engedahl, 1995, 2001), which is based on the Princeton Ocean Model (Blumberg and Mellor, 1987). Lateral forcing includes monthly means of sea surface elevation, currents, salinity and temperature, and fresh and brackish run-off from rivers and/or estuaries. MI–POM is fully coupled to the dynamic-thermodynamic sea ice model, MI–IM (Saetra *et al*., 1999) using the elastic-viscous-plastic (EVP) dynamics of Hunke and Dukowicz (1997) and the thermodynamics of Mellor and Kantha (1989). The ice model also handles all fluxes of heat, moisture and momentum from the atmosphere to the ocean in ice-free waters. Atmospheric data from the ECMWF are applied as forcing fields.

The coupled model system is run once daily to provide a 10–day forecast of 3–dimensional current, temperature and salinity, as well as sea level, ice concentration and ice thickness. Data assimilation is carried out in a 30–hour run-up period. Currently, the operational EUMETSAT OSI–SAF SST and sea ice concentration products are assimilated, using a flux-nudging scheme (Albretsen *et al*., 2004). Forecast products are made available to users through normal public media channels and via met.no's Ice Service.
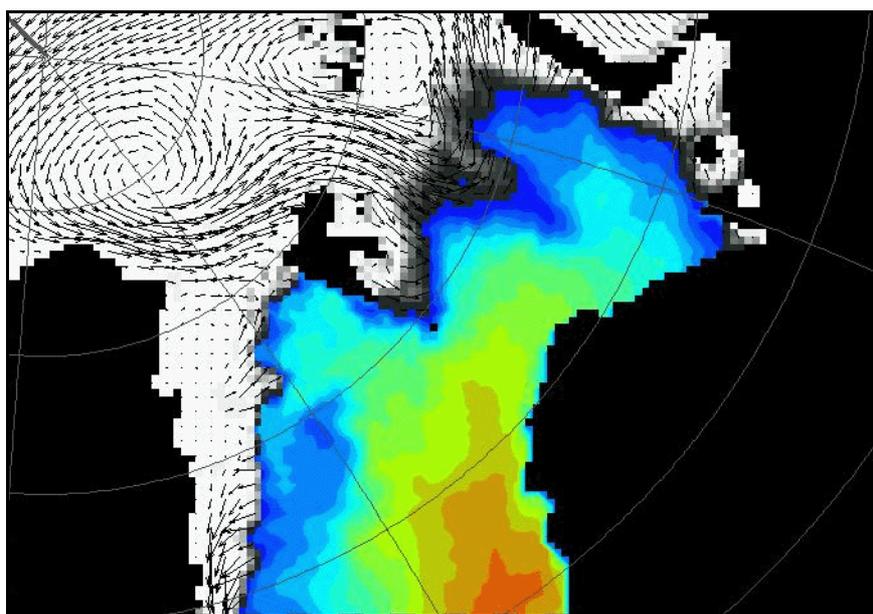

Figure 35 *Example of forecasted ice drift for the Barents Sea and Fram Strait region on 26 March 2004. Ice drift vectors are calculated and overlaid the ice concentration (greyscale) while the colours show SST in open water.*

Modelling and Forecasting

In the current development work a fine-scale atmosphere-ocean-ice-wave forecast model system will be established for the Svalbard area including assimilation of SAR-based ice observations. Furthermore, the assimilation techniques in ocean-ice models will be improved; a high-resolution ocean-ice model for the Barents Sea will be nested to the large scale model, and a primary production ecosystem model will be included in cooperation with the Institute of Marine Research.

4.4 Example of a regional model: the Barents Sea model

A resolution of around 20km, as used in TOPAZ, is too coarse to resolve mesoscale activity which is very important for the local representation of ice edge configuration, ice drift and ice concentration and correspondingly important for the ice thickness distribution. Local and detailed sea ice information, including ice thickness, will in future be essential

for safe navigation and operations in these regions. To support these needs a regional high resolution (4km) model for the Barents Sea and the Kara sea has been established using the same ocean and ice dynamics as in TOPAZ. For the thermodynamics a more complex ice representation is used where each grid cell has several ice thickness classes (Salas, 2002). This ice model also describes the redistribution of ice thickness through ridging and rafting within the grid cell. This coupled ice-ocean model uses atmospheric forcing data from ECMWF.

The Barents Sea model is nested with the TOPAZ system. This means that boundary conditions from the large-scale models are applied using a one-way nesting scheme where the boundary conditions of the regional model are relaxed towards the output from the large-scale model. The Barents Sea model is presently under validation and is planned to be run in real-time and forecasting mode from 2005. Examples of model output are shown in Figure 37.
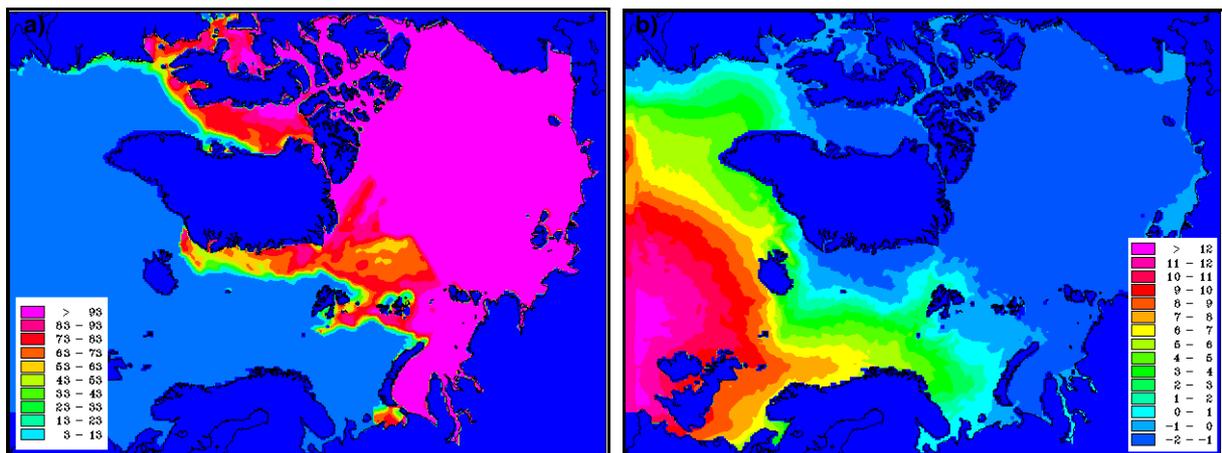

Figure 36 *Examples of output from met.no's ice-ocean modelling system:*
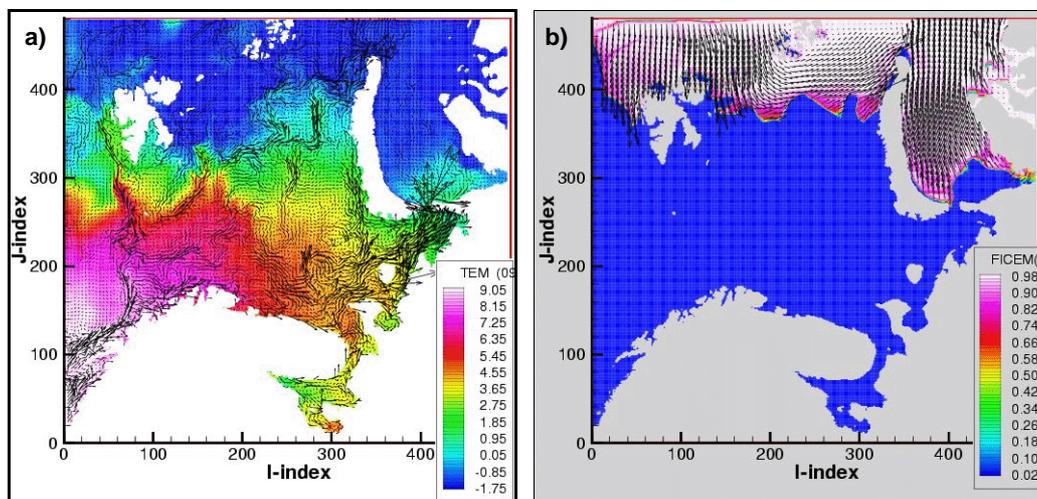*a) ice concentration in %, b) surface temperature in degree C.*

Figure 37 *Examples of Barents Sea model output from test runs for December 2002:*
a) SST and surface current, b) ice concentration and ice drift.

5 Data Exchange

The Arctic Task Team will build on a number of existing data archiving and distribution systems in the Arctic Ocean and surrounding seas to provide environmental information to a wide range of users.

To meet the requirements of all its users it is necessary to:

- identify and make available all data and products to those organisations adding value to the products

- provide international communication networks and efficient standard formats and codes to make best use of them. Such networks and protocols must have bandwidth sufficient to allow straightforward timely interaction with the relevant data centres.

- implement advanced data quality control and validation systems. These systems should ensure that the large volumes of data required and collected are fit for purpose.

- secure archival methods that retain the value of historical data. This requires appropriate collection, maintenance and dissemination of documentation and metadata.

- establish an integrated international database. For users to locate and recover the information they require, the information should be described in and accessible from advanced data processing systems. These systems are developed and maintained at the individual institutions and they will be connected and operated in a co-ordinated manner, so that information stored at different sites are as accessible as if stored in a single location. These systems will provide a standard set of assessment methods allowing investigations of the availability and retrieval of data and products.

- establish link to other data- and modelling centres for retrieval of boundary and forcing fields. The most urgent and vital part of the Arctic Task Team cooperation is the establishment of an efficient system for exchange of data between the participating institutions. The Arctic Task Team will basically follow the EuroGOOS Data Policy; but this data policy is, however, primarily focused on operational data exchange. For the work within the Arctic Task Team it is therefore important to establish good and trustworthy data exchange agreements between the operational and scientific community; since much of the oceanographic work in the Arctic area is and will be initiated and funded by the scientific community.

6 Dissemination

Operational oceanography is a growing activity on the global scale. For the Arctic ocean and surrounding seas there are presently few monitoring and forecasting services in operation, but several new products and services are under development to serve different users, both intermediate users and end users. Intermediate users from the public and private sectors must be involved in establishing a feedback loop delivering continuous assessments of the products in terms of accuracy, reliability, and adequacy to their needs. The design of the information delivery system will be formulated taking into account their specifications, which will allow for specific delivery of information (push) to targeted users, and will plan for easy access by a wider class of customers (pull) such as the scientific community and the general public. Policy makers need simplified information summaries in the form of indicators and indices, but presently few such indicators are readily available from the marine environment. The Arctic Task Team will contribute to developing appropriate indicators on the Arctic marine environment, addressing the objectives and vision of several initiatives such as GMES, GEO and GCOS.

EuroGOOS members already produce a variety of operational oceanographic services on a national scale of which forecast of sea ice distribution and concentration, wave forecasts, drift forecasts are the most advanced. These services are distributed to the users via established communication lines (phone, fax), Internet, and public media (papers, radio, TV). It is obvious that no operational cross boundary system in any domain can be successful without an efficient and robust information exchange and dissemination system. It is even more obvious that systems relying on data collected in different parts of the Arctic area by different parties cannot become really operational without such an information system.

Parallel to the improvement and development of operational oceanographic activities in the Arctic it is important to promote the products and services generated by the Arctic TT members through awareness campaigns addressing a full hierarchy of stakeholders. Governmental agencies and authorities, policy-makers, the marine scientific community, and the marine industries and services sector will be the main target. The campaigns will take an outset in the contacts and the lessons learnt in previous and present EuroGOOS activities and EU funded projects. The purpose will be to build momentum towards societal support and seek commitment from governments for operational ocean monitoring and forecasting. The Arctic Task team will work in close cooperation with the International Polar Year 2007–2008 which offers a unique opportunity to promote monitoring and forecasting in the Arctic regions.

The specific objectives of the dissemination system for the Arctic Ocean and surrounding seas are to

1. prepare promotional material on operational oceanography products based on existing material from the Arctic Task Team

2. develop, validate and demonstrate new products to various users from industry, government, international programmes and other user groups

3. demonstrate through a cost benefit analysis the advantages of operational ocean forecast products available for a range of services and thereby develop a market for such products

4. plan and coordinate marketing activities for the Arctic Task Team

5. establish networks between operational service producers, value-added service providers and end-users.

6. identify existing and possible expansion of the markets for operational oceanography in polar regions

7. establish and run a web site for the Arctic Task Team for promotion and exchange of information.

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8 Contributors

List of contributors to this report

9 Appendix

To be updated or removed

A. Ice strengthened Research Ships and Ice Breakers

A basic component to measure *in situ* data are research vessels. They supply data from ship-borne repeat surveys, and are needed to deploy and recover moored instruments, as well as deploy and eventually recover autonomous floats and vehicles. Ice breaking research vessels will be the backbone of an Arctic measurement system, even if air deployments will play a role as well.

List of available and planned vessels with ice capability

Germany

POLARSTERN, research ice breaker in service

NN, Medium size vessel for ice margin use in advanced planning phase

AURORA BOREALIS, plans as European ice breaker with all year round operation facilities

Norway

LANCE, research vessel for the marginal ice zone in service

NN, Plans for a ice breaker in an less advanced status

Sweden

ODEN, ice breaker available for 180 days during the next 3 to 5 years

UK

JAMES CLARK ROSS, research vessel for the marginal ice zone in service

SHACKLETON, ice breaker available on multi-year commitment

Canada

CCGS LOUIS S. St-LAURENT, Ice breaker but not budget committed

USA

USCGC HEALY, Ice breaker in even years in western Arctic, in odd years in eastern Arctic

Additionally Russian vessels and military submarines are available to a certain extent. However, a sustained observation system requires to consider the further development of the research fleet and appropriate new vessels have to be build.