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ARCOP WP1: Ice information system

Review of ice services in the Northern Hemisphere

Background document for design of an Ice Information System for operations in the Northern Sea Route

Deliverable D1.2

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Table of contents

Executive Summary

Sea ice information in combination with other met-ocean information is essential to support safe and cost-effective operations in Arctic sea areas. This report provides a brief overview of sea ice monitoring and forecasting systems, both established systems used in operational services and new systems which are under development. Offshore operations often demand very specific and advanced information which is not delivered by the operational services. It is therefore necessary to review both existing and upcoming methods for monitoring and forecasting of sea ice conditions.

The report is intended to give an overview of non-Russian systems and services, since another report describes the Russian monitoring and forecasting systems. First, the various ice charting and ice imaging services in Arctic are described, where satellites play the main role to provide data. These services are divided into two categories: one provides global products of ice extent, concentration and drift, while the regional products are usually the ice charts produced by the national ice services in the Northern hemisphere. The ice services in the Baltic Sea is described specifically, using the Finnish Ice Service as example, because this area has a well-developed cooperation between the service providers in the countries and the users. The communication and dissemination system to ships is also describe. Many elements of the Baltic sea ice system can be implemented in the Northern Sea Route.

Furthermore, there is a range of new satellite-based information products which are under development and testing. Of primary interest are products based on Synthetic Aperture Radar (SAR) and altimeter products giving information about the vertical dimension of sea ice. Satellite SAR systems are now developed into operational systems for providing high-resolution information about sea. RADARSAT and ENVISAT are examples of such systems, and new SAR satellites will ensure that there is continuity in the data supply for the future. By combining SAR and altimeter data, there will be a new step forward in monitoring the ice dynamics and thermodynamics, and it will also provide data to improve modeling and forecasting systems.

A brief review of some ice-ocean modeling systems is given to illustrate how models can be used in hindcast studies as well as in forecasting. Operational forecasting of sea ice is presently done on large and regional scale, whereas local forecasting to support offshore operations is in a development phase. Ridge forecasting in the Baltic Sea is developed as part of the IRIS project. In the Northern Sea Route, significant improvement in ice modeling can be expected as more high-resolution information on the sea ice processes becomes available. Use of discrete element modeling to simulate ridge formation floe interaction and break-up is under development, allowing ice models to increase resolution down to the size of individual floes and leads. This modeling concept requires observations with similar resolution.

In situ measurements of sea ice is often a lacking element in an ice information system, especially for local scale and tactical information. Use of ship radar and other ship-based observation methods, automated ice buoys, helicopter surveys and in situ observations by personnel working on the ice are important components if the most detailed level of ice data us needed. Underwater sensors to measure ocean parameters as well as ice thickness and ice drift are used in several regions, but data from such platforms are not yet available in real time.

In future ice information systems, data integration and analysis tools, such as GIS, and dissemination systems for rapid transmission of data and analysed products to the users are essential elements. The amount of data, both observational and modeled data, will grow. With Internet and high-speed computer network, it is feasible to transfer large amounts of data. Ice services become more desentralized and service network are developed where many information providers offer products.

1 Introduction

1.1 Background

The presence of sea ice together with harsh climate and weather conditions in the Arctic impose 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 (Fig. 1). 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 has to be implemented.
Sea ice has a dramatic effect on the physical characteristics of the ocean surface. It modifies the 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 rejects brine which deepens the surface mixed layer and can, through convection, influence the formation of deep and bottom water. 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).

Sea ice observation and mapping today is 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 are presented in Table 1.

Before the various components of an ice information system is described, it is useful to clarify some commonly used terms describing the formats of ice products such as “images”, “maps” and “charts”.

Ice charts are prepared as a result of an ice analysis performed by a person who use satellite data and other available ice data. The format of an ice chart follows a standard defined by WMO. This standard can have regional adaptations, based on an official nomenclature. Use of the “egg code” is an example of a standardized way of presenting ice information.

Ice maps are 2-D presentations of results of satellite algorithms (i.e. ice concentration maps from SSMI, ice thickness maps from radar altimeter data, and ice drift maps from scatterometer) and output from ice models (where all the major ice parameters are calculated). Ice maps are also used a synonym for ice charts.

Ice images are output from satellite and aircraft imaging instruments used to produce ice charts. The most common ice images are derived from SAR, imaging spectrometer, infrared radiometer, scatterometer, scanning laser, etc. An example of product is geolocated SAR image transmitted to icebreakers. Ice images can be useful supplement to ice charts because they contain more detailed information about leads, ridges, floe size and ice types.

1.2 Overview of satellite systems used for ice observation

Table 1. 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. RADARSAT-2 will follow in 2006.	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. Global Monitoring Mode provides low-resolution (1 km) images as a background mode, providing near full coverage of the Arctic every 3 days	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 monitoring at large scale. Resolution 10 - 30 km	Time series of ice area since 1978. Used in EUMETSAT OSI-SAF products
	NASDA & NASA AMSR	2003-	New generation passive microwave instrument. Improved spatial resolution, better spectral coverage: 6 – 10 km	Supplement to the SSM/I data

1.3 Definition of ice information systems

Ice Information System should be defined widely in order to benefit from all available information sources and be useful for all aspects of Arctic operations including strategic, operational and tactical navigation. A system for use exclusively onboard a vessel or platform could be defined as “Tactical Ice Information System” and be a subset of the general Ice Information System.

Any well-designed ice services system must consist of the following main components:

(a) Surface observation network consisting of in-situ and remotely sensed data;
(b) Modelling, data assimilation and forecasting systems
(c) Communication systems to gather and distribute the ice information; and
(d) Data integration, analysis, production and dissemination system.

Surface reports from shore stations, ships and drifting buoys provide accurate information on ice amount, thickness, motion and its deformation over rather small areas. When many vessels and fixed observing points are available accurate information can be provided in restricted waterways. Many areas in Baltic Sea coastline fall into this category and landline facilities are available for relay of these reports to national or regional centres.

When waterways are more open or more remote from populated areas, either satellite data or aerial observations must be integrated into the system. Air reconnaissance data is normally presented in map format as they fly along the prescribed track. An air-to-ship communication line is needed to pass the data directly to vessels in the area. This may be merely a voice channel, a radio facsimile broadcast or digital network link, which enables radar data or the ice chart itself to be passed to the ships. In most cases, these data are also passed to the ice centre for integration into regional-scale analysis products.

Satellite data are typically passed in near real-time (less than 6 hours) from satellite ground stations to the ice centres via high-speed communication links. Visible, infrared, passive microwave, active microwave data are then digitally processed, integrated with meteorological guidance products and ice model outputs and then analysed on computer workstations, typically using GIS environment. Image enhancement techniques and various other automated algorithms are often employed in the production of an ice analysis. Ice analyses are produced as charts on varying scales (typically ranging to 1:2,500,000) depending on the size of the area and the level of detail required. The ice charts are made available as data coverages in GIS formats and/or simple electronic charts in such graphic formats as GIF or PNG, which can be viewed with almost any web browser or graphics viewer and. Charts are typically labeled and coloured using the WMO international sea ice nomenclature (WMO-No.259) and “Ice chart colour code standard” (WMO/TD-No. 1214). Other ice analysis products include annotated satellite imagery usually in JPEG and TIFF formats, text messages and electronic charts.

2 Ice chart and image products for the Arctic

2.1 Global maps of ice concentration, ice type and ice drift

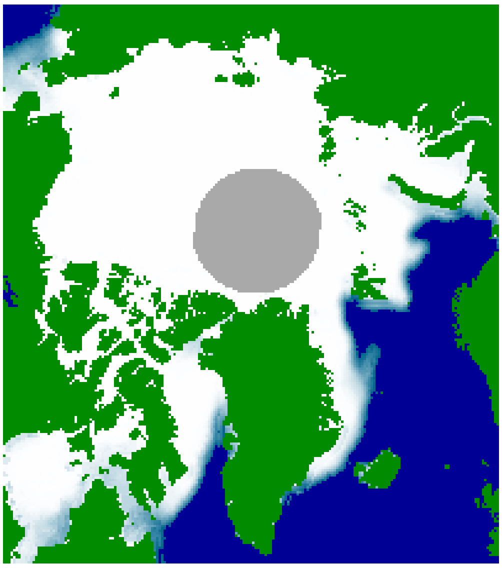
Maps of ice concentration, ice types (MY and FY) and ice drift are produced for the whole Arctic every day. Input data are and passive microwave data from SSM/I and AMSR-E and SeaWinds scatterometer data.

Ice maps from SSMI data

- Provider: NSIDC
- Input data: SSM/I passive microwave data
- Parameters: total ice concentration (Fig. 1a), extent, MY/FY classification
- Geographical coverage: both northern and southern hemisphere
- spatial resolution: ≈ 30 km
- accuracy: ≈ 5 % total ice concentration, uncertain for MY/FY classification which is not possible during the melt season
- Delivery: every day in NRT and archived products since 1978,
- Access to data/products: http://nsidc.org In Europe the data are also available from the DTU web browser: http://www.seaice.dk.
- Use of the products: for large-scale and regional ice mapping in NRT as well as for building up archives, ice modeling, data assimilation

Ice maps from AMSR-E data

- Provider: University of Bremen
- Input data: AMSR-E passive microwave data
- Parameters: total ice extent (Fig. 1b)
- Geographical coverage: both northern and southern hemisphere
- spatial resolution: 6.25 km for hemispheric maps, 3.125 km for regional maps
- accuracy: tbd
- Delivery: every day in NRT
- Products available since 2002
- Access to data/products: http://www.seaice.de
- Use of the products: for large-scale and regional ice mapping in NRT



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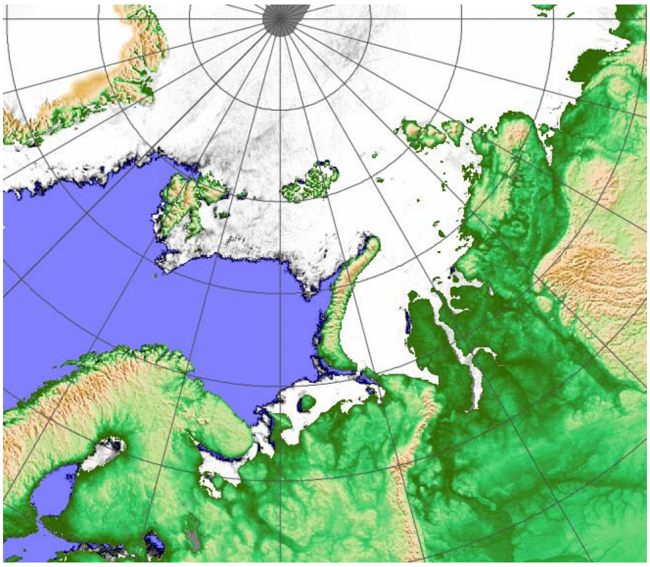

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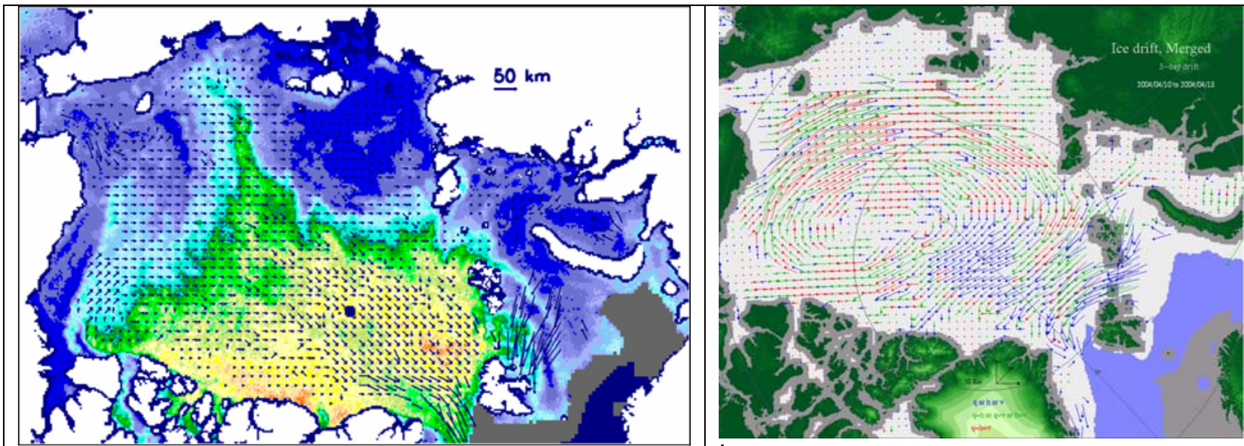
Figure 1. Examples of existing large scale Arctic ice maps which represent the background for the global ICEMON products: a) total ice concentration from SSM/I data produced by NERSC, b) total ice concentration from AMSR-E data produced by IUP-UB, showing a subset of the Northern hemisphere chart.

Scatterometer products are produced every day in NRT from October to April for the Arctic and archived products since 1999. An example of a microwave ice type and ice drift product is shown in Fig. 2.

Ice type and ice drift maps from Quikscat

- Provider: Ifremer,
- Input data: SeaWinds scatterometer data
- Parameters: ice types (MY/FY classification) and ice drift
- spatial resolution: 12.5 km for MY/FY ice maps, 62.5 km for ice drift (Fig 2a);
- spatial resolution for merged scatterometer and AMSR-E data: 31 km (Fig. 2b)
- accuracy: for MY/FY classification (see validation reports), for ice drift 5.1 km

- Delivery: every day in NRT from October to April for the Arctic and archived products since 1999, ice concentration available throughout the year but with less accuracy in the melt season
- Access to data: ftp://ftp.ifremer.fr/ifremer/cersat/products/gridded/mwf-quikscat
- Products available from 1999.
- Use of the products: for large-scale ice mapping in NRT as well as for building up archives, ice modeling, data assimilation



a b

Figure 2. a) Scatterometer ice drift and ice types map for April 1st 2003 produced by Ifremer. The colour code indicates that blue represent firstyear ice and green-yellow represent multiyear ice: b) merged ice drift from scatterometer and AMSR-E data.

Ice concentration and extent maps from OSI SAF

- Provider: EUMETSAT's Ocean and Sea Ice Satellite Application Facility (OSI SAF), hosted by met.no
- Input data: primarily passive microwave data, also scatterometer and AVHRR data
- Parameters: ice concentration and extent
- spatial resolution: 10 km (Fig 3);
- accuracy: (see validation reports)
- Delivery: every day in NRT
- Access to data: http://saf.met.no
- Use of the products: primarily input to weather forecasting models, also general use by all who needs ice maps.

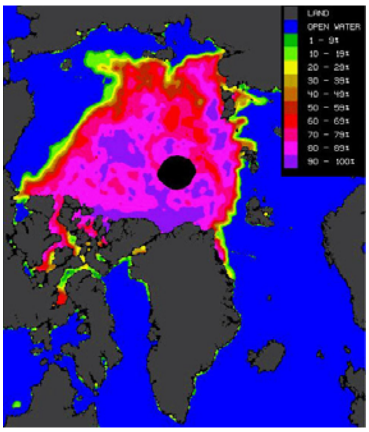


Figure 3. Example of ice concentration and ice extent map produced by OSI-SAF

Image mosaics and drift vectors from ASAR Global Mode

ENVISAT ASAR Global Mode (GM) offers a unique opportunity to observe and monitor the whole Arctic and Antarctic sea ice cover regularly with medium-resolution (1 – 2 km) radar images independent of cloud and light conditions. This capability has not been available from any other space system so far, and ESA started to deliver GM data in April 2004. RADARSAT ScanSAR can provide global SAR coverage of the Polar sea ice, which has been nicely demonstrated by US scientists (i.e. Kwok et al. 2002), but global ScanSAR coverage has not been available in Europe due to data policies and data costs. Development of products is going on at DTU-DCRS, Vexcel UK, met.no, NERSC and others, and specific studies are required to explore and assess the possibilities to retrieve parameters from the GM data such as ice kinematics fields, maps of MY/FY ice, polynya maps, etc. It is foreseen that 2 – 3 years of development and testing is needed to assess how much data will available over a few seasonal cycles.

The first stage in the product development from the GM data is the geolocation, radiometric correction and mosaic composition of radar images . The first analyses suggests data coverage is not sufficient to make a new mosaic every day (Fig. 4), but 3-day or 6 day mosaics are feasible. Also the resolution of the mosaic is being tested: 5 km for global mosaics and 1 km for regional mosaics.

- Parameters: ice drift, ice edge, MY/FY discrimination
- Providers: Vexcel UK, DTU and met.no
- Input data: daily swaths of ASAR Global Monitoring Mode
- Spatial resolution: 1 – 5 km (under investigation)
- Delivery: NRT, every 1 –3 days (under investigation)
- Access to data/products: ICEMON web site (www.icemon.org)

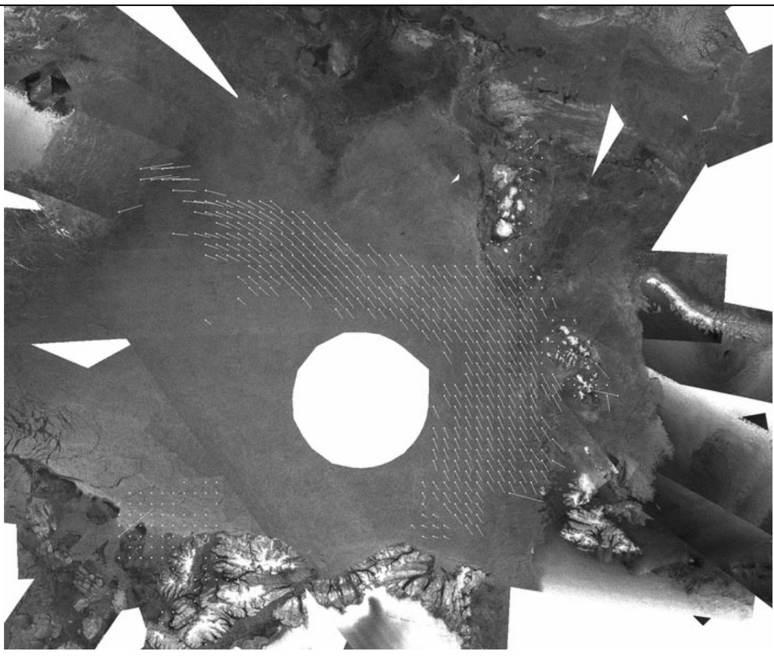


Figure 4. Global Arctic mosaic of ASAR Global mode data produced with 5 km resolution, including ice drift vectors

2.2 Regional ice charts produced by national ice services

National sea ice monitoring services have been established during the last century in all countries where sea ice effects navigation and other marine activities (Fig. 5). In Europe ice services are established in Denmark, Estonia, Finland, Germany, the Netherlands, Norway, Latvia, Lithuania, Poland, Sweden and Russia. Denmark has two services, one for the Baltic Sea and another for the Greenland waters.

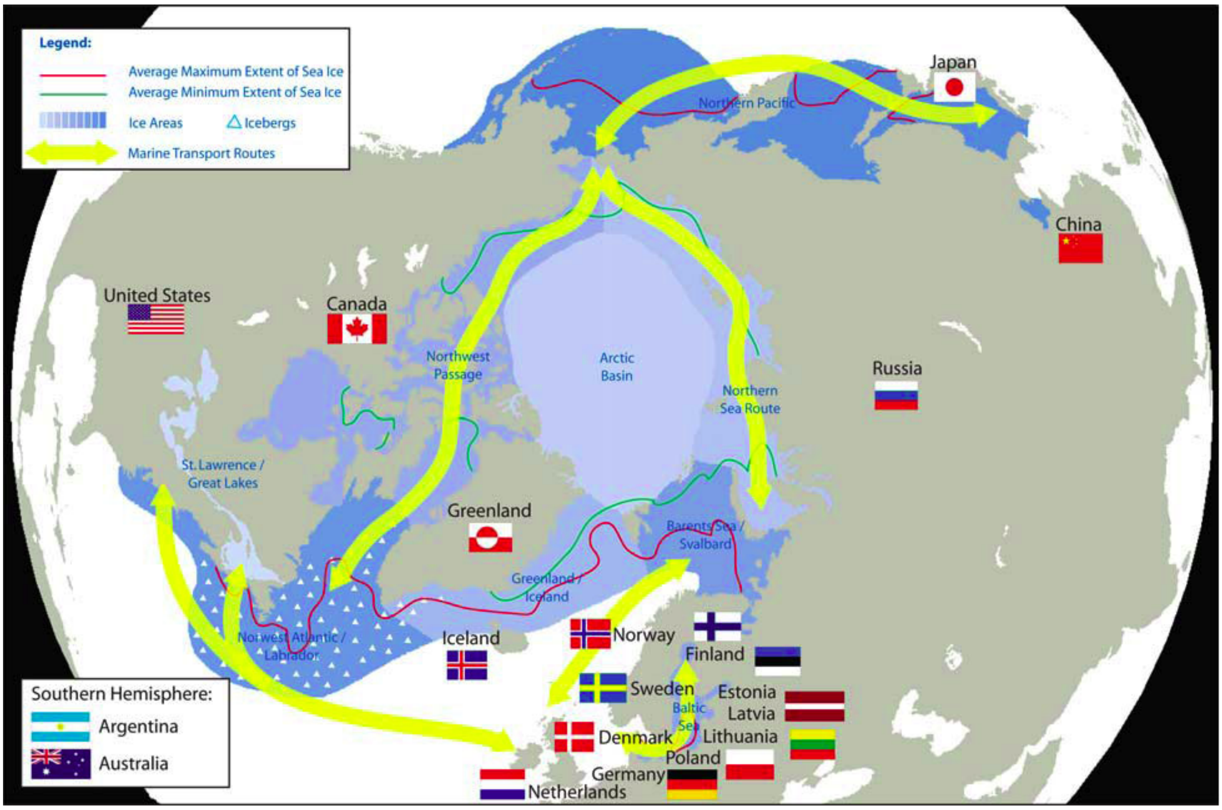


Figure 5. Countries with national ice services in the Northern hemisphere, including ice-affected areas and the main arctic shipping routes (IICWG, 2004).

Extensive ice services are established in USA and Canada. In Asia China and Japan have ice services. The national ice centres produce ice charts according to an international standard defined by WMO. Today the ice centres are organized in the International Ice Charting Working Group (IICWG). The most important international sea ice monitoring organizations are the Expert Team on Sea Ice (ETSI) working under WMO and the International Ice Charting Working Group (IICWG). The operational ice services provided by the IICWG member organizations are based, to a great extent, on information from Earth Observation (EO) satellites. Data from other sources, such as aircraft, in situ, and buoys are also used to some extent.

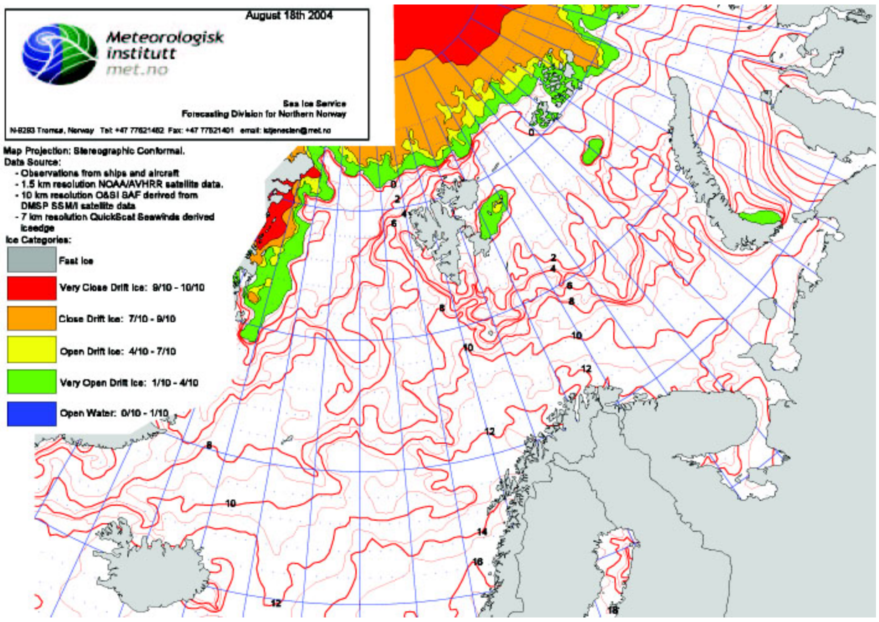
An overview of the data sources used by the national ice services to produce ice charts is given in Table 2. (from Sea-ice information Services in the World –WMO-No.574 – Geneva, 2005).

Table 2. Existing ice services and their chart products in the Northern Hemisphere: L=Large scale (>10km); R=Regional scale (1-10km); S=Local scale (<1km)

1.Country 2.Service provider	1.Monitoring area 2.Typical period	1.Products 2.Frequency 3.Parametres	Satellite data	Aircraft data	Ship, submarine, AUV data	In situ data
1.China 2.NMEFC	1.Bohai Sea 2.Jan-Mar	1.Charts [R] 2.Daily 3.ice-edge, concentration, thickness	NOAA AVHRR, Modis	Aircraft& Helicopter (Vis)	Coastal radar, ships	Stations (temperature, thickness, ice type)
1.Japan 2.JMA&JCG	1.Sea of Okhostk and n part of Japan Sea 2.Nov- Jun	1.Charts [R] 2.Twice/ week 3. Ice edge, concentration	GOES, NOAA AVHRR, DMSP, RADARSAT	Aircrafts (vis.)	Coast radar	Stations (concentration, thickness, difficulties to navigation),
1.Russia 2.AARI	1.Arctic 2.Jan-Dec	1.Charts [L] 2.Weekly 3.ice boundary, concentration	METEOR, OKEAN, NOAA AVHRR, EOS	Aircrafts (vis.&SLAR)	Ships	?
1.Denmark 2.Admiral Danish Fleet HQ	1.Danish waters 2.Dec-Apr	1.Charts [R] 2.Weekly 3.WHO symbols	No	No	Ships	Stations (Concentration, thickness, ice type, navigation conditions)
1.Denmark 2.DMI	1.Greenland 2. 12m/year	1.Charts [R] 2.1-6/week 3. WMO	RADARSAT, Envisat, NOAA AVHRR, DMSP	Helocopters (Vis.)	Ships	No
1. Estonia 2.EMHI	1.Estonian waters 2.Dec-Apr	1.Charts [R] 2.Daily 3.WMO	NOAA AVRRR	No	No	Stations
1.Finland 2.FIMR	1.Baltic Sea 2.Oct-May	1.Charts [R&S] 2.Daily 3.WMO	NOAA AVHRR, RADARSAT, Envisat Meris	No	Ships, icebreakers	Stations (edges, concentration, thickness, ice structure)
1.Germany 2.BSH	1.Baltic Sea 2.Nov-May	1.Charts[R&S] 2.Daily 3.WMO	NOAA AVHRR	No	No	Stations
1.Iceland 2.IMO	1.Icelandic waters 2.	1.Charts [R] 2. 3.Ice-edge	NOAA AVHRR	No	Ships	Stations
1.Latvia 2.LHMA	1.Latvian waters 2.Dec-Apr	1.Charts [R]) 2.1-3/week 3.WMO	No	No	No	Stations
1.Lithuania 2.CMR&LHMS	1.Lithuanian waters 2.Dec-Apr	1.No 2. 3.	No	No	No	Stations
1.Netherlands 2.RIZA	1.Netherland waters 2.Dec-Mar	1.Chats [R] 2.Daily 3.WMO	NOAA AVHRR	N	Ships	Stations
1.Norway 2.met.no	1.Svalbard 2.WMO	1.Charts [R&S] 2.Daily 3.WMO	NOAA AVHRR, Envisat, DMSP	No	No	No
1.Poland 2.IMWM	1.Baltic Sea 2.Dec-May	1.Charts [R] 2.twice/week 3.WMO	NOAA AVHRR, Meteosat, Feng Yun	No	No	Stations
1.Sweden 2.SMHI	1.Baltic Sea 2.Oct-May	1.Chats [R&S] 2.Daily 3.WMO	NOAA AVHRR, RADARSAT	Vis.	Ship, icebreakers	Stations
1.Canada 2.CIS	1.Canadian waters 2.12m/year	1.Daily [L,R,S] 2.Daily 3.WMO	RADARSAT, Envisat ASAR NOAA AVHRR, Meris, DMSP	Vis.&SLAR	Icebreakers	Stations
1.USA 2.NIC	1.USA Waters & Global 2.12m/year	1.Charts [L&R] 2.Daily/weekly /monthly 3.WMO	RADARSAT, Envisat ASAR NOAA AVHRR, Meris, DMSP	Vis.	Ships	Buoys

Norwegian ice service

The Norwegian Meteorological Institute (met.no) produces daily ice charts for the Barents Sea, the Svalbard area and the Norwegian-Greenland Sea regions. The charts also includes sea surface temperature (Fig. 6a). The main data sources are NOAA AVHRR images and SSM/I data observations from ships, aircraft and meteorological observation stations at Jan Mayen, Bear Island, Hopen and in Longyearbyen. Recently, use of SAR data has been introduced to produce higher resolution ice charts to support navigation in the Svalbard area (Sandven et al., 2004).



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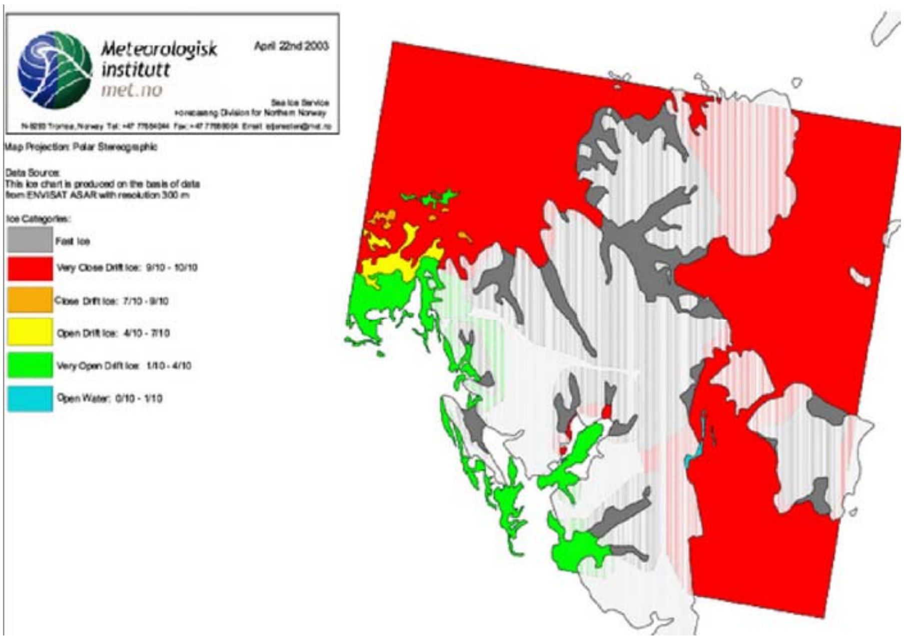

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Fig 6. a) Standard ice chart produced by Norwegian Meteorological Institute in Tromsø; b) High-resolution ice map in Svalbard area based on ASAR wideswth image of 22 April 2003.

The main users of ice charts produced by met.no are ship traffic and fishing vessels. Other users are coastal guard vessels, the governor of Svalbard, cruise and other ship traffic and offshore activities. The marine and offshore activities are growing significantly in this region implying stronger needs for sea ice and weather services.

In addition, high-resolution ice harts for the Svalbard region using NRT SAR images from KSAT. The main parameters shown in the ice chart is ice edge (km), fastice border, and ice concentration (%) The products are delivered on request all year. An example of high-resolution ice chart based on ASAR Wideswath images is show in Figure 6b.

The US National Ice Service (NIC)

The National Ice Center (NIC) is a multi-agency operational center representing the Department of Defense (Navy), the Department of Commerce's National Oceanic and Atmospheric Administration (NOAA), and the United States Coast Guard under the Department of Homeland Security. The NIC includes personnel from the National Environmental Satellite Data Information Service (NESDIS) within NOAA.

The main mission of NIC is to provide the highest quality strategic and tactical ice services tailored to meet the operational requirements of U.S. national interests. To provide specialized meteorological and oceanographic services to United States government agencies.

Satellite imagery constitutes over 95% of the information received and integrated into the NIC ice analysis products. NOAA TIROS-N and Defence Meteorological Satellite Program (DMSP) satellites are the primary source of remote sensing data (Sea Ice Information Services in the World, 2000). NOAA and DMSP OLS imagery are used for global and regional-scale mapping of ice conditions, respectively. Use of visible images is limited by natural light in winter. Cloud cover precludes sea ice observations both with visible and infrared imagery during approximately 80% of time in summer. The Fleet Numerical Meteorological and Oceanographic Centre (FNMOC) and National Centre for Environmental Prediction (NCEP) routinely process SSM/I data using CAL/VAL and NASA Team algorithms, respectively, for ice concentration determination, and transfer the results to NIC. The main disadvantage of passive microwave data is their coarse spatial resolution. After launch of RADARSAT in 1995, Synthetic Aperture Radar images became an important source for global and regional sea ice monitoring. In addition to satellite remote sensing data NIC employs USCG aircraft with side-looking airborne radar (SLAR) for special polar operations, regularly receives ice reports from visual reconnaissance missions, ships, Alaska coastal stations, and obtains information from the observational data network maintained by the International Arctic Buoy Program (IABP).

The NIC issues weekly maps of sea ice distribution in the Arctic, and the regional-scale ice maps on a be-weekly basis. An example of the regional sea ice concentration map of the south-eastern Barents Sea is shown in Figure 7. The National Weather Service in Anchorage produces a daily analysis of ice conditions in Cook Inlet, the eastern Bering, Chukchi and Beaufort Seas. Alphanumeric text messages describing ice conditions are routinely generated and distributed for US Department of Defence customers. The distribution of satellite images annotated with analysis graphics is restricted to authorize users. Users may request and receive fax copies of current NIC products via a fully automated the National/Naval Ice Centre Autopolling Facsimile System, which is available twenty-four hours a day free of charge.

NIC data are the major part of the US contribution to the International systems of global climate and ocean observations. Data of sea ice operative analysis and forecasts are intended for the US Navy, the US Coast Guard, departments of commerce and transport, other governmental and international US agencies as well as for the civilian sector.

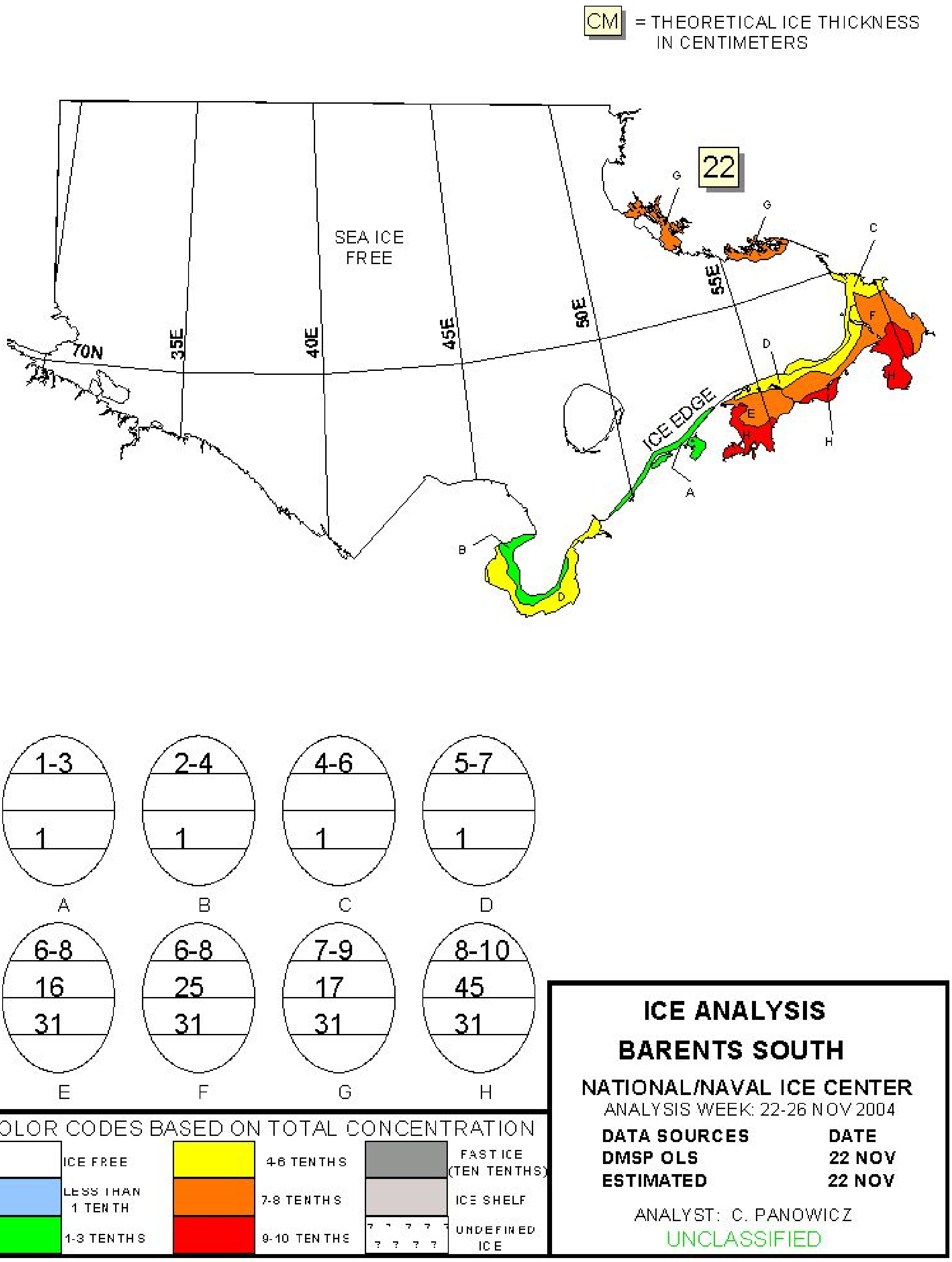


Figure 7. Example of regional ice chart for the south-eastern Barents Sea produced by NIC for 22 November 2004.

The Canadian Ice Service

The Canadian Ice Service (CIS), a branch of the Meteorological Service of Canada (MSC), is the leading authority for information about ice in Canada's navigable waters. CIS provides reliable and timely information about ice conditions in the Canadian waters for safe and efficient maritime operations and environmental protection. In summer it focuses on sea ice conditions in the Arctic and Hudson Bay region, whereas in winter and spring the Labrador Coast, East Newfoundland waters, the Gulf of St. Lawrence and St. Lawrence Seaway are of major importance Ice mapping is divided in to the five regions shown in Figure 8. CIS serves as a central processing and analysis facility where satellite and airborne data, meteorological and surface observations are integrated to produce an overview of current and future ice conditions for all regions of Canada.

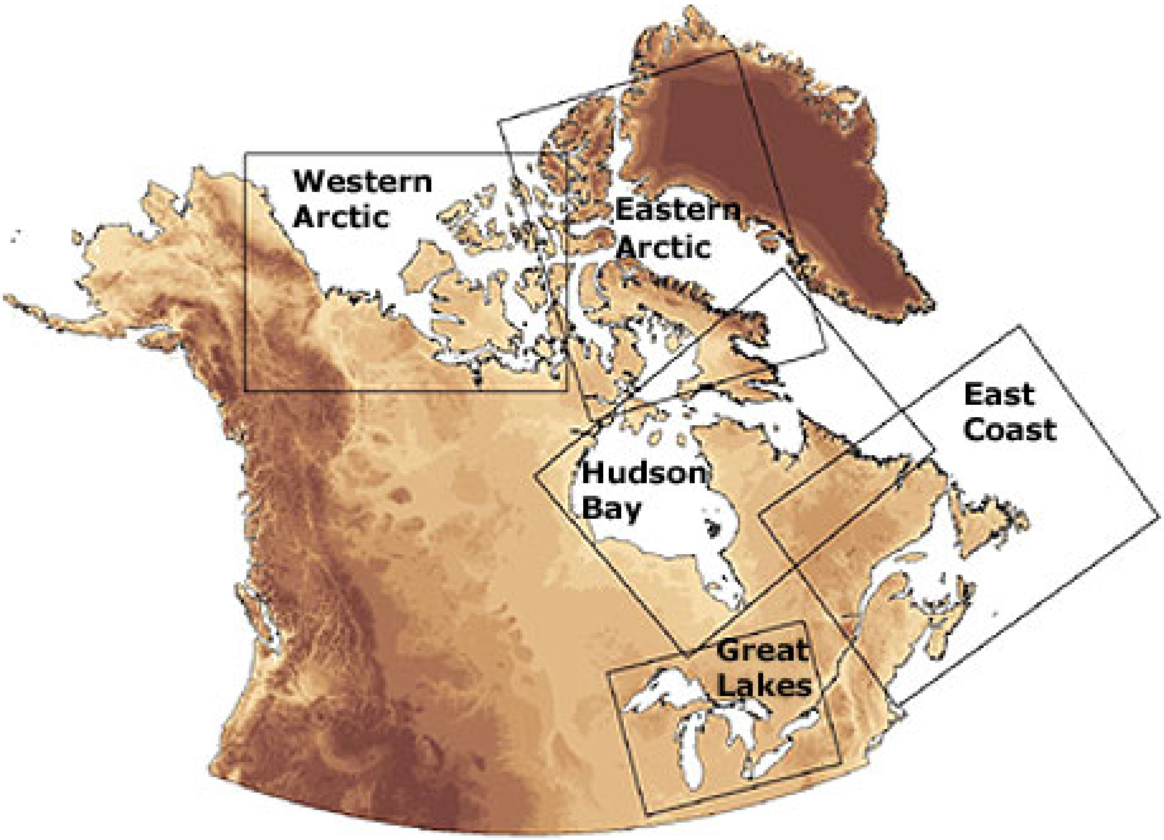


Figure 8. The ice mapping areas covered by the Canadian Ice Service (CIS).

Before the launch of RADARSAT, CIS employed two ice reconnaissance aircrafts for data acquisition, supplemented with NOAA AVHRR, ERS SAR, SSM/I data, and ship and shore reports. Today, RADARSAT ScanSAR Wide data provide daily coverage of the Canadian Arctic, and higher resolution modes are used for sea ice monitoring near the ports, in several selected routes and in the rivers. SAR images are produced at the receiving stations Prince Albert and Gatineau, and transmitted to CIS in near real time. CIS performs ice analysis and produces ice charts for the various users, primarily the Canadian Coast Guard (CCG). Sea ice monitoring is the most successful operational use of RADARSAT images, which provide a useful mix of geographic coverage and spatial resolution. Use of RADARSAT data is a cost-effective solution compared to airborne radar surveys which were the main source of ice data before the launch of RADARSAT [Edel et al., 2004]. Since February 1996 and until the end of 2003, CIS have used approximately 25000 scenes for this purpose (Flett and Vachon, 2004). An example of ice chart produced by CIS is shown in Fig. 9.

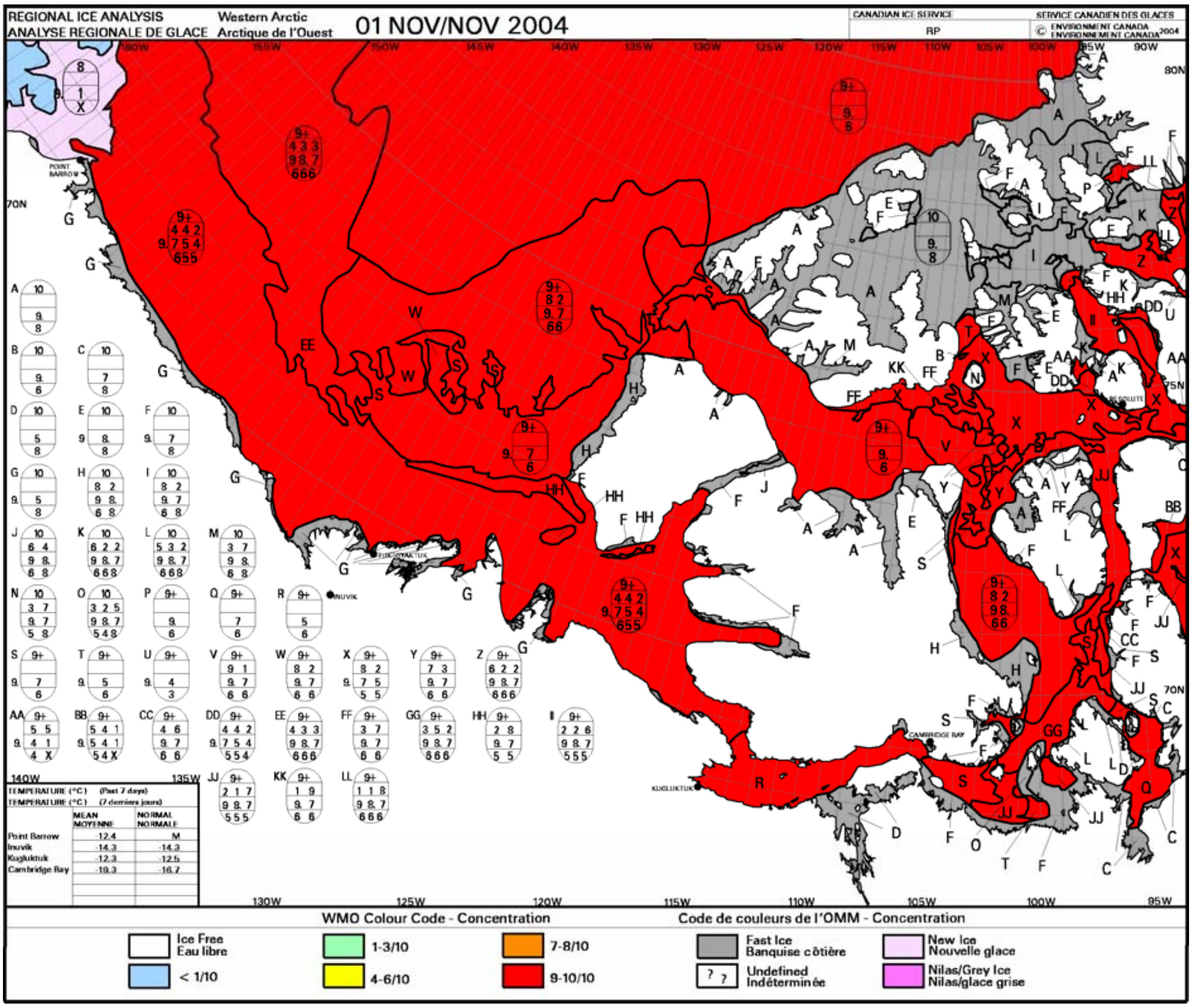


Figure 9. Ice chart of the western Canadian Arctic for 01 November 2004, produced by CIS.

In addition to mapping the sea ice CIS is responsible for the icebergs monitoring. The method involves locating the position of the icebergs using visual observations (aerial, ships and if possible satellites), and prediction of their movement for up to maximum 30 days. The special service implemented iceberg detection and monitoring from satellite SAR images. This service was in operation during 2003 and the International Ice Patrol was the user of this information (Flett and Vachon, 2004).

The CIS provides its clients with a variety of accurate and timely analysis of ice conditions, including ice charts, bulletins, images, and weather maps. Regional weekly ice charts, daily ice analysis and iceberg analysis charts, ice reconnaissance and RADARSAT image analysis charts are available. Raw images are available to users depending on their ability to receive image data. Bulletins provide advice on ice or iceberg conditions in simple text format (Sea Ice Information Services in the World, 2000).

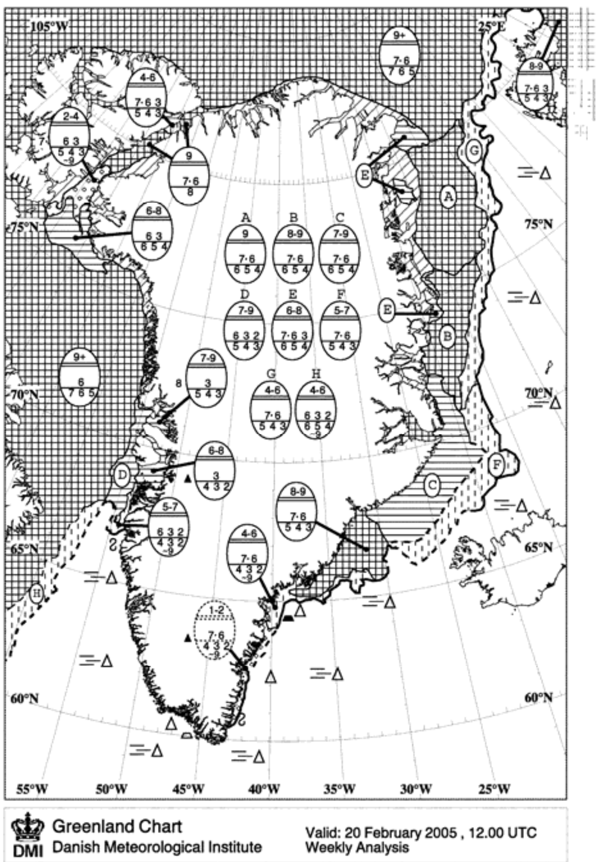
The main users for ice information are the Canadian Coast Guard, the Vessel Traffic Centres, the shipping, fishing and oil and gas industries. Others include the military, the insurance industry, scientists working on, under or around the ice, and other individuals with a need for up to date knowledge of sea ice distribution. Foreign ice services incorporate and exchange sea ice data with CIS, particularly the International Ice Patrol, Greenland Ice Patrol and the U.S. National Ice Centre.

Greenland waters

The Danish Meteorological Institute (DMI) in cooperation with the Greenland Ice Service have the responsibility for monitoring sea ice conditions in the Greenland waters where drifting sea ice and icebergs severely influence the coastal waters and even in summer may restrict the ship traffic. The most important navigation area is around Cape Farewell.

AVHRR images from the NOAA satellites, acquired by DMI receiving stations in Greenland and near Copenhagen, have been used for operational sea ice monitoring in the Greenland Waters since 1991. Cloud cover often renders visible data useless, and therefore SAR data from RADARSAT are now the main data source for sea ice mapping, and airborne reconnaissance is used as a supplement when satellite data do not provide sufficient information [Gill et al., 1997; Gill and Valeur, 1999]. Weekly ice charts are produced for the whole Greenland waters, while ice charts in the Cape Farewell area and on the east and west coasts are produced daily depending on season and requirements from the ship traffic.

The users are primarily commercial vessels passing Cape Farewell and local traffic, especially in West Greenland south of 69°N. The information from the Ice Service is requested by an increasing number of sea cruise ships which are visiting the Greenland waters and companies working with exploration of oil, gas and mineral resources. Fishing vessels are needed an information about the ice edge position. An example of a weekly ice chart for the whole of Greenland is shown in Fig. 10 a.



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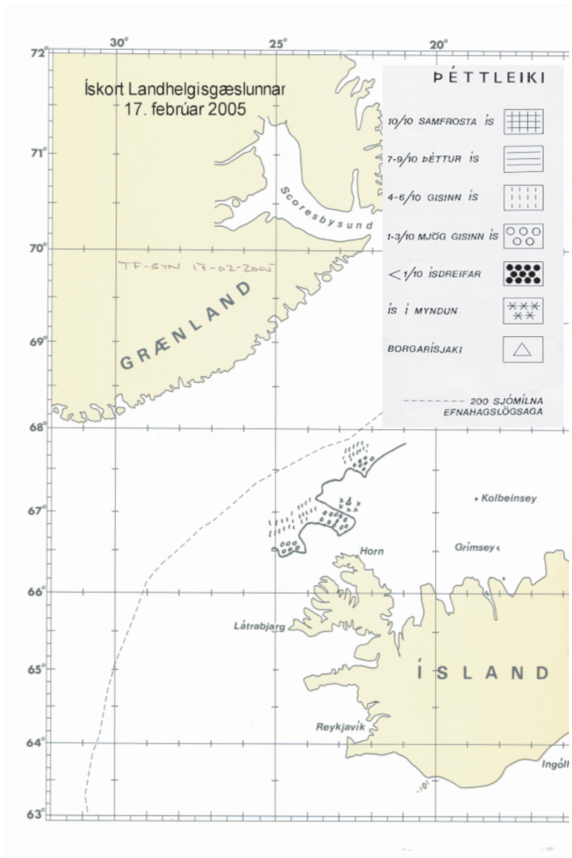

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Figure 10. a) Example of weekly ice chart for the Greenland waters produced by DMI, b) example of ice chart produced by the Icelandic Ice Service for 17 February 2005.

Icelandic waters

The Icelandic Meteorological Office (IMO) is in charge of sea ice monitoring in Icelandic waters in the Greenland Strait (Denmark Strait) between Iceland and Greenland and in the Iceland Sea north of Iceland. Sea ice in the Denmark Strait develops from an average minimum in late September/early October, when the average sea ice extent along the east coast of Greenland reaches Scoresby Sound, until an average maximum in late May.

For ice chart composition IMO uses the Icelandic Coast Guard (ICG) ice reconnaissance flights, visual observations from lighthouses and coastal meteorological stations, visual and radar observations made by ships, and NOAA images. About once a week IMO receives ice charts from the Danish and the Norwegian Meteorological Institutes. Although fog and clouds very often cover the sea-ice edge, and it is still relatively dark in late winter and early spring, when the sea-ice extent is at its maximum, use of SAR images have been considered too expensive. Icelandic sea ice charts give ice edge location, and, when available, concentration and stage of development (Figure 10b). All maps are transmitted to the ships or shipping companies by fax, and ice edge location is sent via HF radio. Some ships can also receive satellite images via INMARSAT.

The traditional users of sea ice data are the fishing fleet, both trawlers and smaller coastal boats, transport vessels along coastal routes, harbour authorities, coastal communities and local natural hazard committees. There is an increasing number of requests for ice information from travel bureaus, agents of large tourist vessels, and transatlantic sailing boats (mainly in summer).

3. Baltic Sea ice services: example from Finland

3.1 The Baltic Sea background

The Baltic Sea freezes annually. The maximum annual ice extent occurs between January and March, when ice covers 52,000-420,000 sq. km, and on average 218,000 sq. km. 0.5 probability of ice cover is at latitude of Stockholm. Ice season lasts from weeks in the south up to seven months in the north. The ice in the Baltic Sea occurs as fast ice and drift ice. Fast ice exists in coastal archipelago areas. Drift ice has a dynamic nature being forced by winds and currents. Ridges and brash ice are the most significant obstructions to navigation in the Baltic Sea. Powerful, ice-strengthened vessels can break through thick level ice, but they are not capable of navigating through ridges and heavy brash ice barriers without icebreaker assistance. Ice dynamics cause high pressure in the ice field and can be dangerous to the vessels and may cause time delays up to several days.

The two most heavily trafficed waterways in the word, where seasonal sea ice plays an important role in navigation, are Gulf of St. Lawrence in Canada and the Baltic Sea in Europe. In Gulf of St. Lawrence some 180 million tons of goods are transported annually. The total cargo turnover in the Baltic Sea in is about 700 million tons, some 40% of which occurs during winter. In Finland almost 90% of foreign trade is transported by sea. Annual turnover in 2004 was 95 million tons. During the winter months there are more than 25,000 port-calls in Finnish harbours transporting about 40 million tons of goods. The winter marine transportation is worth about 28 billion Euro.

The marine transportation has increased World wide. In the Baltic Sea e.g. in 2001 the number of vessels sailed in the Gulf of Finland was 38,000; in 2015 this is expected to rose into 53,000 vessels. Russian oil export is growing rapidly. In 2002, 76 million tons of oil was transported through Gulf of Finland, in 2005 will be 100 million tons, and by 2015 there is expected to transport more than 200 million tons.

Winter navigation is made possible by the use of icebreakers, ice-strengthened vessels and by restricting navigation. Navigation is restricted by closing half of the harbours for the winter and giving assistance only to vessels suitable for ice navigation. Under normal conditions the sailing time from the ice-edge to e.g. the northern Bothnian Bay is one day (400 nautical miles), but under severe conditions it can extend to nearly one week.

During last ten years the marine traffic has increased by 30%, and the trend is expected to continue. In the same period, however, the number of icebreakers has not increased. The smoothness of traffic has been possible due to by better ice monitoring, where use of EO data has become more and more important. Icebreakers need detailed ice information for route planning. Considerable savings in ice navigation could be made by optimising the use of satellite based operational ice monitoring.

3.2 The Finnish ice service

Baltic Sea ice service requirements

National ice services of the Baltic Sea are responsible to collect, analyse and distribute sea ice data. The input data consists of ground truth, visual and/or digital air-borne data, space-borne data of various satellites. All these data are collected by the ice services using various means of communication. The value of an ice chart is determined by its accuracy and validity. The real-time aspect is important as the ice conditions change over time. It is also very important to provide information, which has the best practice to the users. Thus e.g. ships require information in ship's scale.

Ice charts issued on a daily basis are the most important and widely used ice information products of the Finnish ice service. The charts are based on EO data (SAR, visual and infrared), reconnaissance flights, and ground truth (from ships, icebreakers and stations). In Finland and Sweden, digital satellite images are sent to the operative icebreakers daily in the ice season. The Finnish ice service has developed automatic classification maps of SAR images and sent them to the users. The Finnish Institute of Marine Research (FIMR) is responsible for the sea-ice information service in Finland. The Service, called Finnish Ice Service is intended to meet the needs of national and international shipping and activities where sea-ice information is required.

Input data and products

Ice information of ice-edge, boundaries, ice type, ice concentration, ice and sow thickness, and ice structure is collected daily and reported daily/weekly using fax, e-mail or mail by 20-30 ice observation stations. Harbours and pilot stations inform ice conditions depending on severity of ice conditions and if conditions are radically changed. Icebreakers report on ice conditions several times a day along the track. These plain language messages include traffic conditions, best ice navigation routes, ice deformation, ice thickness, concentration, edges and boundaries. These reports include ice monitoring done by ships.

Air borne data. Ice reconnaissance flights using fixed wing planed or helicopters have been reduced and replaced by extensive use of SAR data

Space borne data. The Finnish Ice Service has used satellite data since 1968. Today SAR data of RADARSAT is used in ScanSARWide mode for 100-120 images in a season. Other EO data used are all available passes of NOAA AVHRR in channels 2 and 4, plus combination products of Channels 1, 2 and 3. Also Envisat ASAR data and MERIS –250m data are used, but not routinely.

Output products. Ice charts which are provided in Mercator projection in three nominal scales: Normally covering the Baltic Sea north of 56º45' N in scale of 1:3,100,000 (at 60º N) During severe seasons the total Baltic Sea and the Danish Straits and the Northern Sea east of 7º E in scale of 1:4,600,000 (at 60º N). On request any coverage and scale can be provided. Nominal scale means printed hard copy of the chart. Of course in all digital charts scale is flexible and cannot be defined. The charts contain ice conditions in WMO symbols, position of icebreakers, restrictions to navigation, and traffic information. On Mondays and Thursdays they also contain SST isotherms, 30y average SSTs, 30y mean ice conditions and 30y average ice thickness. On Mondays simplified ice chart is published via Internet, containing ice covered area, SST, and ice thickness. This product is aimed to the great public.

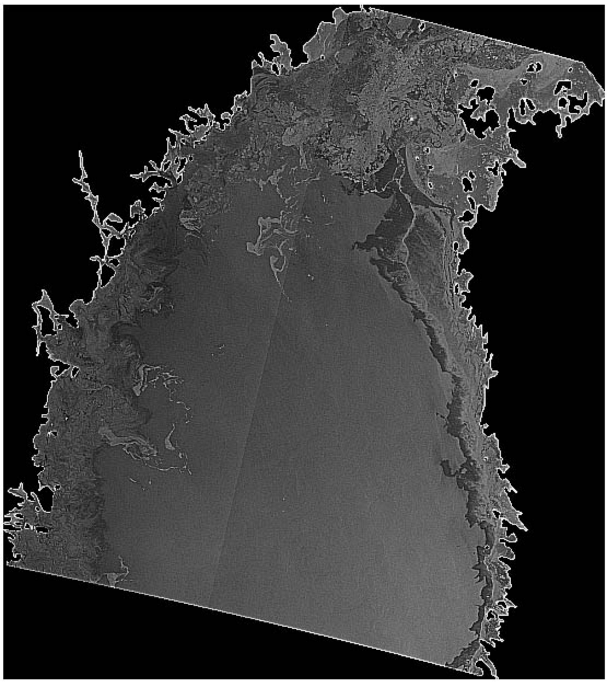
Coded information. A sea-ice bulletin concerning ice and traffic conditions over 130 areas or fairway sections in the Baltic Sea Ice Code is issued twice a day from coastal radio stations and by GTS. These are also published with ice bulletin.

Plain language reports. A sea-ice bulletin with description of ice conditions, restrictions to navigation, operational areas of icebreakers is issued on daily basis in Finnish, Swedish and English. It is broadcasted in Finnish and Swedish by Finnish Broadcasting Company (YLE), and in English two times a day by coastal radio station of Turku. The bulletin is also available by mail, e-mail, fax and call-fax.

Forecasts. Operational dynamic numerical forecasting in Finnish Ice Service started in 1978. Today two dynamic & thermodynamical numerical models are run operational: HELMI and IRIS, both providing forecasts on daily basis for next 54 hours. Forecasted parameters are in 6 hour intervals: ice drift (speed and direction, edges, boundaries, concentration, level ice thickness, deformed ice thickness, ridge location, ridge density and ridge sail height. Ice thickness growth forecasts for +10 days are issued once a week over Finnish harbours. Twice a week +10d oral forecasts for changes in weather and ice conditions of various sea areas is published.

SAR products. Since 1994 SAR based ice information products have been available in Finnish ice service and icebreakers. Today when SAR data is available high-resolution ice thickness chart is produced, where ice thickness are in 500m resolution. Products are in use of users in a about ½-1 h after data is downloaded in the Finnish Ice Service. Examples of products are shown in Fig. 11. At the moment products are in use of Finnish ice service, Finnish and Swedish icebreakers and administrations. For the two last ice seasons products have been available to all interested parties through ICEMON web pages. SAR images in reduced resolution (400m) are in NRT use at the Finnish and Swedish icebreakers. Finnish Ice Service is responsible of the service.

By means of Radarsat SAR imagery and coincident airborne EM ice thickness surveys, algorithms have been developed to derive Baltic ice thickness information from SAR images alone (Karvonen et al., 2005). As SAR backscatter depends other ice properties and their changes, e.g. due to air temperature variability, the algorithms have to be adapted to the specific weather conditions of any particular day. For a long term observation program, therefore repeated HEM flights will be required to initialize the algorithm. However, flights have to be performed only in a small region, and results can then be extrapolated based on the SAR imagery. Ice thickness maps are distributed by FIMR (Fig. 11c).



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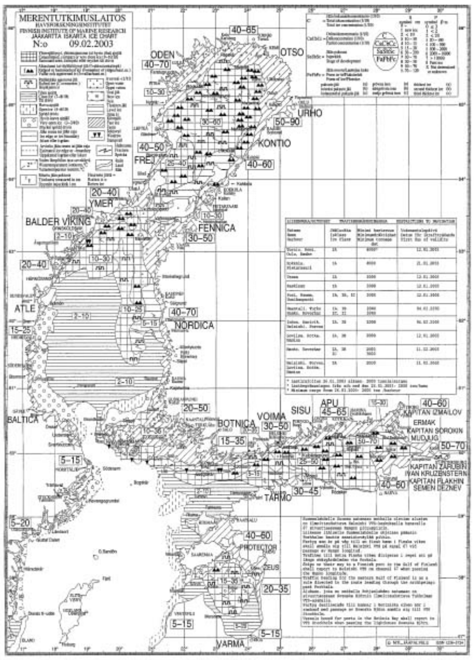

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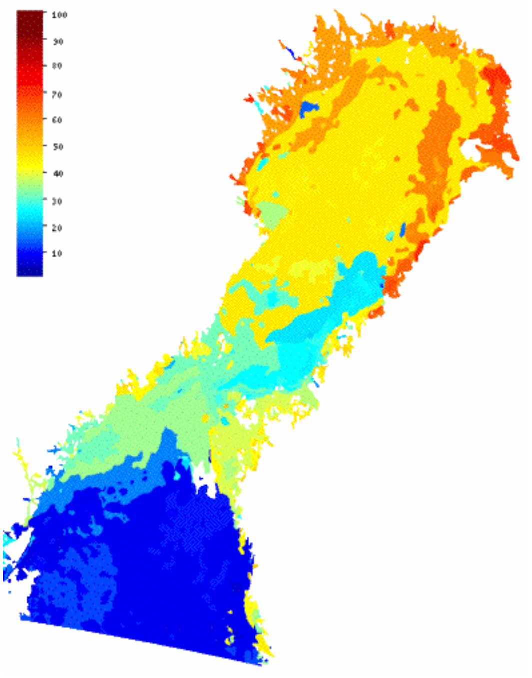

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Figure 11.
a) SAR image with landmask used as input to ice chart production,
b) example of ice chart produced by the Finnish Ice Service,
c) ice thickness map produced in ICEMON with units in cm

Product and service delivery systems. Products are distributed through mail, e-mail, fax, call-fax or intranet to users. Hard copies are distributed by mail, fax or call-fax. Call-fax operates 24h a day, where user could connect server and download charts or ice bulletins. Ice charts, ice bulletins and ice forecasts are distributed by e-mail attachments. Products are ordered beforehand and distributed at the given time. Non-regular users are served by request. On Internet free of charge simplified ice charts are provided. Some experimental products are also available via Internet. IbNet (icebreaker network) connects Finnish and Swedish icebreakers, administrations and ice services. Sea-ice products are among other information distributed to users using IbNet. Almost all icebreakers use satellite communication, thus data volumes could be rather high.

Main users
Main users are shipping, icebreakers, vessels in great, pilot and harbour authorities, maritime authorities, navy, coast guard, weather services, export companies, and so on. It is estimated, that there are 60,000-70,000 users of Finnish Ice Service products in each ice season, excluding Internet users.

4. Example of ice information system for ships in the Baltic Sea

The most advanced users of ice information in the Baltic are the icebreakers. The Swedish and Finnish icebreakers in the Baltic Sea use an information system called IBNet (Fig. 12). This distributed information system provides and distributes information about the icebreaker activities, ship timetables and about ice- and weather conditions. Onboard the icebreakers, IBNet is used as a background information source for assistance planning and for determining the optimal route for the ships to follow. Ice condition information is aquired through satellite images (SAR images are the most important ones), ice charts and ice reports from other icebreakers as well as from merchant ships.) The satellite images are processed at the Ice Service and sent to the icebreakers via IBNet.

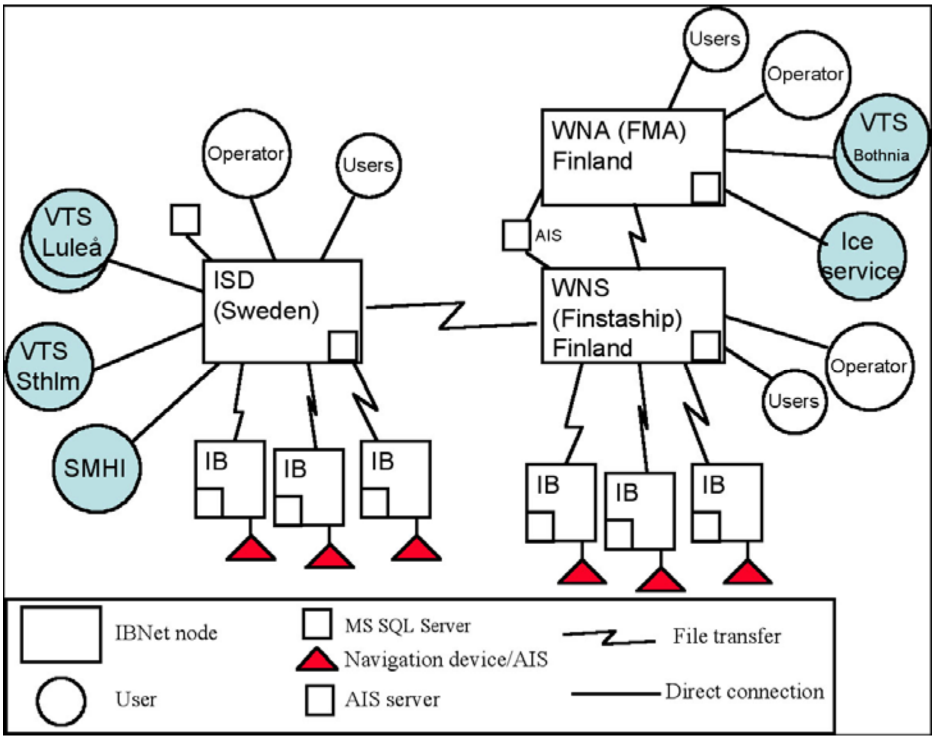

Figure 12. Schematic view of the IBNet system in the Baltic

The IBNet system has been designed with the following technical requirements in mind:

- Autonomous operation of the nodes: the telecommunication links are not that reliable, therefore the system must be able to operate locally even though the telecommunication links are temporarily not available.
- Possibility to utilize different telecommunication channels: not all icebreakers are equipped with high-speed satellite links
- Economic utilization of the telecommunication links: only *changes* in data is transferred between the nodes.
- Interfaces to external information sources to enable automatic import of data concerning ship register- and timetable data as well as position information.

The Automatic Identification System (AIS), which is now a compulsory equipment on all relevant ships in winter traffic, provides a new infrastructure element to determine the ice condition indirectly. Due to the heavy traffic in the Baltic Sea, the ship speed information that can be gathered from almost all ships in the area using AIS, has proven to be very valuable when evaluating how difficult different ice areas are to pass for the ships navigating in the area. Recent ship tracks combined with ice movement forecasts and satellite images give valuable information about the routes to take through the ice field. In IBPlott – the map based user interface to IBNet – the AIS tracks can be displayed on top of the most recent satellite images thus providing an aid for interpretation of the image (Figs. 13 and 14).

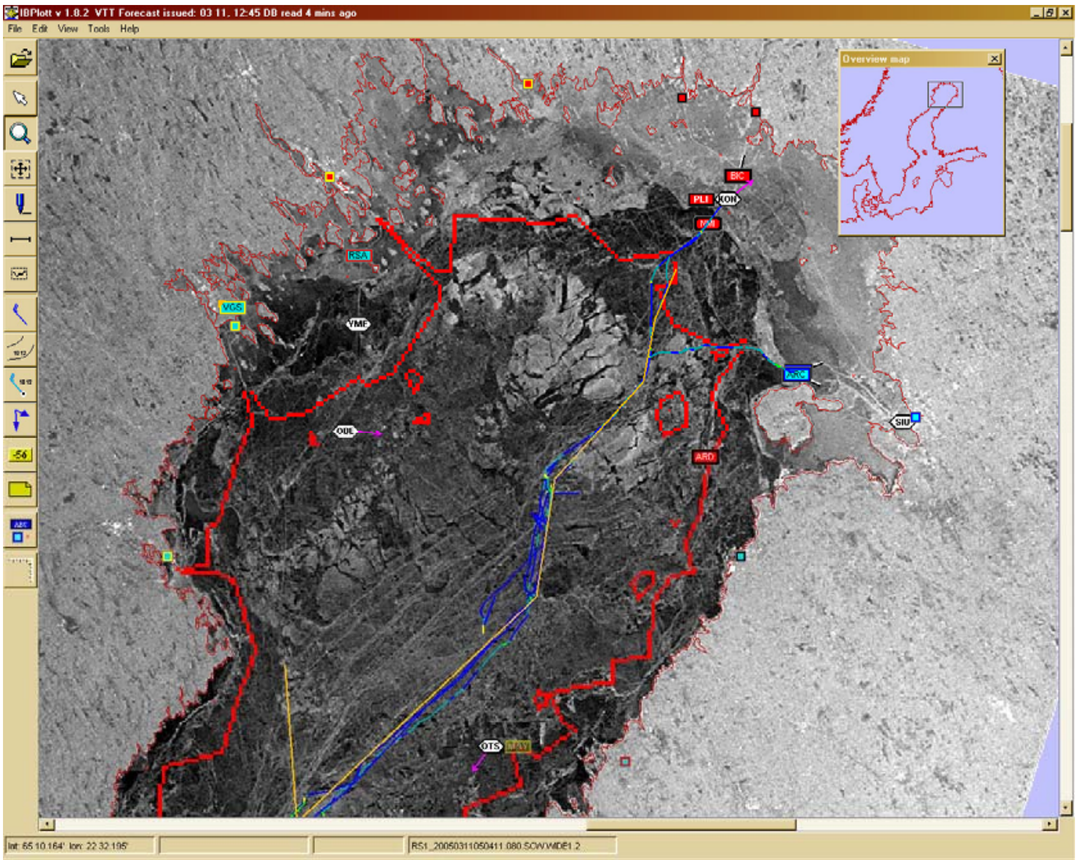

Figure 13. RADARSAT image from Bay of Bothnia. The DirWays (waypoints given by the icebreakers to the ships) are shown in yellow. Icebreakers and merchant ships are shown as symbols. The red lines indicate shallow water area limits where free navigation is not possible. The ship tracks based on AIS information are shown in blue. The RADARSAT image is geolocated enabling automatic overlaying of ship- and coastline information on the image. Screenshot of IBPlott, 11th of March 2005.

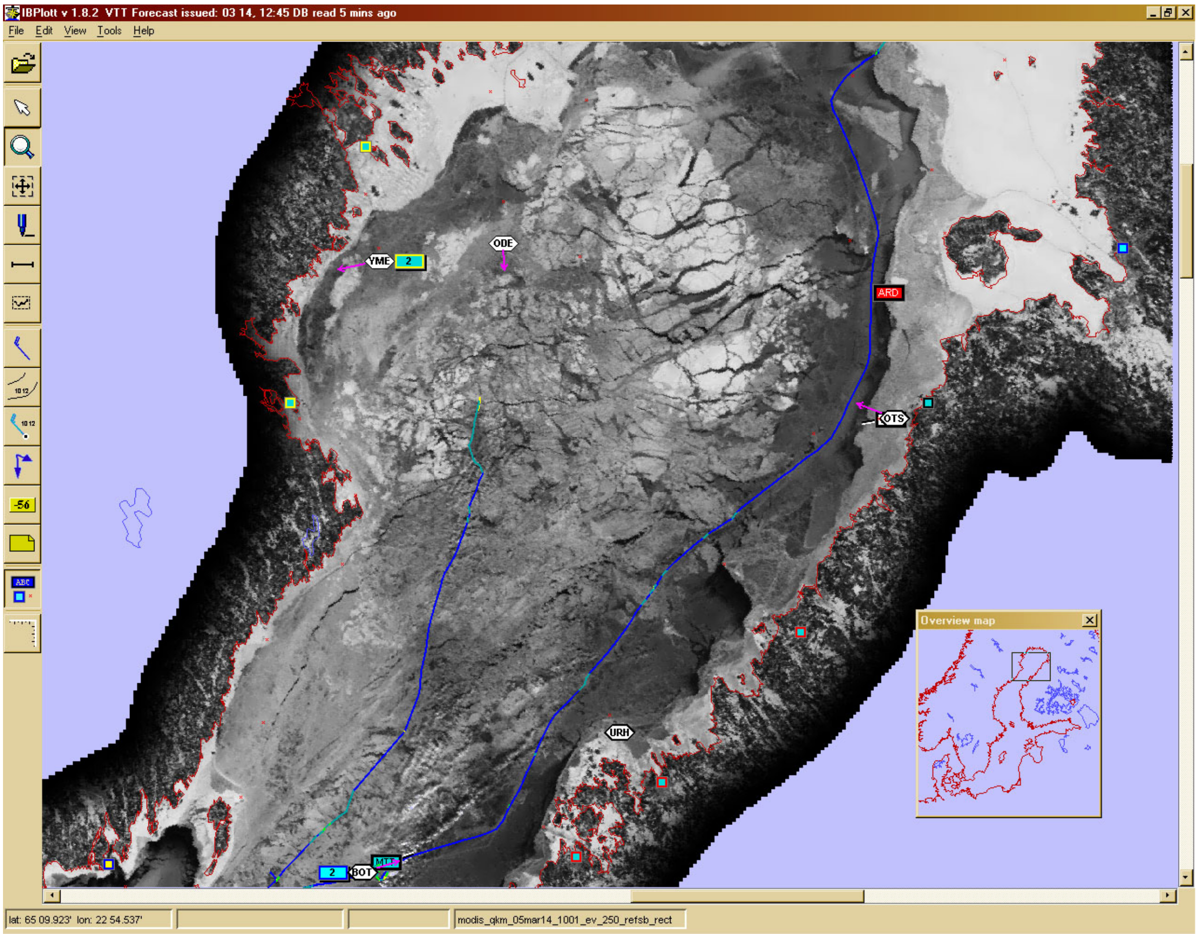

Figure 14. Geolocated MODIS image of the Bay of Bothnia. The position trail of two ships are shown in blue.

For merchant ships navigating in the Baltic there exists a client application called ViewIce, which is similar to IBPlott, but does not include the interface to the IBNet database. Thus ViewIce can be used for presenting satellite images, weather and ice forecasts.

An ideal system for route planning would include an accurate model of the ice cover and a prediction of how the conditions would change during the planned voyage. The system should also be able to estimate the effects of the ice parameters on the performance of the ship. Such a system has been prototyped within an EC-funded project Ice Ridging Information System for decision making in shipping operations (IRIS)[1]. In the IRIS project ice models are used to forecast the development of the ice cover. The information is then transferred to ships and used in combination with ship resistance models to predict the transit time of the ships. On board, the user can visualise different ice parameters as predicted by the model, such as ice concentration, ridge density, ice thickness and ice compression. These parameters are then used to estimate ship speed along the route. The client application includes an optimisation module which determines the least cost route given the most recent ice forecast and using ship specific data for resistance calculations. A

[1] http://www.tkk.fi/Units/Ship/Research/Iris/Public/

demonstration of the system was performed in The Baltic Sea during the winter 2005 (Fig. 15).

The Client application used in IRIS is based on ViewIce. In IRIS, ViewIce is also used to estimate the transit time of the ship through the ice. The IRIS system includes an important element called the Façade. This element acts as a portal for ice information and provides a customer specific tailored view to the available products. The preferences of the client are recorded in a user profile, and these parameters are then used by the façade to determine what to send to the user and/or what products to include in the dynamically built customer specific web page. The Façade also makes it possible to include information from different sources and service providers.

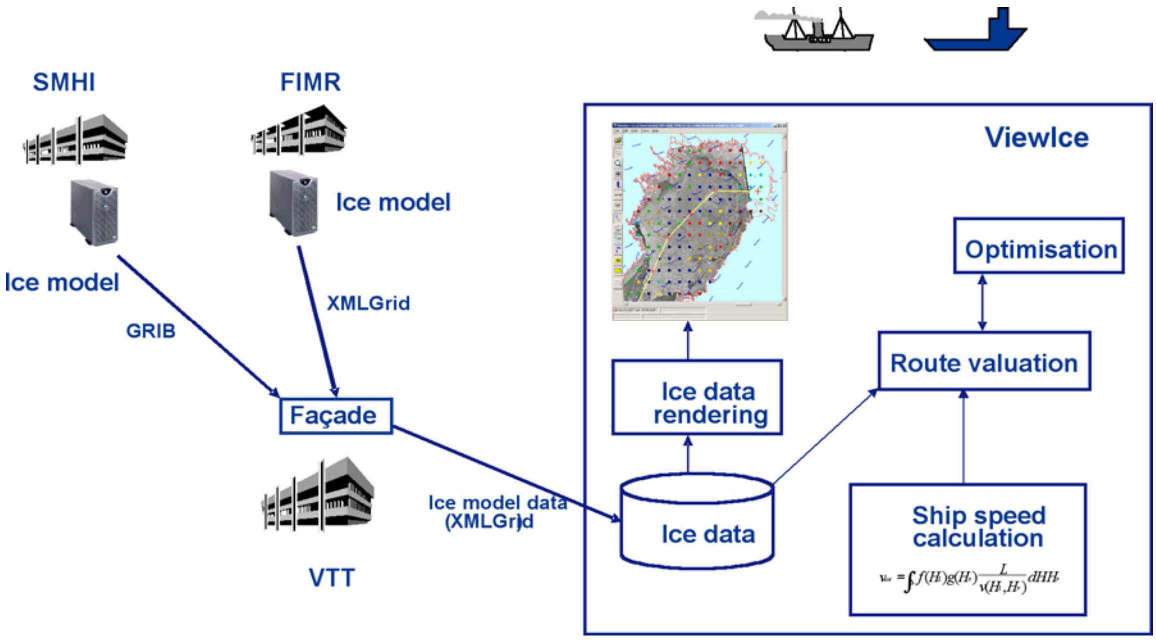

Figure 15. Distribution of ice model information for route optimisation in the IRIS project.

5. Other products and services based on satellite data

5.1 Geolocated SAR ice images delivered to ships in NRT

In areas where icebreakers navigate in sea ice, there is a demand for delivering geolocated high-resolution SAR images to the ships in NRT for optimal route selection (Fig. 16). The SAR images provide additional information which is not included in the available ice charts (Fig. 9), such as ice pressure information, multiyear ice floes, shear zones, cracks, and deformed ice versus level ice. This information is particular useful for icebreaker and other ice-going vessels which need to go though the ice. The geolocated SAR images are transferred to the vessels using e-mail transmitted via Inmarsat or Iridium. Onboard the ships, the SAR image is analysed by the captain in combination with sea charts, weather information and in situ ice observations. There is an ongoing development to include satellite images in ECDIS systems (Electronic Charting and Information System) which are used by many ships today.

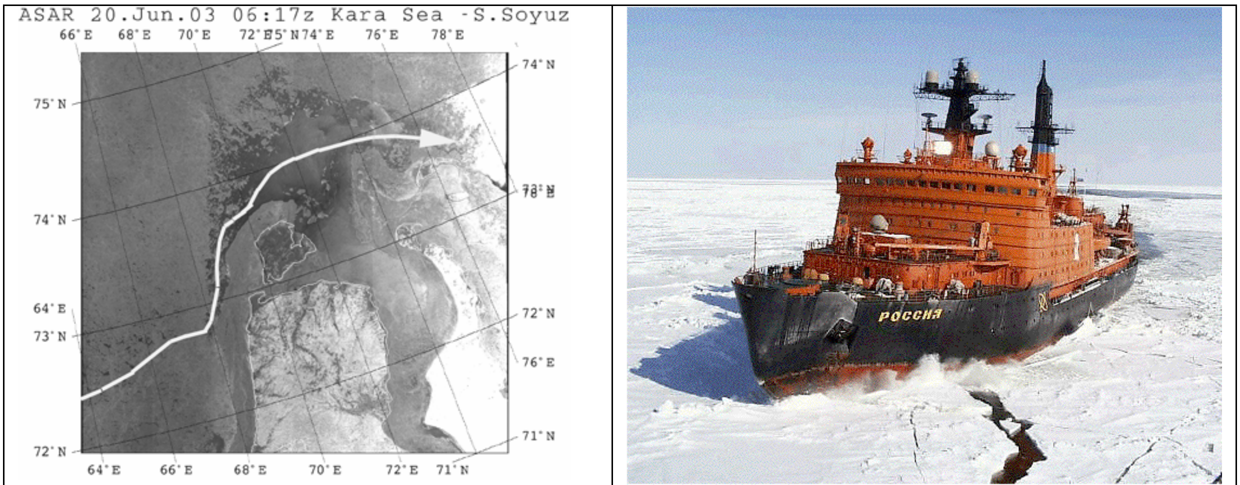

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Figure 16. a) Geolocated SAR ice image from ASAR wideswath mode sent to a Russian icebreaker operating in ice in the Kara Sea; b) Photograph of I/B Rossia, one of the nuclear icebreakers working in the Russian Arctic who received geolocated SAR images.

5.2 Ice drift area flux through straits: example from the Fram Strait

Ice area flux in the Fram Strait derived from a sequence of ASAR images has started to be produced as a seasonal and longterm monitoring in ICEMON (Fig. 17). Since February 2004, NERSC is producing ice area flux profiles across 79 N in order to be used together with thickness data from moorings for estimation of volume fluxes. The time interval between the images is presently 3 days. Time series of ice flux through the Fram Strait is key climate parameter, also discussed in section 6. The monitoring by SAR requires regular acquisition and production of ASAR wideswath data from ENVISAT and later from other SAR missions, such as RADARSAT-2.

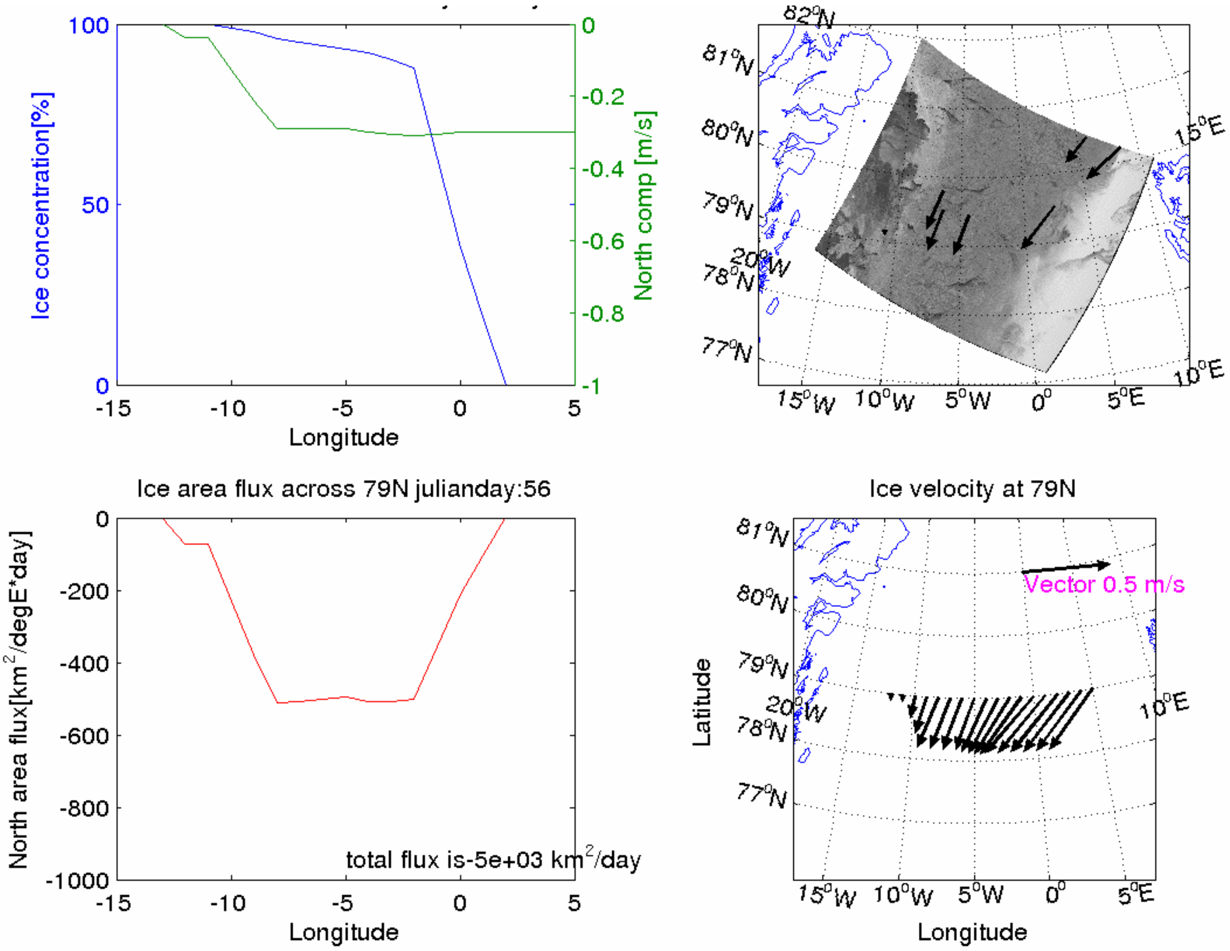

Figure 17. Upper left figure: profiles of ice concentration from SSMI data and north component of ice drift retrieved form ice tracking in the two SAR images from February 22 and 25, 2004 (upper right figure). Lower left figure shows the ice area flux for the three day period, and the lower right figure shows the interpolated ice drift vectors across 79 N.

5.3 Ice thickness from satellite radar altimeter and laser altimeter

A method for ice thickness retrieval from radar altimeters data has been developed by Laxon et al (2003) based on ERS altimeter data which have been obtained up to 81.5°N since 1992. The methods is based on separation of the radar altimeter return pulses from sea ice floes and open water or thin ice in leads, and then calculation of freeboard which is translated into thickness based on climatological estimates of snow cover and ice density. The ice thickness estimates are result of averaging all the data to monthly means values in typically 100 by 100 km grids. This method will be used to retrieve freeboard and ice thickness from CryoSat, scheduled for launch in late 2004. This satellite is planned to provide monthy mean ice thickness fields for nearly the whole Arctic for a period of 3 years. Examples of products retrieved from the ERS altimeter data are shown in Fig. 18.

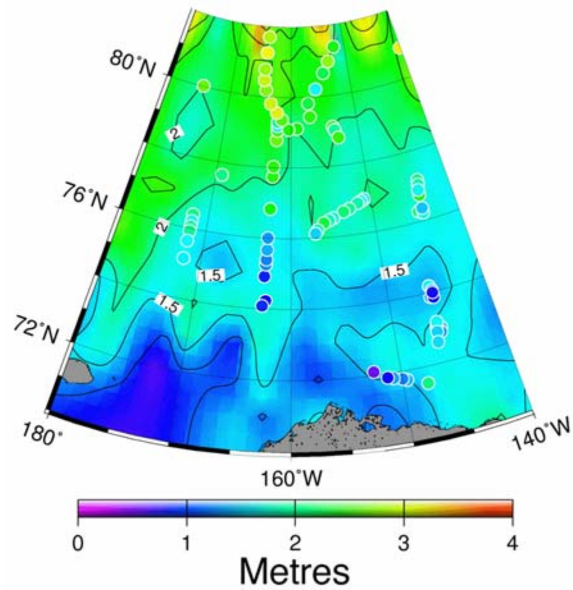

Figure 18. Sea ice thickness map from the Beaufort sea derived from ERS radar altimeter, where the dots represent validation data from submarine sonar profiles. The products have been developed by S. Laxon, Centre for Polar Observation and Modelling, University College London.

In this period, ERS-derived products for the period 1992 will be presented, while products from ENVISAT ASAR, covering the period from 2002 are planned for 2005 – 2008. CryoSat data will be available between 2005 and 2008, providing synoptic estimates of ice thickness of the Arctic. IceSat, which was launched in 2003, has started to provide ice surface height measurements, which can be used to retrieve ice thickness similar to CryoSat. An example of a 10-day mapping if the Arctic ice surface height from IceSat is shown in Fig. 19.

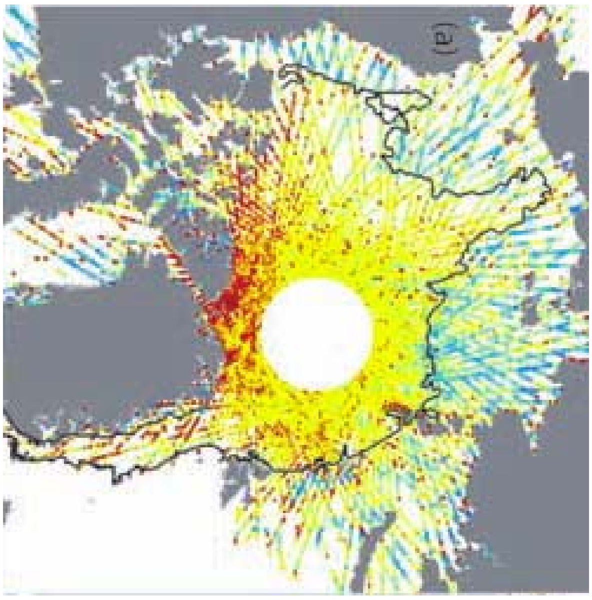

Figure 19. Ice surface height from IceSAt for the period 10 – 18 March 2003. Red shows high values of surface height, while blue shows low values. The grey line is the extent of multiyear ice retrieved from scatterometer data (Kwok et al., 2004).

5.4 Ice deformation and other Linear Kinematics Features

With more systematic acquisition and access to wideswath SAR data with high resolution (≈ 100 m), it will be possible to perform more detailed mapping of sea ice processes than what is possible with coarse resolution data. The launch of RADARSAT-2, tentatively in 2005, will secure access to wideswath SAR data from two satellites throughout this period. Use of SAR data with different coverage, resolution and polarisation will provide more quantitative information about dynamical and thermo-dynamical behaviour of the ice cover throughout the year. When ice thickness data from CryoSat is combined with ice dynamic and ice type information from SAR, it is expected that new data on ice volume and fluxes can be retrieved. Sea ice services will offer more satellite based products in all ice areas both in the Northern Hemisphere and in the Antarctica.

From the sequence of SAR images covering the major part of the Arctic Ocean, ice drift and deformation fields can be estimated according to the approach of the RADARSAT Geophysical Processor System (RGPS) developed by Kwok (1998). For each cell where ice drift is calculated, the formation and aging of new ice as well deformation (ridge formation) during the freezing season is followed in the time series of images. This allows determination of various stages in new and young ice whereas the discrimination between multiyear and firstyear ice area is done by image classification. The age distribution of young ice can be converted to a thickness distribution using a simple empirical relation between accumulated freezing days and thickness (Fig. 20).

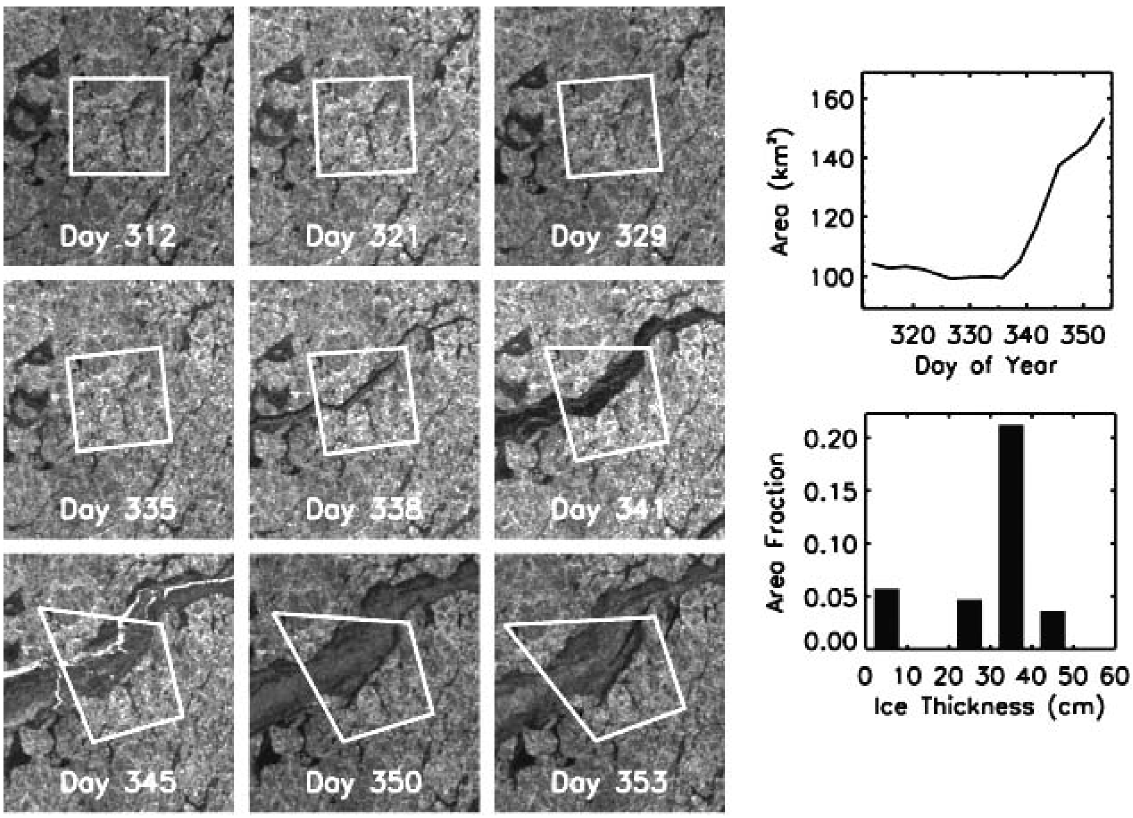

Figure 20. Example of ice drift and deformation of a grid cell of Arctic sea ice observed in a sequence of SAR images. The grid cell is initially 10 by 10 km and grows through the ice season in this case where a lead is opening up and new ice is formed. The thickness distribution of new ice is calculated as freezing progresses.

The RGPS can therefore be used to estimate the thickness distribution of ice volume produced by openings and closings of the ice cover since the beginning of the freezing season. Other products from RGPS are maps of thin ice categories and map of various Linear Kinematics Features (LKFs) derived from the ice drift vectors (Fig. 21). The LKFs include long, narrow features whether or not they contain open water, new ice, nilas, young ice, firstyear ice, rafted ice or ridged ice. Locally, they can be created by divergence, convergence, shear, or a combination of these (Kwok and Cunningham, 2002). Examples of other RGPS products can be found at http://www-radar.jpl.nasa.gov/rgps/radarsat.html.

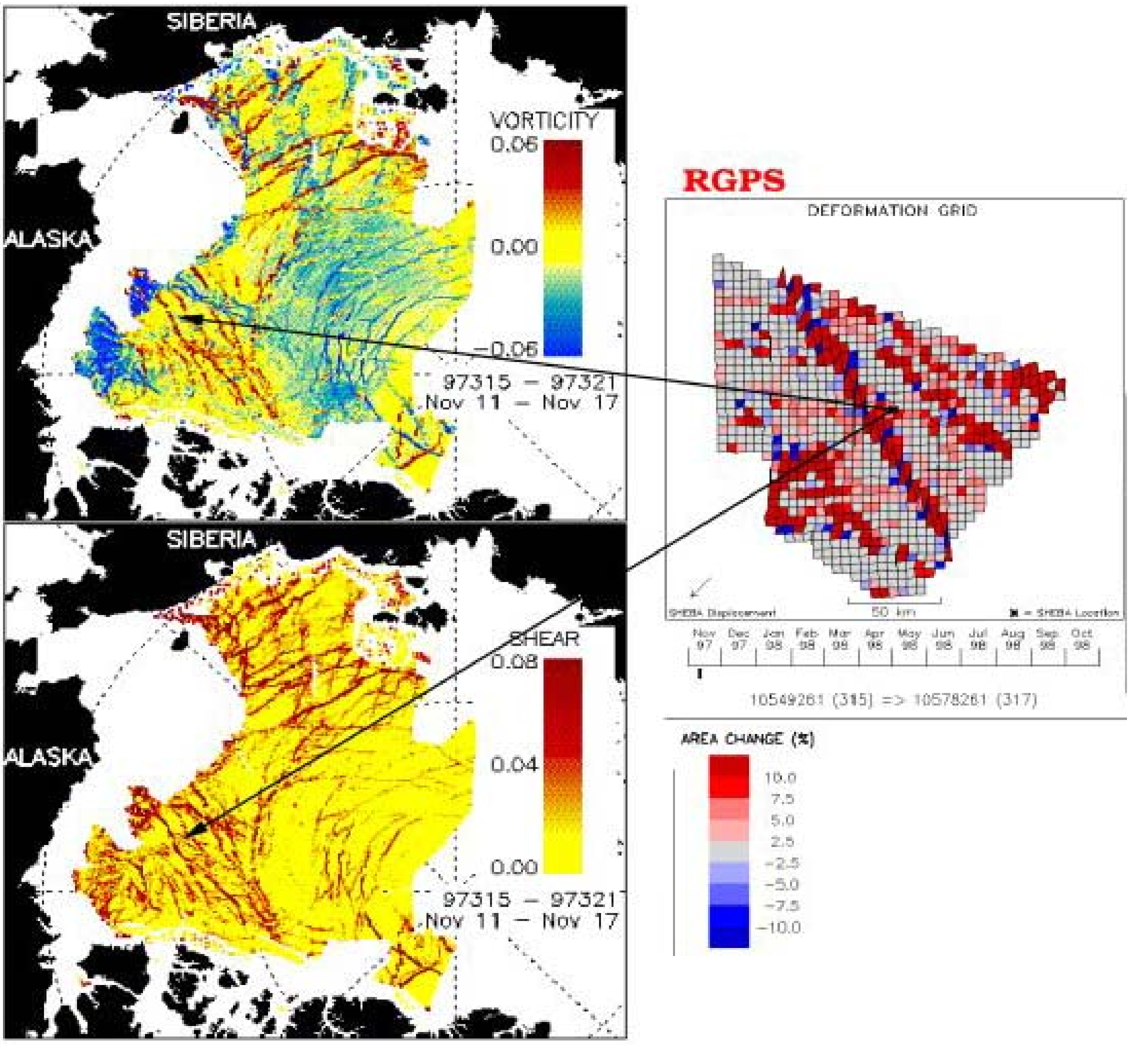

Figure 21. Sea ice vorticity and shear fields are example of Linear Kinematic Field calculated from 6 day interval mosaics of the Arctic ice cover using the deformation grids explained in Fig. 20.

Dual-polarisation SAR data from ENVISAT and later from RADARSAT-2 and other planned SAR missions is expected to improve sea ice classification and feature extraction (i.e. edge detection, ridge detection) and reduce some of the ambiguities and uncertainties that exist in single-channel and single polarisation SAR data. Other new spaceborne SAR systems will contribute to ice observation in the next few years, such as the L-band, polarimetric ALOS PALSAR, and the X- and L-band polarimetric TerraSAR. The possibilities to have SAR data in three frequencies (X-, C- and L-band) in combination with polarimetric capabilities offer unique opportunities to extract more information about various ice classes and ice features from SAR. An example of a three frequency composite (P-, C- and L-band) from airborne SAR is shown in Fig. 22.

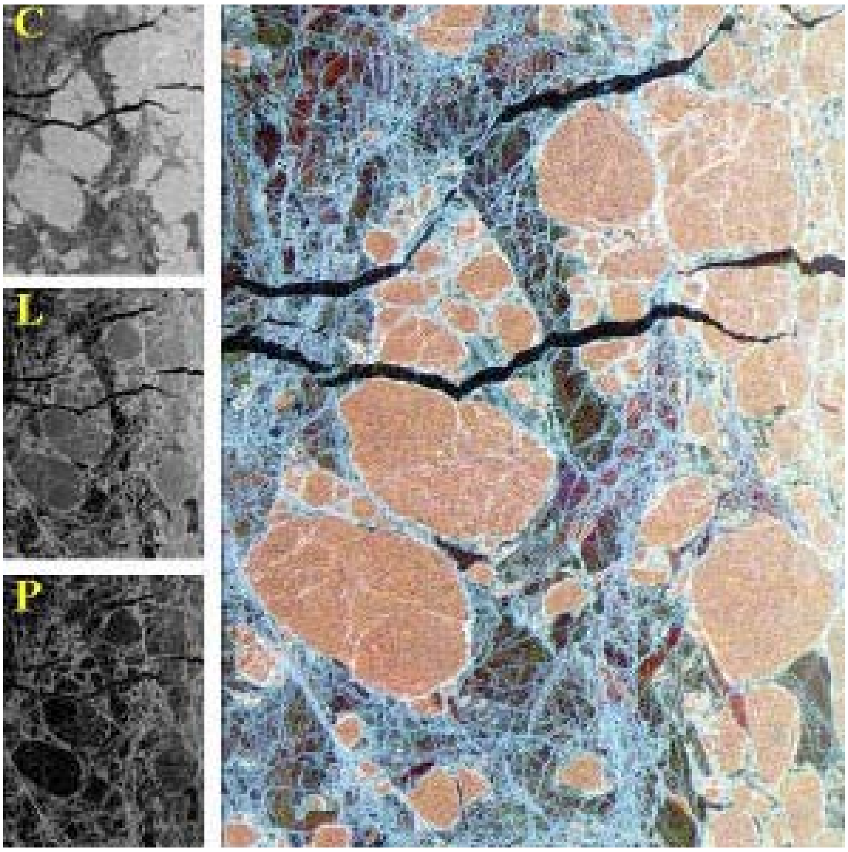

Figure 22. Example of ice classification using several SAR channels (C-, L- and P-band).

5.5 Other met-ice-ocean products from satellite data

A number of met-ocean information products are needed in addition to sea ice for the high latitudes. These products include wind, waves in open sea and in ice, air temperature, humidity, ocean temperature, ocean salinity, currents, icing of vessels and constructions, icebergs, sea level, river flooding, ice in lakes and rivers, coastal erosion, freshwater and sediment transport form rivers to the ocean, and other processes which are characteristic for the high latitudes. Many of these parameters are already provided by existing services. However, the use of new EO-data can improve several of the services. It has been documented that EO data can contribute to a number of new products, such as:

- Mapping of polar lows by wideswath SAR (Fig. 23)
- High – resolution wind fields from SAR near coast and ice edges (Fig. 24)
- Waves in the marginal ice zone can be observed by high-resolution SAR
- Sea surface topography and currents from altimetry
- Heat flux from ocean to atmosphere in leads
- Ice thickness of thin ice using IR data

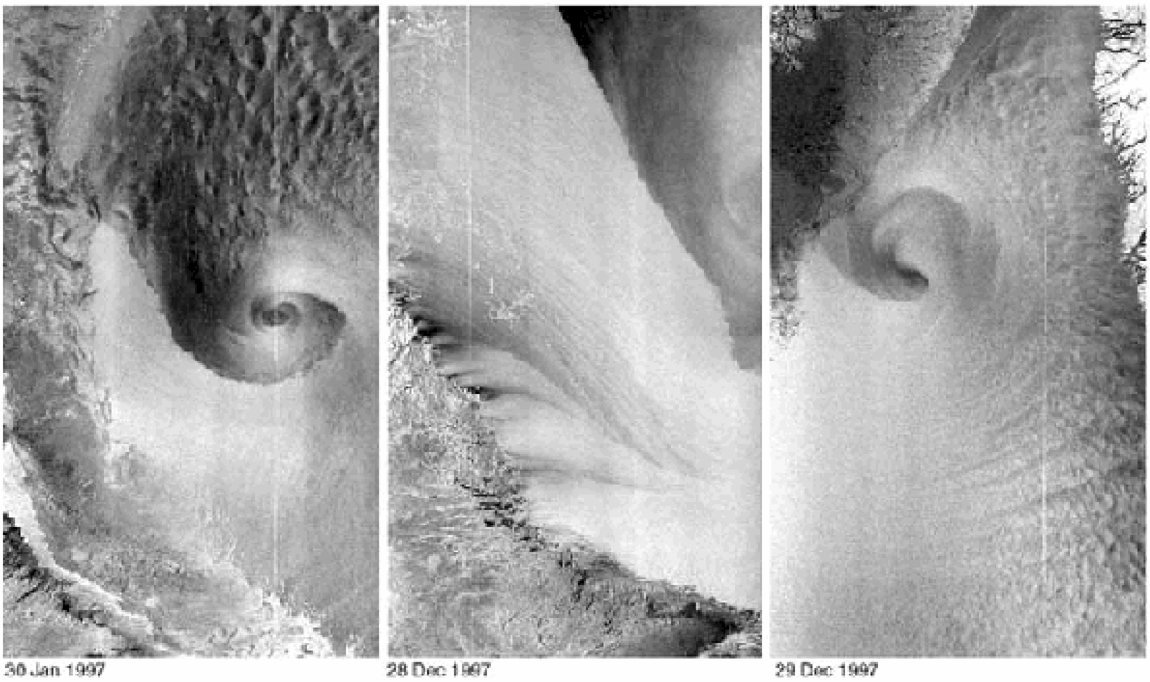

Figure 23. Examples of low pressure systems with wind pattern observed in Labrador Sea from RADARSAT ScanSAR images. The wind speed and direction can be retrieved from the SAR backscatter. Courtesy: Paris Vachon.

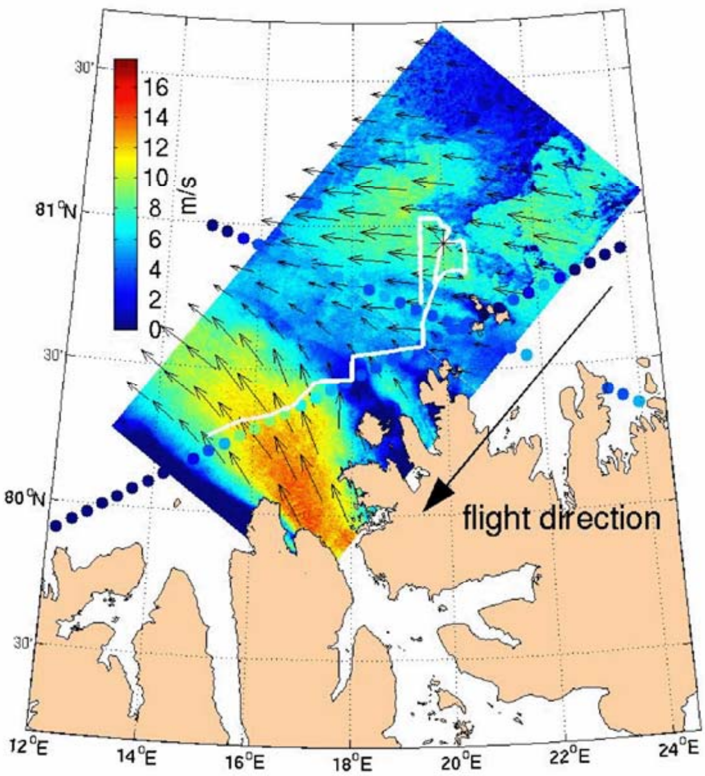

Figure 24. Example of high-resolution wind fields retrieved from ERS SAR images in the Svalbard area, where local topography has strong impact on the wind systems. Courtesy B. Furevik, NERSC.

6. Ice-ocean modeling, hindcasting and forecasting

Ice modelling is required to produce ice forecasts up to typical 5 days to support marine operations in or near sea ice areas. Most operators need forecasting in addition to NRT monitoring, because planning of operations need an estimate of the predicted ice situation a few days ahead. In ICEMON, several modelling systems are needed because they are serving different purposes in different geographical areas. For example, the TOPAZ system is designed for the Arctic Ocean and Nordic Seas, whereas the HELMI and IRIS models are tailored for the Baltic Sea. The latter model is specially designed to simulate ridges which the other models cannot do.

Development and validation of ice modelling requires good data sets, many of them are derived from satellites. For example, the 25 years of ice extent and ice concentration from passive microwave data is one of the main data sets for validation of ice models. Because sea ice is driven by both the atmosphere and the ocean, it is common to run coupled ice-ocean models forced by atmospheric fields. Especially short-term forecasting (up to 5 days) is forced by the predicted atmospheric fields. Furthermore, ice modeling is also used to simulate longer periods from seasons to years, as part of climate models which are normally fully coupled atmosphere-ice-ocean models. The predicted reduction in Arctic ice extent and thickness during this century is based on several climate model simulations. Ice models are also used to produce hindcast data sets, because models require careful comparison with other data obtained in hindcast, for example from monitoring moorings or from specific experiments.

6.1 Modeling systems for the Arctic and North Atlantic

The TOPAZ system

The TOPAZ ice-ocean modeling and data assimilation system has been developed by NERSC through the EU-funded projects DIADEM and TOPAZ over the last 6 – 8 years. The system is presently run operationally at NERSC as a demonstration of 10 – day forecasting of the Atlantic ocean, the Nordic Seas and the Arctic Ocean (Bertino et al., 2004). The ice model uses the Elastic Visco Pl astic theology by Hunke and Dukowicz (1997), coupled to the HYCOM ocean model.The estimated parameters include ice extent, concentration, thickness, drift as well as all the main oceanographical parameters. ECMWF forcing fields are used, with assimilation of weekly sea level height from satellite altimeter and weekly ice concentration from SSM/I data. Examples of model output are shown in Fig. 25.

The POM system

met.no is implementing an ice forecasting service for the Svalbard and Fram Strait area, using ECMWF forcing fields, OSI-SAF SST and ice products and sea ice data from SAR data as the input input. The estimated parameters will include standard sea ice (edge, concentration, and ice age) and oceanographical parameters at spatial resolution of 25 km. Delivery will be 3 day forecasts issued daily Monday – Friday. Users of the ice forecasts will be ship traffic, fishing vessels and other operators in the area. The system is a further development of existing modeling system at met.no: the POM system shown in Fig. 26.

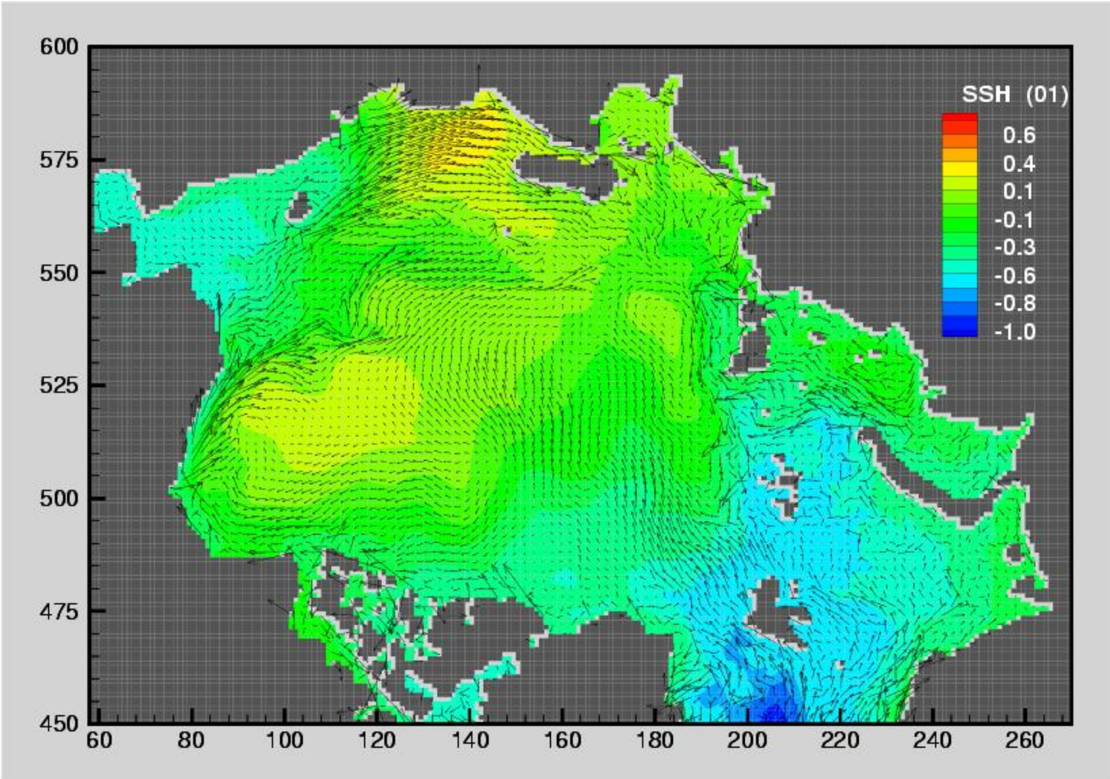

Figure 25. Examples of output from the TOPAZ modeling and assimilation system: sea surface height anomaly (colour coded) and surface currents (velocity vectors).

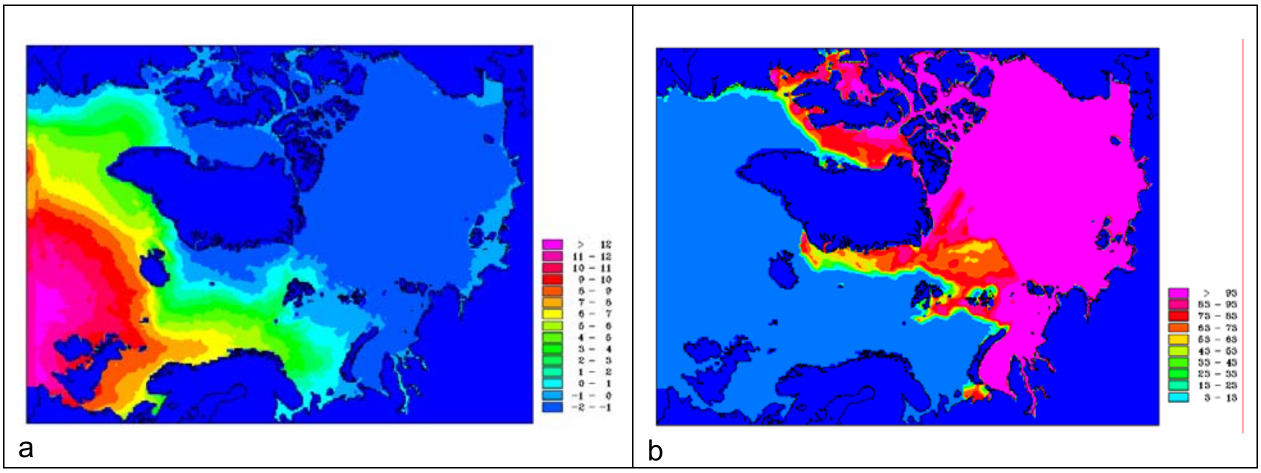

Figure 26. Examples of output form the POM modelling system at met.no. Since January 2002, the coupled ice-ocean model has been run pre-operationally on a 20 km polar stereographic grid, producing 10-day forecasts once per day (Courtesy B. Hackett, met.no).

High-resolution ice-ocean model for the Barents and Kara Sea

NERSC is developing a high-resolution (4 km) ice-ocean model for the Barents and Kara Seas, which is nesting with the TOPAZ system on the boundaries. ECMWF forcing fields are used and assimilation of weekly sea level height from satellite altimeter and weekly ice concentration from SSM/I data. The estimated parameters are ice extent, concentration, thickness, drift as well as all the main oceanographical parameters. Examples of model output are shown in Fig. 27.

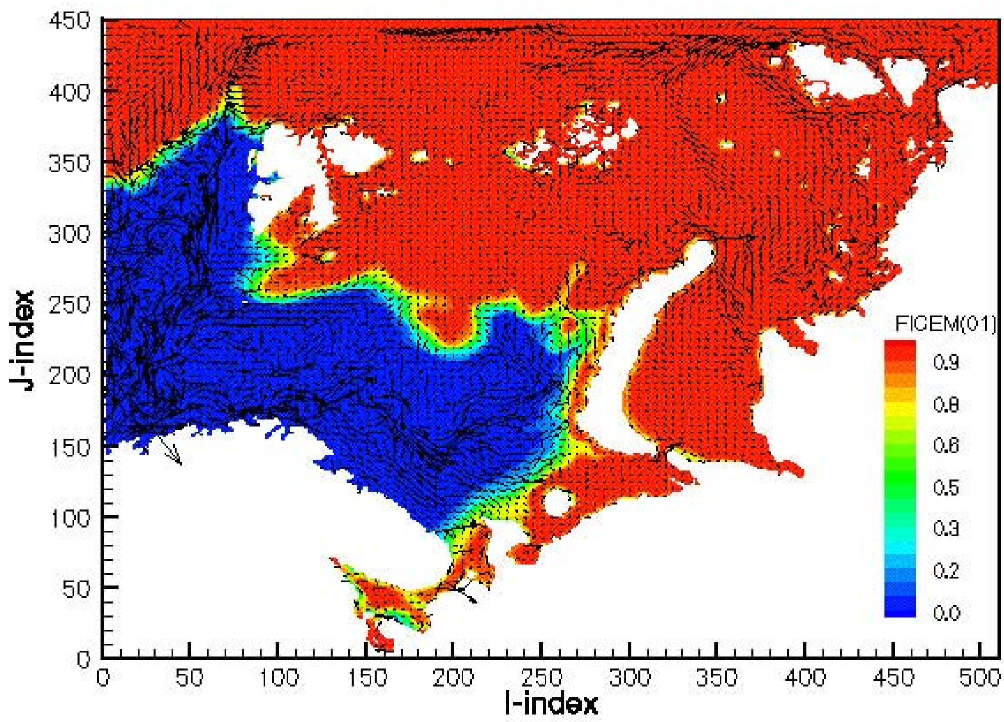

Figure 27. Examples of output from the Barents Sea model system, showing monthly sea ice concentration and surface current from test runs in hindcast mode in January 1979, using atmospheric forcing fields from ERA40 climatology.

6.2 Ice forecasting in the Baltic Sea: the HELMI and IRIS models

FIMR runs two ice forecasting systems for the Baltic Sea, both uses ECMWF forcing fields, SAR data, in situ data from icebreakers and coastal stations. The estimated parameters from the HELMI model include: ice edge (km), ice concentration (%), ice drift (km/h, deg) as shown in Fig. 28. The IRIS model also estimates mean level thickness (cm), ridged ice thickness (cm), ridge density (number per km) and ridge height (cm), as shown in Fig. 29. Ice modeling products are important because operational users need ice forecasts to plan and support winter navigation in Baltic ice areas. Reliable forecasts of ice is equally important as reliable weather forecasts.

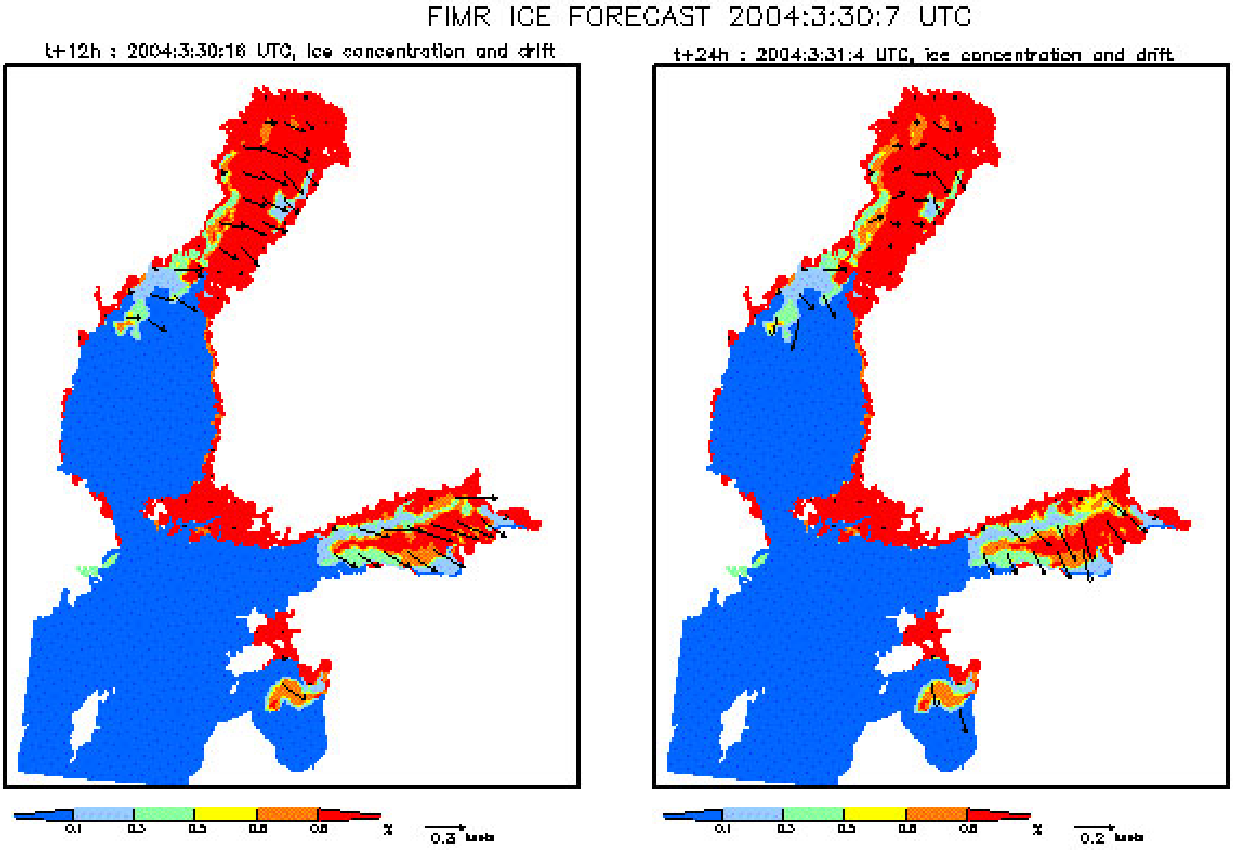

Figure 28. Example of HELMI ice forecasts for 12 and 24 hours of ice concentration and drift

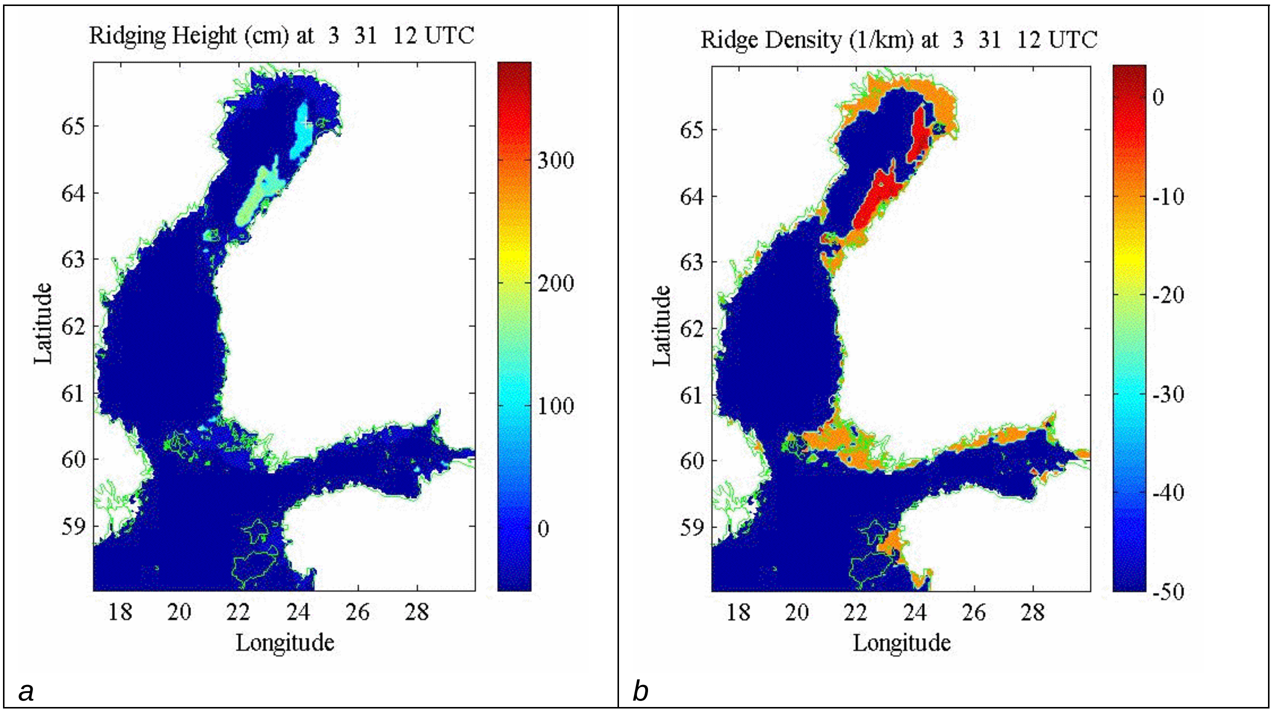

Figure 29. Examples of products from the IRIS model, showing ridge heights (a) and ridge density (b).

6.3 Further development of ice modeling and forecasting

In the next three - five years there will be significant improvement in the ice modeling capabilities in Europe, with several modeling systems in operations and more use of assimilation of EO data. Several other institutions developed ice models which can be used in operational services. Through the EU-funded MERSEA project the TOPAZ modeling systems will be consolidated and promoted to users in this period. More potential service providers will offer forecasting services. Improvement will be made in terms of increased resolution, forecast duration, validation routines and user interaction. Validation is a particular important element in all modeling and forecasting work, and various procedures to validate the models will be installed where EO data play a central role. Requirements from users will be one of the main drivers for the modeling work. With increased offshore activities and sea transportation in ice-covered seas, it is expected that new services will be established, using both EO data and modeling systems. Operational forecasting (up to 10 days) will be established as routine services, while seasonal and long-term forecasting will be developed in parallel, probably with services being delivered within 3 – 4 years. Climate model experiments running simulations over several centennials will continue and be validated, especially for the Arctic region. The relatively large discrepancy between the different IPCC models in the Arctic need to be investigated in order to obtain more reliable long-term forecasting in this region.

7. Information from airborne and in situ observing systems

The thickness of sea ice needs to be measured by different techniques that include in situ, airborne and underwater systems. Most of the recent 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). Recently first trials of ULSs mounted on floats suggest that wider spatial coverage can be achieved floating systems. However, at present 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), but for the satellite data are mainly intended to provide climate information and not directly support to marine operations. It is therefore important to have various non-space observing systems which can give data to support ice operations.

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 Fig. 30 (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.

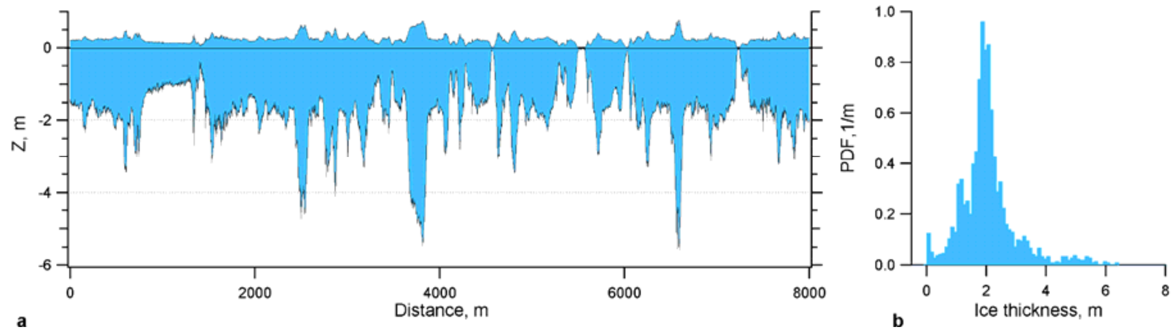

Figure 30. a) Example of profile of ice thickness and surface height derived from electromagnetic induction measurements from helicopter flights, b) ice thickness distribution function derived form the profile data in a).

Another innovative technique to observe sea ice freeboard from aircraft surveys is possible as a result of the improvements in Arctic gravimetry and Global Positioning System (GPS). The basic idea is to use kinematic GPS in combination with laser to map the surface of the ice at 10 cm accuracy over longer distances which includes variations of geoide and sea surface topography (Hvidegaard and Forsberg, 2002). By using results from airborne gravity and all other gravity sources. we can get the geoid to the same accuracy level, at least at wavelengths below 200 km. The height difference between geoid and laser/GPS is sea-surface topography plus ice freeboard. Ice thickness can then be derived from freeboard if the snow and ice density and the snow thickness is known. Several field campaigns have been conducted in the Fram Strait and north of Greenland during the SITHOS project, where ice freeboard data have been obtained from laser altimeter data and compared with EM data from helicopter (Sandven et al., 2005). Examples of these data are shown in Fig. 31.

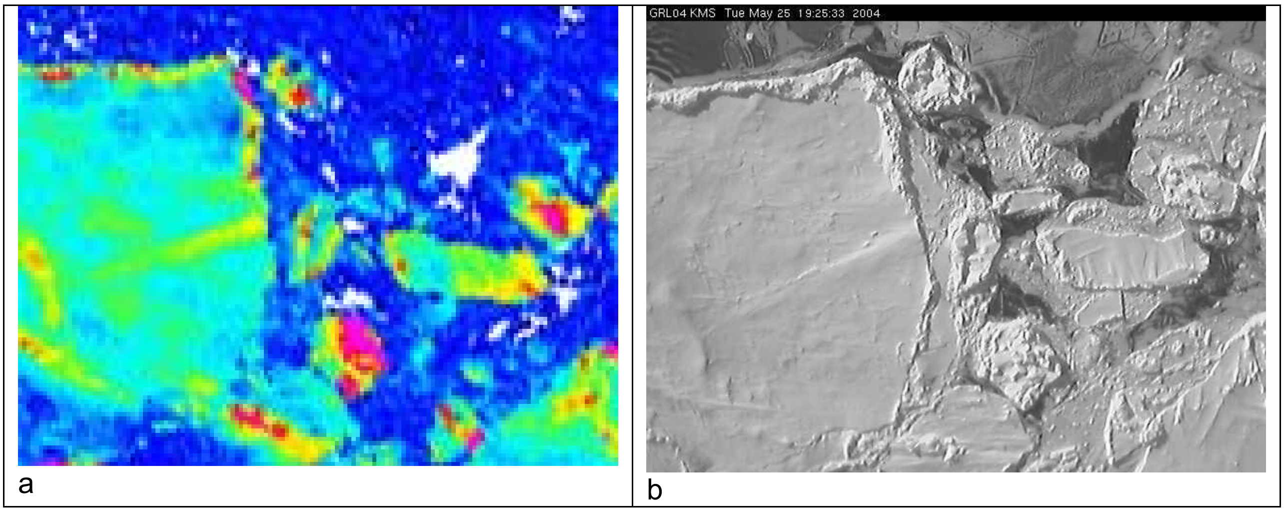

Figure 31. a) Ice freeboard image from scanning laser, where dark blue is thin or open water, while ridges with up to 2 m freeboard are yellow – red; b) same area as in a) observed by vertical video camera. The size of the area is about 100 by 100 m.

During the 1990s ice thickness has been monitored by moored upward looking sonars (ULS) in areas such as the Fram Strait at 79° N by the Norwegian Polar Institute (Vinje et al., 1998) and in the east Greenland Currrent at 75°N by Alfred Wegener Institute and others (Fig. 32a). A number of other ULS systems are in operations in the western Arctic (Fig. 32 b) The mean and variability of the ice thickness are recorded in fixed locations because the ice drifts continuously southwards in this region. The data are important for estimation of ice flux out of the Arctic Ocean and to validate the ice flux estimated by ice-ocean models. The data are not readily available in near real time, but they can provide important statistics of ice thickness including max draft of ice keels which are of relevance for ice navigation and offshore operations.

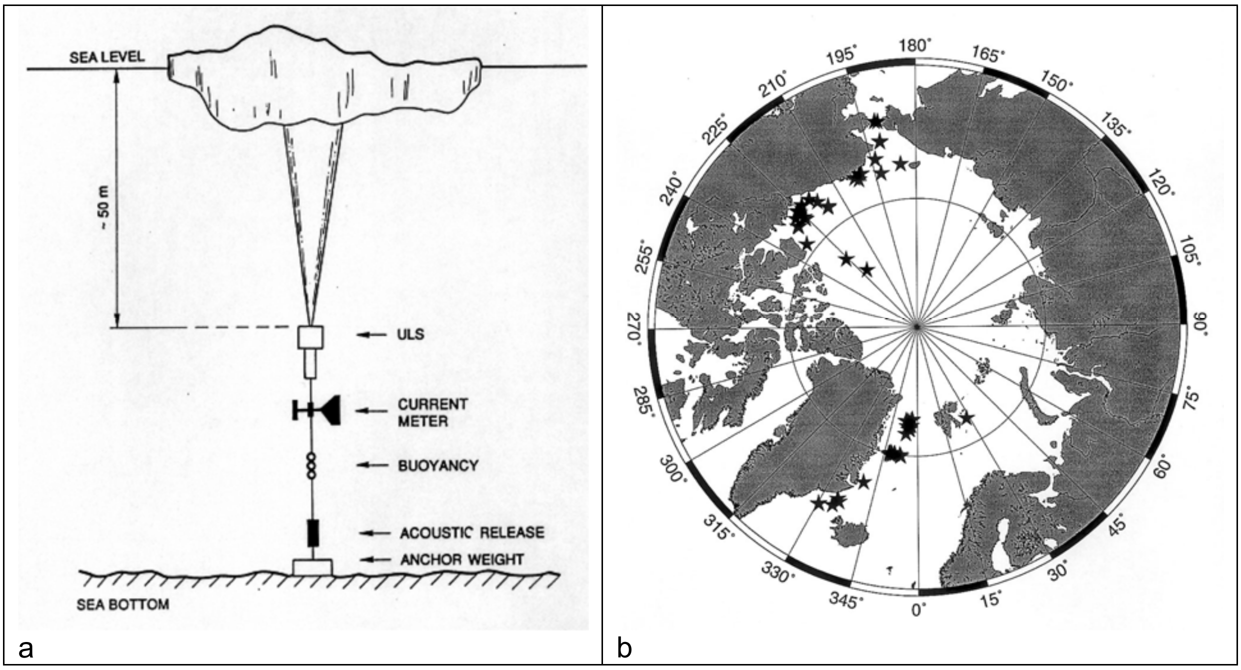

Figure 32. a) Illustration of Upward-Looking Sonar mooring deployed under the ice, b) map of ULS-moorings deployed in various parts of the Arctic Ocean (courtesy NPI).

Upward sonar profiling has been used by submarines to get synoptic profiles of ice draft across the deep Arctic Basin since the 1950s. Several tens of thousands of km of such profiles, which have been obtained by US and UK submarines, have been declassified, making it possible to analyze ice spatial and temporal variability of thickness in the Arctic. The sampling of the data have not been systematic, but attempts have been made to find trends in ice thickness variability over four decades (i.e Rothrock et al., 1999). The ice thickness profiles are useful to validation of ice models. Example of such validation is shown in Fig. 33 where the thickness estimate from a NERSC ice model is compared with a submarine profile for the same year and month.

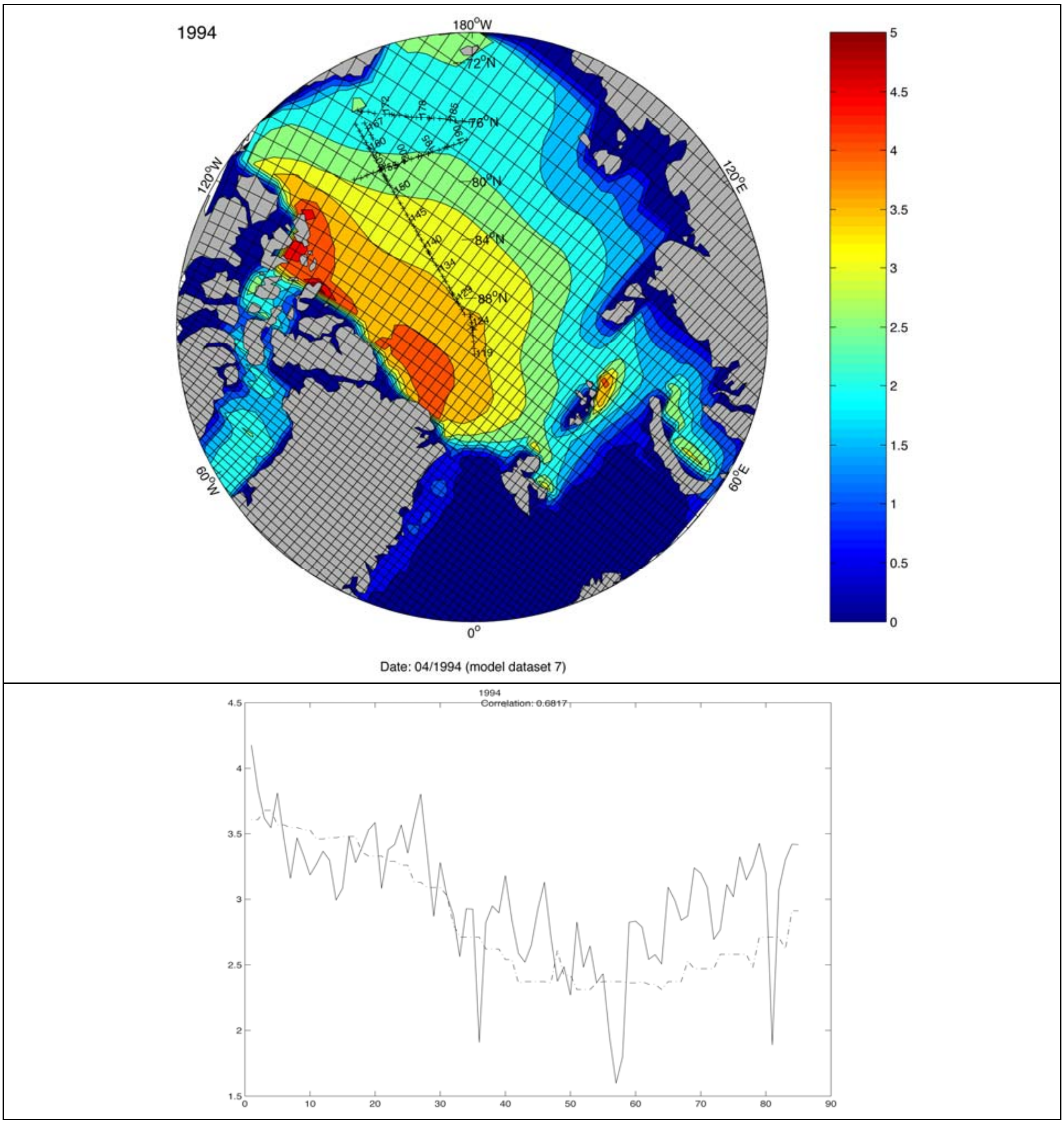

Figure 33. a) map of ice thickness fro a NERSC ice model for April 1994 (Lisæter et al., 2003) with submarine tracks superimposed; b) profile of ice thickness from submarine data (full line) and from the NERSC model (dashed line).

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 in operation in September 2005 and their trajectories for the previous 60 days are shown in Fig. 34. Most of the buoys are located in the deep Arctic Basin, but a few buoys can also be located on the Russian shelf.

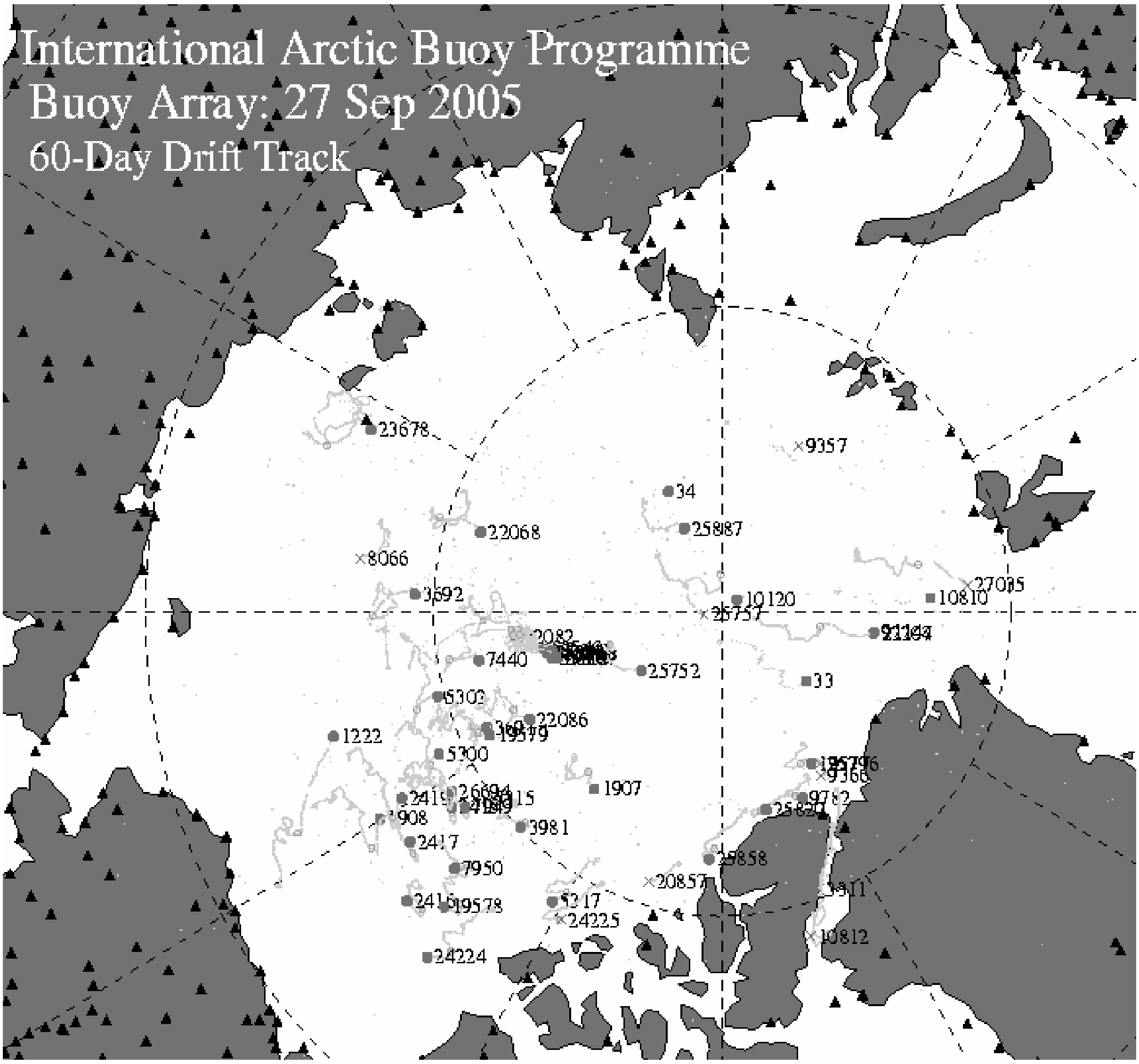

Figure 34. Location and drift trajectories for IABP buoys in operation in September 2005. More information is found at http://iabp.apl.washington.edu/.

The most important and classical methods is to obtain thickness data is to drill holes in the ice. This method is laborious and can only provde very limited amount of data. But the method will always be used to control other methods. A more efficient method to measure thick ´ness in situ is to use ground-penetrating radar (GPR) from a sled. GPRs use electromagnetic pulses at frequencies at about 50 MHz, which will penetrate through the ice. If there are changes of the dielectric properties of the media on distinct horizontal layers, the EM pulses are partly reflected from these layers. An example for such a horizontal layer would be the ice underside where the media changes from ice to water. For interpretation the signal, traces of every shot are plotted next to each other in a radargram similar to seismic surveys (Fig. 35). The grayscale displays the amplitude of the received waveform. After the reflected waveform of the ice underside is identified, the travel time of the wave down and up can be derived (between 20 – 30 ns in this example). With the help of drilling information or using standard values for the propagation velocity, the travel time can be converted into ice thickness. In Figure 35 the bars represent the drilling information.

The propagation velocity depends on the dielectric permittivity of the media. The reflectivity is related to changes in the dielectric properties, determining the velocity. Apart from the wave travel velocity, the damping of the wave depends on the conductivity of the media and the antenna frequency (50 MHz up to 1.5 GHz). Damping increases with frequency and conductivity. In Figure 35 a dominant reflector corresponds nicely with the drilling information. A second reflector at around 10 ms maps the snow-ice interface as the antennas are pulled over the snow surface. Only where the ice gets too thick or consists of many little broken pieces it is difficult to find a reflected signal in the data. GPR is a useful supplement to drilling holes and can be used very efficiently if ice conditions allow to pull a sledge. It there are heavy ridges and wide cracks in the ice, the method is not feasible.

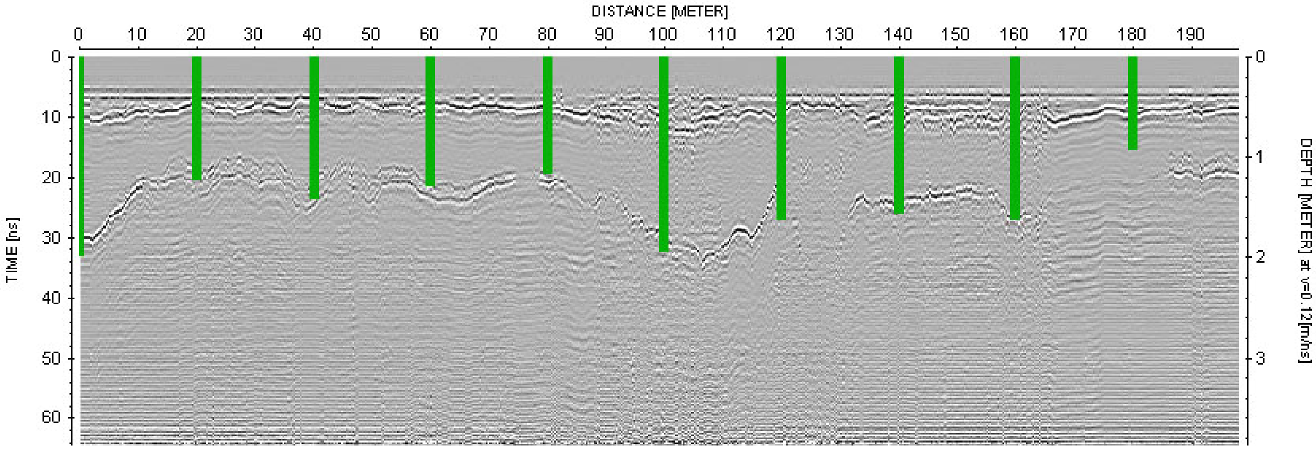

Figure 35: GPR section (radargram), Antenna: shielded 800 MHz, Date: 20030312. Drilling information plotted as black bars.

8. Concluding remarks

Ice information systems are to a large extent based on satellite data and numerical modeling, supported by in situ observations from ships, aircraft and other available data. Particularly on large and regional scale, satellite data are playing an increasingly important role. This is mainly because wideswath SAR data have been adopted by many national ice services in their regional ice charting services. On global scale, passive microwave data is the work horse, supplemented by scatterometer, infrared radiometer and optical data.

On local scale, where tactical information is needed for ice navigation and other marine operations, the most important information come from ships, aircraft/helicopters, and possibly from ice buoys. High resolution satellite data is part of the input data, but the usefulness of the satellite images depends very much on delivery in near real time. SAR images can be delivered to ships with a 2 – 4 hours delay, provided that the SAR images have been ordered for the area where they are needed. The current SAR systems require pre-ordering, and this is a limiting factor for providing high-resolution, narrow-swath SAR images in areas which are not pre-defined. In tactical ice navigation it is necessary to have a flexible ordering system where users can order data with one day. For fixed installations, such as platforms, pipelines and terminals, high-resolution SAR can be pre-ordered for example for every third day. But users need data coverage every day, and this is not feasible with the present SAR systems. New SAR systems such as RADARSAT-2 and TerraSAR-X can provide very high resolution SAR images, with pixel size of about 3 m, and a swathwidth between 10 and 40 km. Also polarimetric capabilitity of the new SAR systems will increase the possibility to classify ice types and ice features. Such data will be very useful to map details in the ice cover such as ridges, leads, floe size on local scale, although the data will not be available every day. High resolution optical images (MODIS, Landsat, SPOT, etc.) can used as a supplement to SAR, but there are limitation due to clouds and darkness. Even if the data can be obtained every day, useful information can only be obtained during daylight and cloudfree conditions.

To support information provided by satellites, it is common to use data from ships and coastal stations, where direct observations and ship radar data are the most important. Aircraft surveys include visual observations, vertical video recording and Side-Looking Radar. Recently, use of scanning laser and GPS have been demonstrated as useful tool to measure the surface topography of sea ice, especially ridges. Helicopter surveys using laser and electromagnetic induction provide data on ridges as well as thickness. Group penetrating radar is used for measuring thickness on local scale. For tactical information, it is particular useful to collect ridge and thickness data because the satellite data do not provide any quantitative estimates of these parameters.

Ice modeling is used to provide forecasts on global and regional scale, but the quality of ice forecasts needs improvement in particular on regional and local scales. The most commonly used plastic-viscous ice rheology is applicable on scales of 10 km and upwards, but on local scale it is necessary to apply discrete element modeling or similar approached where individual ridges and floes are simulated. Ice forecasting also depends heavily on atmospheric forcing fields. In most polar regions, the atmospheric forecasts are not satisfactory on local scale. In order to improve the ice forecasts, improvements are needed both in the atmospheric forcing fields and in the oceanographical models which are coupled to the ice models.

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Appendix B: Acronyms

AATSR	Advanced Along Track Scanning Radiometer
AIS	Automatic Identification System
ASAR	Advanced Synthetic Aperture Radar
AMSR	Advanced Microwave Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
AWI	Alfred Wegener Institute for Polar and Marine Research
CAL/VAL	Calibration - Validation
CCG	Canadian Coast Guard
CIS	Canadian Ice Service
DMI	Danish Meteorological Institute
DTU DCRS	Danish Technical University, Danish Center for Remote Sensing
DMSP	Defence Meteorological Satellite Program
DNV	Det Norske Veritas
ECDIS	Electronic Charting and Information System
ECMWF	European Centre for Medium Range Forecasting

EM	Elektromagnetic
EO	Earth Observation
ESA	European Space Agency
ETSI	Expert Team on Sea Ice
FIMR	Finnish Institute of Marine Research
FNMOC	Fleet Numerical Meteorological and Oceanographic Center
GIF	Graphical Interchange Format
GIS	Geographic Information System
GMM	Global Monitoring Mode
GMES	Global Monitoring of Environment and Security
GPR	Groud-penetrating radar
GPS	Global Positioning System
HF	High Frequency
IABP	International Arctic Buoy Programme
IBNet	Icebreaker Network
IBPlott	Map-based interface to IBNet
ICEMON	Sea Ice Monitoring Project (ESA GMES project)
ICG	Icelandic Coast Guard
IICWG	International Ice Charting Working Group
IMO	International Maritime Organisation
IFREMER	French Research Institute for Exploitation of the Sea
INMARSAT	International Maritime Satellite Organisation
IUP UB	Institute for Environmental Physics, University of Bremen
JPEG	Joint Photographics Experts Group
KSAT	Kongsberg Satellite Services
KSPT	Kongsberg Spacetec
LKF	Linear Kinematics Features
met.no	Norwegian Meteorological Institute
MSC	Meteorological Services of Canada
MY/FY	Multiyear / Firstyear ice
NASA	National Aeronautic and Space Administration
NCEP	National Center for Environmental Prediction
NERSC	Nansen Environmental and Remote Sensing Center
NESDIS	National Environmental Satellite Data Information Service
NIC	National Ice Center
NOAA	National Oceanographic and Atmospheric Administration
NPI	Norwegian Polar Institute
NRT	Near Real Time
OSI-SAF	Ocean and Sea Ice Satellite Application Facility
PNG	Portable Network Graphics
RGPS	RADARSAT Geophysical Processor System
SAR	Synthetic Aperture Radar
SSM/I	Special Sensor Microwave Image
SST	Sea Surface Temperatures
SLAR	Side-Looking Airborne Radar
SLR	Side-Looking Radar
SLT	Seasonal and Longterm
TBC	To Be Confirmed
TBD	To Be Decided
USGC	US Coast Guard
WMO	World Meteorological Organisation