Ice Information Services:
Socio-Economic Benefits and Earth Observation Requirements

2007 Update

The International Ice Charting Working Group (IICWG)

Originally prepared for:
The Group on Earth Observation (GEO)
and
Global Monitoring for Environment and Security (GMES)

With funding from:
The European Space Agency, GSE Contract 17062, "The Northern View"
The Canadian Space Agency, Government Related Initiatives Program (GRIP)

Published: September 2004 **Updated: September 2007**

Ice Information Services

INTRODUCTION

Ice – sea ice, icebergs, and ice covered lakes and rivers – affects large regions of economic, environmental, and social importance. In recent years, the uniqueness of the Earth's ice-affected regions and their importance to the world is being increasingly recognized. They are considered vital and valuable for a variety of reasons:

Ice affects large regions of economic, environmental, and social importance.

- Marine Transport – Marine trade is a vital part of world economies, and it is increasing. Sea ice is a serious obstacle in the North, and icebergs affect marine transport even in temperate waters (the Titanic disaster occurred at about the same latitude as Boston). A single iceberg report can cause tens of thousands of square miles of ocean to be declared unsafe for shipping transit.

- Weather and Climate Change – As a key component of the world's weather and climate system, knowledge of current and changing ice conditions is critical to the prediction of weather and climate events.

- Natural Resources – Ice-affected regions are rich in resources such as oil and gas, minerals, timber, and fish, but their production is often impeded by ice.

OPERATIONAL ICE INFORMATION:

- Enables year-round operations of critical shipping ports such as:
  - Montreal/Quebec City - Helsinki
  - Boston/New York - St. Petersburg
- Supports icebreaking operations for 3,500 ships through Baltic waters; delivering 32 million tons of cargo to and from Finnish ports alone;
- Helps ensure the safe & efficient transit of 1,500 ships across the Gulf of St. Lawrence, Canada;
- Provides logistics and safety support to offshore structures, in the Bohai Bay, Barents, Kara, and Caspian Seas, Sakhalin Island, and Grand Banks;
- Provides strategic and tactical ice information for sovereignty and national defence interests;
- Assists trans-Atlantic shipping by helping to prevent a recurrence of the 1912 TITANIC disaster where over 1,500 lives were lost.

- Environment – Ice-affected ecosystems are adapted to, and depend upon, ice. They are increasingly under threat from climate change, resource exploitation, marine traffic, and human habitation.

- Habitation – The North is home to an increasing population that must cope with a hostile icescape and adapt to changing environmental conditions.

Many stakeholders – mariners, scientists, the resource industry, and northern residents – need ice information. They are assisted in understanding and coping with ice by the world's national ice services. These organizations are represented by the International Ice Charting Working Group (IICWG), which is composed of the ice services and research institutes from 11 countries and the International Ice Patrol. They share an interest in the analysis and forecasting of ice conditions for safety at sea, economic development, and environmental protection.

Many stakeholders depend on the national ice services to understand and cope with ice.

The national ice services depend on Earth Observation.

The operational ice services provided by the IICWG member organizations are based, to a great extent, on information from Earth Observation (EO) satellites. Earth Observation is a powerful tool for ice monitoring. Due to the extent, harshness, and isolation of ice-affected regions, Earth Observation is often the only cost effective and technically feasible means of obtaining information. Also, modern sensors like synthetic aperture radar (SAR), can provide types of information that are not available from any other source.

The IICWG supports the objectives of GEO and GMES to ensure the availability of Earth Observation information.

Because of its heavy dependence on Earth Observation information, the IICWG supports the objectives of the Group on Earth Observation (GEO) and Global Monitoring for Environment and Security (GMES) to define and ensure the availability of future Earth Observation missions.

GEO is an intergovernmental working group, created during the 2003 Earth Observation Summit in Washington, D.C. The Summit participants affirmed the need for timely, quality, long-term, global information as a basis for sound decision making. GEO has been given responsibility for producing a ten-year program to co-ordinate space and ground based global monitoring systems, to be known as the Global Earth Observation System of Systems (GEOSS). The aim of GEOSS is to maximize the effectiveness of Earth Observation by minimizing data gaps, building capacity and exchanging information as fully and quickly as possible.

SHIP NAVIGATION

The use of ice information by ships provides major benefits to ship operators:

- Increased safety for ships and personnel by either avoiding ice altogether or by choosing a route through the ice that is within the capabilities of the vessel.
- Reduced transit times by permitting the most direct route, concomitant with safety. Savings of up to $3,000 per ship per day have been estimated.
- Better ship designs that increase safety, increase environmental operating conditions, and decrease operating costs.
- Reduced danger to the environment from ship accidents, especially from oil tankers.

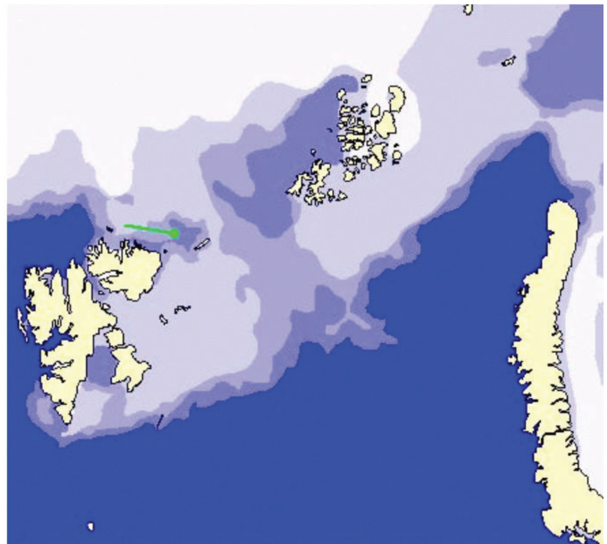
GMES is a joint initiative of the European Commission and the European Space Agency, which is designed to establish a European capacity for the provision and use of operational information for Global Monitoring of Environment and Security. The IICWG is participating with the GMES project concerned with ice and iceberg monitoring – the PolarView.

The IICWG seeks to ensure that plans for future Earth Observation missions provide for the continuity of satellite data on which the ice services, and their clients, depend. The IICWG is a strong community of practice that contributes to the work of GEO and GMES by assisting the definition of user requirements and the identification of socio-economic benefits of Earth Observation for ice information.

ICE INFORMATION USERS

Ice information is required by a wide spectrum of users operating in ice-affected regions over a wide range of latitudes:

- Marine transportation operators and regulators – to support the viability, safety, and efficiency of wintertime shipping at mid-latitudes, and to ship resources in and out of the North;
- Marine security agencies – to enhance maritime domain awareness for national defense forces and improve the ability to secure national borders from polar threats;
- Meteorological organizations – for improved prediction of severe weather events and climate change scenarios;
- Search and rescue organizations – dedicated to the mitigation of loss of life or property due to accidents, pollution events, or other hazardous conditions;
- Resource developers – for oil and gas, timber, minerals, and fish;
- Policy-makers in Circumpolar nations – to better understand and monitor the polar region in order to protect the environment from the direct impact of development activities, and the indirect impact of climate change;
- Marine Engineers – for the design of safe structures and vessels to withstand ice conditions; and
- Residents in ice-affected regions – to maintain a high quality of life and safety



POLAR BEARS

Scientists worry that receding sea ice areas will adversely affect polar animals, particularly polar bears. Polar bears need sea ice to access their food, and to move from hunting grounds to their denning or summer resting areas. The Norwegian Polar Institute is using sea ice information and the movements of polar bears to help understand the relationship between ice extent. and bear health.

Ice is an important indicator of climate change, and observations show that Arctic ice is decreasing in both thickness and extent. Over the next 20 years, the volume of Arctic sea ice is predicted to decrease a further 40%, and the lateral extent of sea ice to be reduced by at least 20% in summer. Climate models predict the summertime disappearance of the Arctic ice in this century.

The need for ice information is increasing because of climate change and increasing economic activity.

These changes have important implications for activity in ice-affected regions. Melting of the Greenland glaciers may result in an increased number of icebergs in the trans-Atlantic shipping lanes. Farther north, the opportunities for marine transport will increase substantially. The Northern Sea Route and the Northwest Passage are already experiencing an increase in commercial ship traffic. As ice continues to diminish, the summer navigation season will grow longer and demand less capable vessels. By 2015, the Northern Sea Route and the Northwest Passage may be economically attractive to commercial vessels for 3-5 months of the year. Even vessels with the lowest ice class may be able to navigate the Northern Sea Route for two months each summer. The Sea of Okhotsk and the Sea of Japan may also have less ice in the high sea areas.

It is clear that economic development in ice-affected regions is proceeding at an accelerating rate. Significant resources – oil and gas, metals and minerals, and even diamonds – are being discovered and extracted. Northern communities are obtaining political and economic independence, and working to ensure that they grow and prosper, while maintaining traditional values and lifestyles. Nations are also taking a greater interest in asserting their right to manage, develop and secure their northern territories. Ice information is critical to national defense force working in or near ice-affected regions.

All of this development requires information to support the design and construction of specialized structures, such as ships and offshore oil platforms, which will provide the necessary levels of performance and safety in the harsh ice environment.

In summary, the increase in marine traffic through ice-affected regions, the recognition of the environmental significance of ice, the continuing development of resources in ice-affected regions, and the growing population of the North, all mean that the importance of ice information will continue to rise.

The following graphic shows the regions, the ice extent, key shipping routes, and the countries with active ice services. The accompanying table on the following page describes ice affected regions in both polar and mid-latitudes.

Countries with National Ice Services, Ice-affected Areas, and Major Marine Transport Routes

Ice-affected regions can be identified by broad geo-economic areas that are defined by their natural characteristics and type of human activity. The use of ice information varies by region and application.

Area	Ice Conditions	Human Activity	Issues
Baltic Sea	Sea ice exists from October to June, covering, on average, half of the Baltic Sea.	Heavy marine traffic assisted by ship routing and icebreakers.	Ship damage. Marine pollution from vessels.
St. Lawrence / Great Lakes	Sea and lake ice from December to May.	Heavy marine traffic assisted by ship routing and icebreakers. Shipping season interrupted by ice	Ship damage. Marine pollution from vessels.
North West Atlantic / Labrador	Icebergs are common from February to August.	Heavy marine traffic. Most ships avoid areas of known ice. Offshore oil operations. Fishing.	Safety of marine traffic from sea ice and icebergs. Environmental risk from offshore oil operations.
Northwest Passage	Frozen over for most of the year. Minimum ice extent in September.	Local marine traffic during the summer. Hunting and tourism activity at the ice edge.	Potential for this route to open due to climate change with a resulting increase in marine pollution from vessels. Safety of people at the ice edge.
Northern Sea Route	The winter season extends from November to May. The western half is navigable year-round, the eastern half for 3-4 months in the summer.	Shortest route between Europe and the Far East. Passage currently requires icebreaker support. The area includes many navigated rivers and inland waterways connected to the ocean.	Potential for this route to open further due to climate change with a resulting increase in marine pollution from vessels.
Barents Sea / Svalbard	Ice often blocks the west coast and occasionally the north eastern coast. Icebergs can be present. The ports of Murmansk and Vard remain ice-free year round.	Marine traffic. Fishing.	Entry or exit from the Northern Sea Route.
Greenland / Iceland	Access to the east coast of Greenland is only possible from August to October with icebreaker support. Icelandic waters are generally ice-free, except for the north coast. Icebergs are common.	Fishing.	Entry or exit from the Northwest Passage.
Antarctica	Icebergs are of greater number and size compared to the Arctic. Freeze-up begins in March, with the maximum extent in September.	Limited marine traffic. Scientific research.	Decrease in ice extent and volume due to climate change. Oil and mineral exploration and fishing grounds investigation could increase.
Arctic Basin	Currently ice covered year-round.	Very limited scientific research.	Decrease in ice extent and volume due to climate change.

TYPES OF ICE

Sea ice – Sea ice is formed from the freezing of seawater. Offshore, drift ice is dynamic, being moved by winds and currents. Near the shore, 'fast ice' forms early in the season and remains stationary. In the late winter, sea ice typically covers about 14 to 16 million square kilometers in the Arctic and 17 to 20 million square kilometers in the Antarctic. Sea ice impacts climate in many ways: its high albedo affects the planet's heat budget; its thermal insulation controls heat and mass fluxes between the atmosphere and the polar oceans, and its role in destabilizing the water column through brine rejection drives deep convection. Sea ice restricts the routes and seasons for marine vessels. Multi year ice and ice ridges in particular can create serious impediments to navigation. The ice edge is a region of intense biological activity: nutrient rich water feeds a food chain of plankton, fish, and the many polar animals that depend upon the sea ice for their habitat.

Icebergs – Icebergs are formed from the 'calving' of pieces of glacier into the sea. The majority of the icebergs in the North Atlantic come from about 100 glaciers along the Greenland coast. About 40,000 medium to large sized icebergs calve annually in Greenland, and about 400-800 take up to three years to transit into the shipping lanes. They can travel as far south as Philadelphia. The average iceberg in the Grand Banks is one to two hundred thousand tonnes and is about the size of 15-story building. Icebergs can also be found throughout the Arctic Ocean including the Barents Sea and Greenland Seas. Icebergs in the Antarctic originate from Antarctic ice shelves. They are far more abundant and much larger than Arctic icebergs – 93% of the world's mass of icebergs is found surrounding Antarctica. Icebergs often 'ground' on the seabed where this scouring impacts the ecosystem of the ocean floor and can destroy communications cable, pipelines and other logistical infrastructure. Icebergs are serious threats to navigation – the Titanic disaster resulted in numerous changes to marine practices. Icebergs are also an ongoing concern for offshore oil platforms requiring expensive design, ongoing monitoring, and occasional interception

Lake and river ice – The build-up or break-up of river ice can impact infrastructure and people upstream and downstream if water backs up as a result of an ice jam. A sudden break-up of river ice can threaten the safety of lives and property. The break-up of ice is usually short in duration and detection must be monitored regularly and reported quickly when it does occur. When a lake freezes over and is sufficiently thick to support a load, ice roads are built to connect some northern communities or to access remote locations of importance to local populations. Weather forecast models use the dates when lakes freeze over or when they become ice-free as thermodynamic model inputs. Scientists are also using these dates as an indicator of climate change.

ICE INFORMATION SOCIO-ECONOMIC BENEFITS

Ice information provides benefits to industry, governments, citizens, and society in a number of ways – either directly, or as an important contributor to improved weather and climate prediction.

Ice information provides benefits to industry, governments, citizens, and to society.

- Reduction of risk to life and property – Ice information allows better decisions to be made that reduce the likelihood of accidents and disasters.
- Increase in economic activity – Ice information allows economic activity to proceed where it might otherwise be too costly or dangerous.
- Reduction of operating costs – Ice information increases efficiency or decreases the cost of economic activity.
- Protection of the Environment – Ice information allows us to understand and mitigate the environmental impact of human activities.
- Contribution to scientific knowledge and policy development – Ice information increases our knowledge of the physical and ecological sciences in ice-affected regions and supports sound, science-based policy development.
- Improvement in quality of life – Ice information allows residents and visitors to ice affected regions to pursue activities on and around the ice more safely and effectively.

The national ice services have been established primarily to support marine transport operations, and the benefits of that application alone have been sufficient for governments to justify their continued operation. The ice information products to support the broader benefit areas are often the same as those used for operations, or may be derived from the same observations and analysis infrastructure at low incremental cost. The benefit areas are inter-related and frequently cascade from one area to the next.

Ice information provides safety, economic, environmental, knowledge, and quality of life benefits.

The following tables summarize the major benefits provided by ice information and relate them to the preliminary benefit areas defined by the GEO User Requirements and Outreach Subgroup.

The major benefits provided by ice information.

	Marine Transport	Resource Exploitation	Environmental Monitoring	Regional Development
Risk to life and property	Increased safety for ships and offshore platforms. Support for Maritime Defense and Search and Rescue	Increased safety for fishing vessels and offshore oil platforms.	Increased safety for montoring platforms (e.g. ships).	Improved flood warnings and mitigation. Improved ice edge and coverage information.
Economic activity	Year-round operation of ports.	Development in areas that would not otherwise be possible.	Mitigation of pollution risk due to icebergs and heavy ice.	Increased economic activity for northern communities.
Operating costs	Decreased transit costs and time. More effective tasking of icebreakers.	Decreased operating costs for fishing vessels and offshore oil platforms.	Improved weather forecasts for marine and land weather-sensitive industries.	Decreased costs of living for northern communities.
Environment	Decreased marine pollution from marine accidents.	Decreased marine pollution from offshore oil platform accidents.	Improved understanding of polar ecosystems and environment. Improved understanding of climate change.	Decreased impacts of human activity.
Knowledge	Better ship design.	Better offshore oil platform design. Better resource exploitation policies.	Increased knowledge of the polar environment. Better environmental policies.	Better regional development policies.
Quality of life	Not Applicable	Sustainable resources for increased economic benefits.	Protects the environment.	Permits people to live where and how they choose.

The benefits of ice information include many of the preliminary benefit areas defined by the GEO User Requirements and Outreach Subgroup.

	Marine Transport	Resource Exploitation	Environmental Monitoring	Regional Development
Reducing loss of life and property from natural and human-induced disasters	❄	❄	❄	❄
Understanding environmental factors affecting human health and well being			❄	❄
Improving management of energy resources		❄		❄
Understanding, assessing, predicting, mitigating and adapting to climate variability and change			❄	❄
Improving water resource management through better understanding of the water cycle			❄	❄
Improving weather information, forecasting and warning	❄	❄	❄	❄

ICE INFORMATION REQUIREMENTS

A wide variety of user requirement inventories for ice information have been developed to support different benefit areas. The key features of ice user requirements are:

- The ice parameters to be measured
- The spatial scale of the observations
- The frequency of the observation

ICE EDGE

The diversity of wildlife at the ice-edge is an important resource for northern communities and has a major cultural and economic significance. Knowledge of the location and structure of the ice-edge is needed for navigation and safety in the area. The traditional knowledge that formerly allowed local inhabitants to navigate safely and effectively in the icescape seems to be becoming less reliable, possibly due to climate change. Arctic communities are now using satellite images to complement traditional knowledge.

In addition, the time between an observation and the delivery of a useful information product to the user is an important characteristic, particularly for operational users. Because ice conditions can be highly dynamic (ice drift can be up to 50km/day), users engaged in operations in or around ice require information with fast turnaround (1-6 hours) and on a regular and reliable basis (every 6-24 hours, every day). Typically, users of this information are transport ships, ferries, icebreakers, national coast guards, fishing vessels, offshore oil and gas companies, and meteorological forecast operations. The Near-Real-Time (NRT) requirement of these users has significant implications for the revisit capabilities of observation systems, and the speed and robustness of the reception, processing, and delivery infrastructure.

Another significant group consists of users that require access to an archive of imagery, observations, and derived ice products. There is a wide range of applications for time series of consistent, objective sea ice measurements - from calculating ice statistics for defining the best location and design of a wharf, to large-scale global change climate studies.

Both user groups have identified access to data, including data sharing among multiple users, as a key factor in maximizing the quality of ice information that may be derived from Earth Observation.

The table on the following page summarizes the observational requirements for three key user areas:

- Near-Real-Time Marine Operations
- Regional Numerical Weather Forecasting
- Climate Monitoring and Science

Observational Requirements for Key Ice Features
Optimum Future Value *(Current Threshold Value)*

Parameters	Marine Operations	Weather Forecasting Regional NWP	Climate Monitoring and Science
Ice Extent – relative edge location Ice Edge Location - absolute	- ± 50m-100m *(750m)*	5km *(50km)* -	15km *(50km)* -
Ice Concentration Accuracy Ice Concentration Range	±10% *(±20%)* 5% - 100%	5% *(50%)* 5% - 100%	5% *(50%)* 5% - 100%
Ice Stage of Development -probability of correct ice typing Ice Stage of Development Ice Thickness	90% *(70%)* Distinguish new, young, first-year and multi-year ice 10cm *(20cm-50cm)*	- - 50cm *(100cm)*	- - 50cm *(100cm)*
Fast Ice Boundary Forms of Floating Ice - floe diameter	Same as for ice edge 10m *(50m-100m)*	Same as for ice edge -	Same as for ice edge -
Leads/Polynas	25m width *(250m)*	-	1% of ice area *(10%)*
State of Decay - % area of meltponds	10% *(50%)*	10% *(-)*	5% *(25%)*
Sea Ice Topography - ridge height	1m *(2m)*	2m *(-)*	-
Ice Motion Accuracy Ice Motion Range	± 1km/day 0-50 km/day	-	± 1km/day 0-50 km/day
Icebergs – max. waterline dimension	25m *(-)*	-	-
River Ice Extent – relative edge location River Ice Edge Location Accuracy - absolute	3m-10m 3m *(10m)*	- -	- -
River Ice Concentration Accuracy River Ice Concentration Range	5% *(20%)* 5% -100%	- -	- -
Timeliness	< 1 hr *(3-6 hr)*	< 1 hr *(3-6 hr)*	-
Sampling Frequency	24 hr *(48 hr)*	1 day *(7 days)*	3 days *(7-30 days)*
Geographic Coverage	North of 30° north and south of 45° south	North of 30° north and south of 45° south	North of 30° north and south of 45° south

Adapted from:

- CEOS Ice Hazards Report, 2001
- WMO Satellite Observational Requirements
- WCRP Satellite Observational Requirements
- GMES - Polar View
  - Data Needs and Availability Prospectus
  - Global User Needs Directory
  - Core User Needs Dossier
- GMES - ICEMON
  - Data Needs and Availability Prospectus
  - Global User Needs Directory
  - Core User Needs Dossier

ICE INFORMATION PRODUCTION

The increasing activity in ice-affected waters has led to a growing requirement for ice information services. The regular provision of ice information is an integral part of the operational programs of national meteorological and oceanographic services of nations that conduct activities in ice-affected seas. The national ice services have a long history of international cooperation, and numerous regional and international organizations exist to share information and resources.

Ice information is provided by the national meteorological and oceanographic services of nations conducting activities in ice-affected waters.

The majority of ice services concentrate on sea ice and weather information to support marine transport. In addition, icebergs are monitored by the International Ice Patrol, and additionally by Argentina, Canada, Denmark, and the United States. Lake ice is of interest to Canada and the United States, and river ice is actively monitored in Canada, the United States, the Netherlands, and Russia.

Examples of near-real-time ice information products include ice charts, bulletins, images, weather maps, and direct consultation services on current or near-term ice conditions. The analysis of archived ice observations is used to create non-real-time products such as climatological atlases of ice conditions, statistics on the presence of ice and the occurrence of extreme ice events, and the long-term record of changing ice conditions.

COUNTRIES WITH NATIONAL ICE SERVICES

- Argentina	- Australia	- Canada
- China	- Denmark	- Estonia
- Finland	- Germany	- Greenland
- Iceland	- Japan	- Latvia
- Lithuania	- Netherlands	- Norway
- Poland	- Russia	- Sweden
- United States		

INTERNATIONAL ICE ORGANIZATIONS

- International Ice Charting Working Group
- International Ice Patrol
- Expert Team on Sea Ice of the World Meteorological Organization and the Intergovernmental Oceanographic Commission
- Baltic Sea Ice Meeting
- North American Ice Service

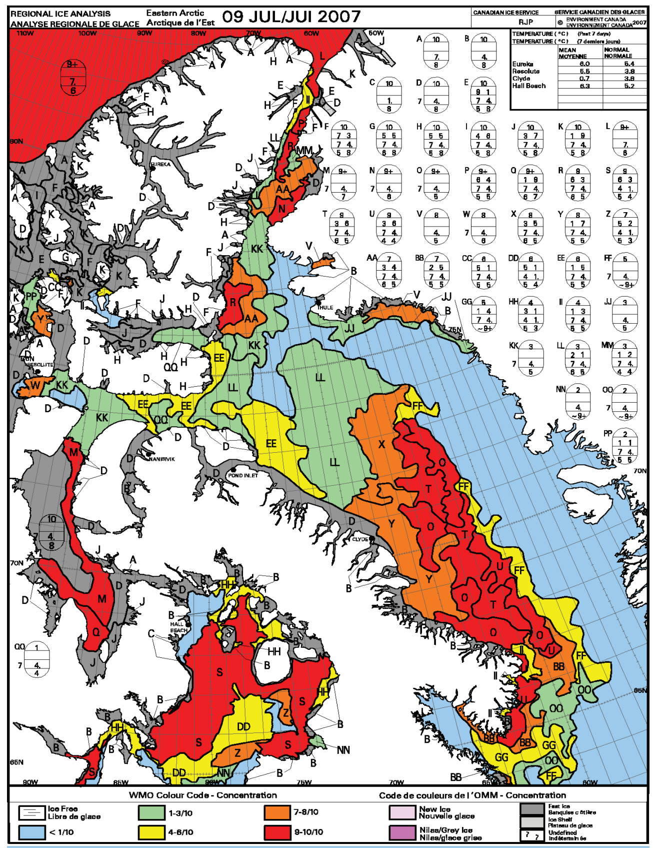
Ice products are created by combining data from satellites, aerial and shipboard observations, and in-situ sensors, using computer models and expert analysis. The different data sources each have their advantages and disadvantages. Information from vessels and weather stations is specific, but sparse. Visual and airborne radar surveys are detailed, but expensive, provide only limited coverage, and are frequently restricted by adverse weather conditions. Satellites, while not as detailed or specific as other sources, provide the best means of observing large areas in remote and hostile conditions in a systematic, cost effective way.

Ice information is produced using computer models and expert analysis to combine data from satellites, ships, aircraft, and in-situ sensors.

Satellites cannot completely replace other information sources, but they provide observations over a wider geographical area, at much lower cost and in much less time than aircraft alone. As a result, ice information is more accurate and costs less to produce using satellites. For example, it is estimated that the Canadian Ice Service is saving CDN$7.7 million per year by using satellites to reduce the use of aircraft for strategic ice reconnaissance.

Satellites provide the best means of observing large areas in adverse conditions.

A variety of Earth Observation sensors are used to map ice conditions. Visible-Infrared sensors at moderate-resolution (e.g. NOAA-AVHRR, METEOR) have been used extensively because of their easy accessibility, low cost, and frequent coverage. However, clouds, fog, relatively poor resolution (e.g. 1km), and polar darkenss limit the use of this type of sensor to fully meet operational ice mapping requirements, particularly in cloud- and fog-prone marginal ice zones.



A Sample Sea Ice Chart

Microwave sensors offer the advantage of all-weather observation independent of solar illumination and are used extensively for both near-real-time and archive applications. Passive microwave radiometers (e.g, ESMR, SSM/I, AMSR/E) have poor resolution (e.g. 12km-25km), but provide a global, long-term record of observations well suited to climate change monitoring. Passive microwave sensors, and more recently active microwave scatterometers, are used in near-real-time for daily ice edge, ice concentration, and large-scale ice motion products.

Wide-swath, C-band Synthetic Aperture Radar (SAR) (e.g. RADARSAT, ENVISAT ASAR) is now considered the preferred sensor for detailed regional ice mapping because of the their high resolution and high information content on ice concentration, ice type, and ice topography. The ground segment to support near-real-time operations has been implemented in several regions, but data accessibility and cost are still perceived as barriers to broader operational use. The current 400km-500km wide-swath capability provides good revisit frequency at high latitudes, but does not allow for daily coverage in the active mid-latitude shipping areas.

The table on the next page links the major ice information categories to the types of available Earth Observation sensors and their capabilities.

Earth Observation Sensor Capabilities for Various Ice Types

Information Requirement	Sensor Type	Capability
Sea Ice	Synthetic Aperture Radar (SAR)	The high spatial resolution of SAR sensors, wide swath modes, and the ability to detect most of the features of interest to the ice community (especially C-band SAR) make them the most suitable and preferred sensor for regional sea ice mapping and monitoring. A wide swath imaging mode provides daily coverage at high latitudes and is suitable to support operations and science requirements. Revisit frequency at mid-latitudes provides coverage only once every 2-3 days, and does not fully support operational requirements.
	Visible-infrared	Polar orbiting satellites' visible, infrared, and thermal channels are used for mapping sea ice, and the thermal channel measures sea surface temperature. Multiple satellites, frequent revisit, near real-time access, and low cost for reception make them a basic part of ice monitoring operations. However, their relatively coarse spatial resolution and inability to see ice through frequent cloud cover are significant constraints.
	Passive Microwave	Simultaneous imaging at multiple frequencies and polarizations enable automated discrimination between ice types and very wide swaths provide twice-a-day coverage at high latitudes. However, their coarse spatial resolution (12km-25km) limits their use to support tactical operations, and their use near coastlines and regions surrounded by land. The latter includes the regions with the highest shipping activity, such as the Baltic Sea. Integrated ice edge and sea-surface wind products are a useful strategic-scale product.
	Scatterometers	Scatterometers can be used to map sea ice extent and ice motion at a scale similar to the passive microwave data. However, the coarse spatial resolution places utility constraints similar to passive microwave sensors. Integrated ice edge and sea surface wind products are a useful strategic-scale product.
	Altimeters	The major sea-ice parameters measured with laser altimeter are surface elevation, surface roughness, and reflectivity. Recent work with satellite radar-altimeter data indicates the possibility of estimating sea-ice freeboard, a proxy indicator for sea ice thickness. Operationalization of advanced sensor technology and near-real-time access to data may add another tool for ice services in the future.
Icebergs	Synthetic Aperture Radar (SAR)	SAR is the most suitable satellite sensor for smaller icebergs because of the higher spatial resolution. The success of detection decreases with increased sea state because of increased background sea clutter. The ability to distinguish an iceberg from a ship is a critical requirement for any microwave sensor.
	Visible-infrared	Very large icebergs (in the order of 10 km in length), such as those calved off Antarctica, are detectable using polar orbiting visible infrared sensors.
	Altimeters	The laser altimeter on ICESat may also have some application for iceberg detection.
Lake and River Ice	Synthetic Aperture Radar (SAR)	SAR is the optimal sensor class because it has a higher spatial resolution and is able to image through cloud and in darkness. The latter characteristic is important for episodic events such as river and lake ice break-up.
	Visible-infrared	Mapping ice on lakes and rivers requires a finer spatial resolution than for most sea ice mapping applications because of the small size of some lakes and narrow river channels. On larger lakes and rivers, like the Great Lakes and St. Lawrence River, polar orbiting visible infrared sensors provide useful information on the ice cover.
Sea Surface Information	Synthetic Aperture Radar (SAR)	SAR is capable of providing wave direction and wave spectra to augment surface measurements.
	Visible-infrared	Sensors with thermal channels (AVHRR for example) can provide sea surface temperature. Wind speed can be inferred from cloud motion by geostationary satellites.
	Passive Microwave	Passive microwave is capable of measuring surface wind speed and sea surface temperature.
	Scatterometers	Scatterometers are widely used for deriving wind speed and direction over open oceans
	Altimeters	Altimeters can provide wave height.

SENSOR TYPE	Polar Visible / Infrared								Passive Microwave		Real Aperture Radar	Synthetic Aperture Radar							Scatterometer		Altimeter	
												C-band			L-band	X-band						
SATELLITE	NOAA	DMSP	ENVISAT	ENVISAT	MetOp-A	Meteor-3	EOS TERRA	AQUA	DMSP	EOS AQUA	Okean-O	Radarsat-1	*Radarsat-2*	ENVISAT	ALOS	TerraSAR-X	*COSMO -Skymed*	*Kompsat-5*	QUIKSCAT	MetOp	*Cryosat-2*	ICESAT
Program Start / Expected End	1978 / 2013	1965 / 2018	2002 / 2010	2002 / 2010	2006 / 2011	1985	1999 / 2005	2002 / 2009	1965 / 2018	2002 / 2009	1999	1995 / 2008	*2007 / 2014*	2002 / 2011	2006 / 2011	2007 / 2015	*2007 / 2012*	*2009 / 2014*	1999	2006	*2009*	2003
SENSOR																						
Name	AVHRR	OLS	AATSR	MERIS	AVHRR		MODIS	MODIS	SSM/I(S)	AMSR-E	SLAR	SAR	SAR	ASAR	PALSAR	SAR	SAR	SAR	SEAWINDS	ASCAT	SIRAL	GLAS
Spatial Resolution (m)	1100 & 4000	550 & 2700	1000	300 or 1200 No IR	1100 & 1100	1400 & 3000	250-1000	250-1000	30-70 km	5-60 km	1500-2000	10 - 100	3 - 100	30 - 150	100	1 - 16	1 - 100	1 - 20	25000	25000		70
Revisit Time (days)	~0.25	~0.25	6	3	~0.25	1	1-2	1-2	~0.25	3	3	~3 to ~5	~3 to ~5	3	3	11	1	1	~1	~1	369 30 dy sub	8
Swath Width (km)	2600-3000	2600-3000	512	1150	3000	3000	2330	2330	1700	1445	450	20-500	20-500	100-400	350	100	10-200	5-100	1800	2x550		
Country of Origin	USA	USA	EU	EU	EU	Russia	USA	USA	USA	USA / Japan	Russia	Canada	Canada	EU	Japan	Germany	Italy	Korea	USA	EU	EU	USA
FEATURE																						
Total Ice Conc'n	○	○	○	○	○	○	●	●	○	●	○	●	●	●	○	○	○	○	○	○		
Location Ice Edge	○	○	○	○	○	○	●	●	○	○	○	●	●	●	○	○	○	○	○	○	•	•
Ice Type	○	○	○	○	○	○	●	●	○	○	○	●	●	●	○	○	○	○	○	○		
Ice Thickness	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•			•	•
Floe Size	•	•	•	•	•	•	○	○			•	●	●	●	○	○	○	○				
Ice Topography											•	•	•	•	•	•	•	•			•	•
Landfast Ice	•	•	•	○	•	•	○	○			○	●	●	●	○	○	○	○				
Leads/Polynyas	•	•	•	○	•	•	○	○			○	●	●	●	○	○	○	○				
Pressure / Kinematics	○	○	○	○	○	○	○	○	•	•	○	●	●	●	○	○	○	○	○	○		
Icebergs												•	•	•	•	•	•	•				
Deterioration / Decay									•	•	●	●	●	●	○	○	○	○				
Snow cover / Depth									•	•												
River Ice Conc'n												●	●	●	○	○	○	○				
River Ice Thickness												•	•	•	•	•	•	•				
Lake Ice Conc'n	•	•	•	•	•	•	•	•				●	●	●	○	○	○	○				
Lake Ice Thickness	•	•	•	•	•	•	•	•				•	•	•	•	•	•	•				
Surface Temp	●	●	●		●	●	●	●	○	○												
Wave Height Spectra												○	○	○	○	○	○	○	●	●	○	○
Currents												•	•	•	•	•	•	•			•	•
Surface Winds									○	○		•	•	•	•	•	•	•	●	●		

LEGEND

- ☐ Does not meet threshold requirement
- • Incremental benefit over threshold but alternatives exist
- ○ Meets requirements most of the time (70%+)
- ● Satisfies Requirement (85%+)

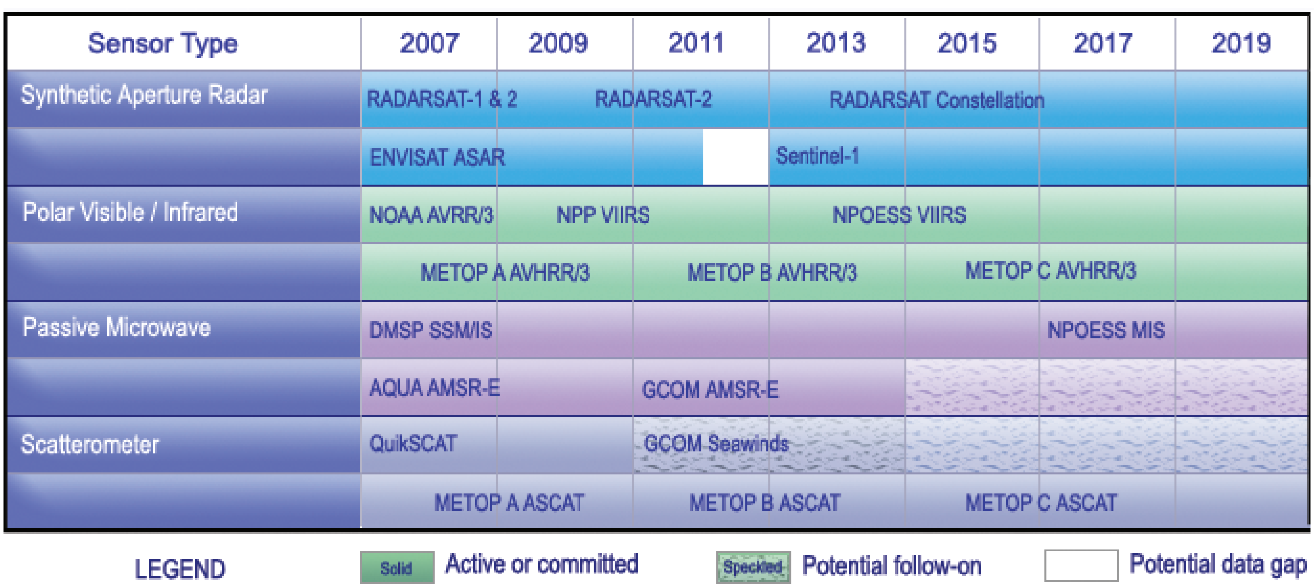
This table shows the capability of existing and near-future satellite sensors to provide information relevant to ice service operations. The larger the bubble in the cell, the better it meets the requirement. Satellite sensors used by the ice services are operated by a number of nations around the world. Polar orbiting visible/infrared sensors are an important source of data because of their frequent revisit, moderate spatial resolution, and low cost. Microwave sensors' capability to image through most clouds and in the dark provides a reliable source of data for ice monitoring. The Synthetic Aperture Radar's high spatial resolution and sensitivity to sea ice features make it the most suitable sensor for sea ice mapping. Scatterometers provide useful information on ocean state and winds, as well as coarse mapping of some sea ice features. Ice thickness and topography can be inferred using altimeters for hemispheric scale analysis.

ICE SERVICES AND THE FUTURE OF EARTH OBSERVATION

The ice services are leaders in the operational adoption of EO technology and are critically reliant on EO systems to support their users. The benefits of ice information cannot be realized without the continued availability and reliability of such systems. The table below summarizes currently planned EO missions of key interest to the ice community.

It is believed the long term plans for polar-orbiting meteorological satellites (e.g. NPOESS, METOP) will continue to meet the requirements for visible-infrared and coarse-resolution microwave data for several decades. While the recent delay and rescoping of the NPOESS mission may represent a short term risk to the supply of these data, it is expected that this risk will be mitigated through increased use of METOP-A AVHRR and DMSP OLS and SSM/I. QuikSCAT/Seawinds data is now considered a useful operational dataset for ice monitoring. As such, a similar follow-on scatterometer mission would be welcomed by ice services. The development of future operational missions for ice thickness and topography would be of interest if the current (IceSAT) and future experimental missions (Cryosat-2) demonstrate operational promise.

In terms of SAR, the current and planned systems provide both short-term and long term redundancy of wide-swath coverage. Wide-swath C-band SAR is considered a critical data source for operational sea ice monitoring. In order to meet revisit and reliability requirements, a scenario of two or more wide-swath (500km) SARs at 100 m-200 m resolution, or equivalent, is required to provide daily global ice mapping capability. Improved near-real-time processing and delivery, and improved opportunities for data sharing among ice services, are also of high interest. Currently, these requirements are being met with RADARSAT-1 and Envisat ASAR. RADARSAT-2 is expected to replace RADARSAT-1 after its launch in late 2007.



There is international commitment to ensure data continuity for visible/infrared, passive microwave, scatterometer data, and most importantly SAR data.

The commitment of Canadian and European space agencies to ensure continuity of this important dataset with new C-band SAR missions have provided national ice services with the promise of long term, continual SAR data with good operational redundancy for the first time. Next decade, both Canada's RADARSAT Constellation Mission and Europe's Sentinel-1 mission will provide wide swath C-band SAR data to support ice monitoring. The strong focus of these new missions on operational, near-real time surveillance and mapping is welcome. To faciliate optimal use of these new data streams within and between national ice services, cooperation and integration of these two missions where possible is strongly encouraged.

The SAR sensors on the European Space Agency's ENVISAT satellite and the Canadian Space Agency's RADARSAT satellite are excellent tools for observing ice.

In the years preceding this next generation of SAR sensors, there is a possibility that the ice services' requirement of having two concurrent C-band sensors in orbit may not be met. The outstanding launch and commissioning of RADARSAT-2 and the expected end of the Envisat mission in 2010 presently represent identifiable risks to operational ice monitoring efforts at the start of the next decade. ESA is currently considering various scenarios under which Envisat could continue to operate beyond 2010. Operational ice services welcome this possibility and advocate the extension of Envisat ASAR imaging until Sentinel-1 is launched and declared operational, estimated now to be early 2012.

Finally, the IICWG strongly supports cooperation among nations in defining future satellite systems. The EO requirements of the operational ice services have been recognized and considered by GEO and GMES in the 10-year implementation plan for GEOSS. The socio-economic benefits of ice information are numerous and are already being realized. Meeting the requirements of the ice services in future missions will help ensure continuing benefits and the realization of even more.

REFERENCES

Barber, D., M. Manore, T. Agnew, H. Welch, E. Soulis, and E. LeDrew (1992), Science Issues Relating to Marine Aspects of the Cryosphere: Implications for Remote Sensing. Cdn J. of R.S., vol 18, No. 1. pp. 46-54.

Bertoia, C. and J. Falkingham, F.Fetterer (1998), Polar SAR Data for Operational Sea Ice Mapping, in R. Kwok and C. Tsatsoulis (Eds.). Recent Advances in the Analysis of SAR Data of the Polar Oceans, Springer Verlag: Berlin, pp. 201-234.

Bertoia,C., Michael Manore, Henrik Steen Andersen, Chris O'Connors, Keld Q. Hansen, Craig Evanego (To be published 2004), "Synthetic Aperture Radar Marine User's Manual", National Oceanic and Atmospheric Administration, Center for Satellite Application and Research, NOAA/NESDIS, C.R. Jackson and J.R. Apel, editors, Washington, D.C., USA.

CEOS (2001), "Ice Hazards", Final Report of the CEOS Disaster Management Support Group.

Duchoissois, G. and G. Sommeria (2003), WRCP Satellite Working Group Report on Update of Space Mission Requirements for WCRP.

European Environment Agency (2004), "Arctic Environment: European Perspectives".

Goss Gilroy Inc. (2001) "Economic Benefits from the Utilisation of RADARSAT-1 for Surveillance of Ice Conditions in Canada".

ICEMON (2004) "C10 - Data Sources Inventory", prepared under the GMES Service Element for the European Space Agency.

ICEMON (2004) "U1 - Global User Needs Directory", prepared under the GMES Service Element for the European Space Agency.

ICEMON (2004) "U5 - Core User Needs Dossier", prepared under the GMES Service Element for the European Space Agency.

ICEMON (2004), "C12 - Data Needs and Availability Prospectus", prepared under the GMES Service Element for the European Space Agency.

ICEMON (2004), "C2 - Cost Benefit Analysis", prepared under the GMES Service Element for the European Space Agency.

ICEMON (2004), "S2 - Methods Compendium", prepared under the GMES Service Element for the European Space Agency.

ICEMON (2004), "U2 - Key User Segment Profiles", prepared under the GMES Service Element for the European Space Agency.

National Ice Center (2004), "Table on Observational Requirements for Ice Hazards", received via e-mail from Paul Seymour.

Nelson, C and J.D. Cunningham (2003), "The National Polar-Orbiting Operational Environmental Satellite System Future US Environmental Observing". IGARSS Proc.

Northern View (2004) "C2 - Cost Benefit Analysis", prepared under the GMES Service Element for the European Space Agency.

Northern View (2004), "C10 - Data Sources Inventory", prepared under the GMES Service Element for the European Space Agency.

Northern View (2004), "C12 - Data Needs and Availability Prospectus", prepared under the GMES Service Element for the European Space Agency.

Northern View (2004), "U5 - Core User Needs Dossier", prepared under the GMES Service Element for the European Space Agency.

Northern View Global (2004), "U1 - Global User Needs Directory", prepared under the GMES Service Element for the European Space Agency.

Ramsay, B., T. Hirose, M. Manore, J. Falkingham, R. Gale, D. Barber, M. Shokr, B. Danielowicz, B. Gorman, and C. Livingstone (1993), "Potential of RADARSAT for Sea Ice Applications". Cdn. J. of R.S., Vol. 19, No. 4. pp. 352-362.

Sandven, S., H. Gronvall, A. Seina, H.H. Valeur, M. Nizovsky, H. Steen Andersen, VEJ Haugen (1998), "Operational Sea Ice Monitoring by Satellites in Europe". Final Report. OSIMS Report No. 4. European Commission Environment and Climate Programme 1994-1998.

WCRP Satellite Observational Requirements - http://alto-stratus.wmo.ch/sat/stations/SatSystem.html

WMO Satellite Observational Requirements - http://alto-stratus.wmo.ch/sat/stations/SatSystem.html