TEAM REPORT

Ice

A Report of the CEOS Disaster Management Support Group 2000

ICE HAZARDS

CEOS DISASTER MANAGEMENT SUPPORT GROUP

EXECUTIVE SUMMARY

This purpose of this report is to identify requirements and review the current and projected utility of earth observation space technology as applied to the detection, mapping and management of ice hazards. Ice hazards include sea ice (ice that is formed from sea water) and icebergs (floating glacial ice). This study was developed under the auspices of the Disaster Management Support Group (DMSG) of the Committee on Earth Observation Satellites (CEOS). This document was prepared by an international working group composed of representatives with experience in remote sensing as applied in the production of operational ice guidance products and services.

It is well known that sea ice and icebergs pose a serious hazard to shipping and other maritime activities in the Polar Regions. The role of EOS data in operational ice monitoring is well documented and has grown in importance over the years. EOS data from visible/infrared sensors are potentially available to all ice services but are useful only under cloud-free conditions. Passive microwave sensors can penetrate cloud cover but their effectiveness in ice monitoring is limited by coarse resolution. Active microwave sensors, such as the Synthetic Aperture Radar (SAR), are ideal for ice mapping because of their high resolution, all weather, wide swath ice detection capability; however it does not always provide unambiguous interpretation. Therefore it is extremely important that all ice centers have access to EOS data in the various spectral ranges (e.g. visible, infrared and microwave) to allow for the most accurate analysis of ice conditions. Investigations have also shown that these data are also valuable in their ability to quantify other ice parameters in addition to ice extent (concentration) and ice type (stage of development), such as ice topography, presence of open water or thin ice openings within the sea ice pack, stages of ice decay and others. Sea ice guidance products derived in real-time from these data are used operationally to ensure safety of navigation by all vessels, maximize time and fuel savings of icebreaker lead convoys, determination of most efficient and safest route, and protect life and property associated with human activities on the ice. In contrast, the utility of EOS observations for iceberg detection is considered limited using presently available sensors. Space-borne SAR sensors can be effective in depicting the location and size of icebergs but only under low surface wind speed conditions.

The following recommendations support these requirements:

1. New and updated EOS sensors provide great promise for improving the applications of sea ice mapping and iceberg detection.
2. Data from multi-spectral visible/infrared radiometers and scatterometers can be used to generate automated sea ice maps.
3. SAR satellites with right/left looking beam steering, multiple polarization modes and enhanced downlink capabilities will provide more valuable data in a shorter period of time to the end user.
4. The coincident collection of EOS data from multiple instruments "fused" with ancillary environmental data can be used to resolve ambiguities and eliminate biases in conventional, single sensor algorithms.
5. Affordable data continuity, accessible rapidly for near real time support.
6. Data policies must exist for easy and rapid access to EOS data for ice hazard detection and monitoring.
7. Collaborative efforts are needed between all the national ice services to ensure that EOS data are shared, that ice products are issued in standard formats and most importantly that customers are educated on the strengths, weaknesses and value of EOS data and Ice Hazard products.
8. Improved/new sea ice/iceberg detection and classification algorithms.

9. Higher resolution coupled ice/ocean/atmosphere forecasting models to improve sea ice forecasts in the Marginal Ice Zone(MIZ) and iceberg drift and ablation rates.

INTRODUCTION

Eighteen nations, including Australia, Argentina, Canada, China, Denmark, Estonia, Finland, Germany, Iceland, Japan, Latvia, Lithuania, Netherlands, Norway, Poland, the Russian Federation, Sweden and the United States operate national ice services that support shipping and other maritime activities in ice encumbered waters. This support is outlined in the World Meteorological Organization (WMO) publication N0-574. From 1920 to the early 1960's, "in-situ" visual ice observations from coastal stations, transiting ships and aircraft reconnaissance and patrols represented the primary source of data on sea ice conditions and the location of icebergs. The paucity of information made available by these collection methods and the serious hazard posed by glacial ice to vessel operations gained international recognition and notoriety with the sinking of the TITANTIC on April 15, 1912 (struck the iceberg on 14 April, sank in very early morning hours on 15 April). As a result of this accident, the U.S. Coast Guard (USCG) International Ice Patrol (IIP) was formed to provide iceberg detection and warning services to vessels operating in the North Atlantic shipping lanes. Similarly, interest in many nations to develop more accurate methods for the detection, monitoring and forecasting of sea ice did not occur until there were significant incidents that threatened the safety of navigation and life and property at sea.

In winter 1937, which was logistically unexpected and different from the previous mild ones, within the area of the Northern Sea Route (NSR) from Franz-Josef Land to New Siberian Islands 26 cargo ships with approximately 1000 people were beset by ice. That catastrophe led to the establishment of the Russian Ice Service much similar to the present, total duration of ice air reconnaissance being one order greater in 1938 than in 1937. In 1951, operating under the code name *Operation Bluejay,* 30 ships of a 33 U.S. Navy vessel convoy were severely damaged while attempting to navigate along the west coast of Greenland to establish a Distant Early Warning station and air base at Thule, Greenland (McDowell, 1990). In 1952, as a direct result of this accident, the U.S. Navy established a formal sea ice monitoring program. Outside Russia and Denmark, most national ice services at this time were fledgling programs that needed to collect information to build their knowledge on sea ice characteristics and behavior. Beginning in the early 1960's, the capability to collect data was enhanced when the Canadian Ice Service (CIS) introduced the use of search radars on ice reconnaissance aircraft (Bertoia et al 1998). These radars provided, for the first time, a long-range, cloud independent capability to detect ice. Unfortunately, these early instruments were forward-looking, non-imaging sweep radars that were useful only in the accurate measurement of range and bearing to the ice edge.

Due to limited range and expense, aerial reconnaissance was typically flown only in support of specific vessel operations. Knowledge on the overall extent, thickness and behavior of the polar ice cover in both hemispheres was viewed as incomplete, thus posing a continual hazard to vessel operations. It was only during the 1960's that sea ice detection and monitoring entered a new era of remote sensing with the launch of weather satellites by the United States. The usefulness of "pictures" taken by vidicon cameras for gross ice mapping was recognized immediately after the launch of the first TIROS research and development satellite in 1960 (Wark and Popham, 1962). By the late 1960's and 1970's, improvements in satellite technology (ESSA satellites on polar orbits) allowed for the real-time use of these data for operational ice mapping (Strübing 1970). NOAA-2 (launched in October, 1972) carried a dual channel Very High Resolution Radiometer (VHRR) that provided visual and thermal imagery via direct global and local read-out. The NASA research satellite, NIMBUS-5 (launched in December, 1972) included an Electrically Scanning Microwave Radiometer (ESMR) that provided coarse resolution, all-weather, passive microwave data. These data, coupled with traditional data sources, allowed the U.S. National Ice Center (NIC) to initiate weekly global ice mapping program of all Arctic and Antarctic seas.

In the early 1970's, improvements in radar technology resulted in the deployment and use of real aperture Side-Looking Airborne Radar (SLAR) on patrol aircraft. Several national ice services used these SLAR data to extend the range of aircraft providing traditional visual observations and to complement the visual, thermal and passive microwave imagery received from satellites. In June 1978, the benefits of merging rapid advancements in radar technology and satellites were seen in the launch of the NASA research satellite, SEASAT. SEASAT was the first satellite dedicated to using active microwave sensors for ocean observation. Although limited to only 105 days in orbit, SEASAT provided high resolution images which confirmed that a space-borne Synthetic Aperture Radar (SAR) can be a powerful tool in ice detection and mapping (Teleki et. al., 1979).

Today, Earth Observation Satellites (EOS) are used almost exclusively to provide operational information on the extent, concentration, distribution and thickness of sea/lake ice. In demonstration projects, EOS data are now being used to detect, forecast and assess the damage of destructive river ice break-up and ice jams. Additionally, EOS data are being used for research purposes by the USCG IIP and CIS to detect and map icebergs in the North Atlantic.

GENERAL APPLICATION DESCRIPTION

The requirement for the detection, mitigation and management of the potential hazards posed by ice originated with early 19th and 20th century polar exploration. Vessel expeditions attempting to find and exploit the Northwest Passage, the Russian Northern Sea Route or the resources found in or beneath the frozen waters of the Arctic and Antarctic were often damaged, beset or destroyed by sea ice. Today, the operational detection of sea ice, icebergs and river/lake ice is vital to ensuring the safety of vessel operations and the commercial viability of associated industries, such as marine transportation, fishing, oil exploration and tourism. National governments are also interested in these data to support components of national defense, scientific research, long-term climate monitoring and environmental programs. Local interest is typically centered on the effect a heavy ice cover has on local economies. For example, native and indigenous people often use unstable shorefast ice as platforms for marine mammal hunts and ice angling. Additionally, severe ice conditions like those observed along the U.S. east coast (e.g. Chesapeake Bay) in the winter of 1976-77 (Foster, 1982) can cause a disruption of maritime fuel oil deliveries, the closure of fishing areas and local navigation as well as extensive infrastructure damage such as loss of coastal navigational aides and docking facilities.

Specific user requirements for ice information can often be quite diverse depending on the user application or the capabilities of a vessel. Non-ice strengthened vessels require timely ice edge and iceberg limit information in order to plan their routes to avoid all known ice. For example, highly vulnerable crab and fishing ships operate directly adjacent to the rapidly changing ice edge in the Bering Sea during the volatile winter weather months. In contrast, vessels with hull strengthening and some degree of ice capability require information detailing ice concentration distribution and associated ice thickness. This information can be used to exploit the ice cover by planning routes more effectively. Even the most capable icebreakers use information on openings in the ice (e.g. leads and polynyas) to choose the path of least resistance in order to achieve greatest fuel economy. Additionally, submarines operating under the ice require ice opening and ice thickness information to assist in surfacing within the ice and in the successful transit of shallow ice-covered waterways.

In the polar regions, sea ice varies both spatially and temporally due to high variability in the environmental processes that form, advect and decay the ice. All international ice service organizations produce ice analyses describing current sea ice conditions. The production of these analyses is dependent almost exclusively on the availability and use of EOS data. Although accurate spatial depiction of ice conditions is important to the mariner, temporal accuracy is generally of much greater importance. Ideally, vessels at sea prefer to receive high-resolution satellite images that are less than 6 hours old and have been interpreted to provide the information necessary to avoid or exploit the ice. Sea ice parameters required by users at sea include the location of the ice edge, concentration distribution, stage of development, floe size, amount of pressure ridging or topography, location and orientation of ice openings, degree of ice compaction and divergence and stage of decay during the summer melt season. Additionally, information on the location and size of icebergs is essential in waters located near or downstream of ice shelves and glaciers.

Mitigation and preparedness for hazards posed by ice requires not only accurate ice analyses (describing current ice conditions) but also short (less than 72 hour) to long-term (168 hour to monthly/seasonal) ice forecasts. Most national ice services have developed and are using coupled ice/ocean/atmospheric models to predict short-term changes the movement, formation and ablation of sea ice and icebergs. Long-term monthly and seasonal forecasts are important to mission planning, particularly the prediction of the opening and closing of well-known navigational chokepoints (e.g Bering strait, north slope of Alaska east to Prudhoe Bay and various locations along the Russian Northern Sea Route). Additionally, to effectively describe the sea ice cover, nations with Arctic interests have developed a set of common terminology to describe the nature of sea ice and its behavior. This compendium of internationally accepted ice terminology and symbology was adopted by the World Meteorological Organization (WMO) in 1968. This terminology was compiled into a volume including illustrative sea ice and iceberg photographs and was issued as a publication entitled *WMO Sea-ice Nomenclature* (Publication No. 259) in 1970. This publication, supplemented from time to time, remains the source of accepted terminology and symbology for sea ice mapping and the identification of icebergs.

SPECIFIC APPLICATION DESCRIPTION

a) *Hazard Type*:	Sea Ice/Lake Ice Cover
User Level:	International, Regional, National, State
Disaster Mgmt Category:	Mitigation/Preparedness (surveillance, detection, and warning)
Operational Status:	Operational over all ice-covered seas

The majority of national ice services presently produce sea ice/lake ice guidance products in a digital workstation environment using data from polar orbiting satellites, ship/shore station reports, drifting buoys, meteorological guidance products, ice model predictions and on a limited basis, aerial ice reconnaissance flights. Among the presently available operational data sources, satellite imagery now constitutes the largest percentage of information received and integrated into global ice analysis products. Traditional data collection methods, such as visual aerial ice reconnaissance, require extensive pre-planning, are limited in geographic scope and are generally not cost effective. Real-time satellite data in the visible, infrared and microwave bands of the spectrum are now used extensively, and are an essential requirement for ice services to ensure safety of navigation and protect life and property in ice-covered seas and lakes.

Today's commonly used optical, thermal, passive microwave and active radar satellite systems possess characteristic strengths and weaknesses with respect to spatial resolution, detection capability and classification accuracy of the sea and lake ice cover. Additionally, the orbit of the satellite directly effects the geographical coverage and revisit time. Meteorological satellites fall into two categories based on their orbits: Geostationary or Polar. Orbiting at an altitude of 35,800 km and at the same rate as the earth, geostationary satellites provide superior temporal resolution with images available every 15-30 minutes. Thus, visible and infrared imagery from geostationary (e.g. GOES-8, GOES-10, METEOSAT and GMS) are used by several national ice services to monitor ice in lower latitude seas and lakes. Unlike the polar regions, these lower latitudes do not suffer from persistent illumination problems that can restrict the use of visible imagery. In North American areas, this is important because the Geostationary Environmental Satellite (GOES) 8/10 Imager instrument consists of visible and infrared channels that have spatial resolutions of 1 km and 4 km, respectively. The latter does not provide data of sufficient spatial resolution to do detailed ice mapping.

In terms of geographic coverage in the polar regions, polar orbiting satellites are the primary source for visible and infrared data for ice monitoring. The National Oceanic Atmospheric Administration (NOAA) and Defense Meteorological Satellite Program (DMSP) Polar Environmental Satellite (POES) operate at an altitude of approximately 830 km with a period of 102 minutes. With multiple satellites operating at any one time, many images are available each day in the polar regions. With five or six (NOAA-15) spectral channels and a 1.1 km spatial resolution (at nadir), visible and infrared imagery from the Advanced Very High Resolution Radiometer (AVHRR) is an effective tool for ice mapping. AVHRR imagery can be used to accurately depict the location of the ice edge, ice concentration, ice stage of development and physical surface temperature (Emery et al. 1991, 1994; Massom and Comiso 1994). In contrast, the DMSP Operational Linescan System (OLS) provides visible and thermal data from only two spectral channels but at improved 0.55 km spatial resolution that is consistent across the width of the swath. Additionally, the OLS visible channel often produces images with better sea ice and water contrast than either AVHRR channels 1 or 2. This effect occurs because the broad spectral wavelength of the OLS suppresses optically thin clouds when compared to surface features (Isaacs and Barnes 1987). Creating bispectral composite AVHRR images based on the difference between the visible and near-infrared channels (Lee et al. 1993) can generate a similar but improved effect. Unfortunately, these arithmetic image manipulation functions are limited in their effectiveness when extensive, heavy cloud cover is present.

Climatologically, cloud cover may be present over 80% of the time over the Arctic ice pack and the Marginal Ice Zone (MIZ) during the important summer shipping months (Benner et al. 1992). Visible and infrared data also require considerable expertise in manual image interpretation techniques that use texture, tone, shape and persistence to separate ice from clouds and water. Additionally, due to the fact that thermal contrasts between water and ice are not as large as reflectance (albedo) differences, infrared imagery generally requires image enhancement.

Passive microwave sensors are useful for sea ice mapping because emitted energy in this portion of the electromagnetic spectrum are not limited by clouds or illumination. Additionally, the measured brightness temperature (Tb) is a function that depends more directly upon the geophysical parameters of the sea ice (Comiso 1983; Cavalieri et al. 1984; Kwok et al. 1992; Kwok and Cunningham 1994 and Fung 1994). The Special Sensor Microwave Imager (SSM/I), a multi-channel microwave radiometer onboard the DMSP satellites, can be used to generate global ice concentration and first year/multiyear ice classification products (Cavalieri 1994; Kwok et al. 1996). Many national ice services employ algorithms using some combination of the 19 and 37 GHz channels to produce 25 km gridded mosaic ice maps. These products assist in the general delineation of the ice edge and inner pack concentrations in cloud-covered areas. Unfortunately, the coarse resolution precludes detailed analyses and great care must be taken to account for contamination errors induced by surface meltwater and coastlines.

Similar to passive microwave, SAR satellite systems (Canadian RADARSAT; European ERS-2; Japanese JERS (recently failed) and Russian ALMAZ) are not affected by clouds or darkness. SAR instruments use active microwave pulses to collect high spatial resolution (10-100 meter) data over varying swaths at fixed or selectable incidence angles. ERS-2 is presently being used by some European ice services to routinely map and monitor ice in portions of the Baltic Sea. In general though, the ERS is limited in its effectiveness to accomplish large-scale ice mapping because the single frequency/single polarization SAR has a fixed incidence angle and relatively narrow swath width (100km). In comparison, RADARSAT's C-band SAR has a steerable beam (thus variable incidence angle) and a SCANSAR mode that provides data with a 100 m spatial resolution and a 500 km wide swath. These characteristics back-up the Canadian Space Agency's (CSA) claim that RADARSAT is the world's first radar satellite specifically designed to maximize its usefulness for sea ice monitoring. RADARSAT's wide swath provides high repeat imaging capability that can image every point on the earth's surface north of 65N latitude at least once every day. North of 45N, the entire globe can be covered in 3 days or less. Four Command Data Acquisition (CDA) stations (Fairbanks, Alaska; Gatineau, Canada; West Freugh, Scotland and Tromso, Norway) provide near complete Arctic coverage. Arctic images are typically quick-look processed and transferred via dedicated communications lines or Internet to national ice centers within three hours of acquisition. No SAR imagery are routinely integrated into ice analyses of the Antarctic seas because of tape recorder limitations and data delivery delays associated with communications to/from the McMurdo ground receiving station.

The Russian OKEAN-01 polar orbiting satellite series is unique for ice mapping because it carries three intermediate resolution instruments that have the capability of simultaneously collecting passive microwave, Real Aperture Radar (RAR) and optical imagery. The passive microwave instrument (36 GHz horizontal), X-band RAR and single channel (0.8-1.1um) optical sensor provides imagery with 15km, 1.2km and 1.0km spatial resolution, respectively. Ice maps produced using simultaneously acquired passive and active microwave OKEAN data have compared favorably to concurrent SSM/I and AVHRR ice classifications in several case studies of northern Russian seas (Belchansky G. et al, 2000).

b) *Hazard Type*:	Icebergs
User Level:	International, Regional, and National
Disaster Mgmt Category:	Mitigation/Preparedness (surveillance, detection, and warning)
Operational Status:	Operational in North Atlantic and Antarctic

Icebergs are masses of freshwater ice that have broken off or calved from the edges of glaciers whose termini make contact with the sea or that have resulted from the fragmentation of larger icebergs already afloat (Loset et al. 1993.) The rate of production of icebergs is highly variable, being influenced by glacier velocity, degree of crevassing, ocean waves, swell and tidal variations, temperature and sea ice extent (Loset et al. 1993; Vinje 1989). Maximum production tends to occur in the summer when sea ice extent is at a minimum, temperature (and the glaciers) are at the warmest and wave action is most intense (Vinje 1989). Icebergs are classified on the basis of size and shape. The WMO (1970) system defines three size classes (icebergs, bergy bits and growlers) and six shape classes (tabular, dome, sloping, pinnacled, weathered and glacier). Presently, operational data collection by the International Ice Patrol is limited to visual observations, Side Looking Airborne Radar (SLAR), and Forward Looking Airborne Radar (FLAR) data from planned aerial reconnaissance flights and opportunistic ship reports. Attempts have been made to include EOS data to give synoptic views of large areas. Unfortunately, until recently, the utility of satellite observations (visible, infrared and passive microwave) were considered limited due to an inability to penetrate cloud cover and darkness, inadequate spatial resolution and/or poor revisit times. Research activities are presently evaluating the effectiveness of space-borne SAR's to detect icebergs.

Active microwave systems provide two-dimensional images of variations in backscatter that are difficult to interpret when compared to visible/infrared imagery. First, imaging radars are subject to speckle noise. This noise can be reduced by spatial averaging of the image resulting in a higher signal/noise ratio but at the expense of spatial resolution (Rees 1990). High speckle noise can inhibit the effectiveness of detecting small icebergs and often results in a significant number of false alarms (Willis et al. 1996). Backscatter differences are the result of surface and volume scattering of the target (in this case, an iceberg) and surrounding medium (sea water or sea ice). High wind speeds and resulting rough seas can mask the signal from an iceberg (Steffen et al. 1992a). In calmer conditions, icebergs sometimes give a bright target return with neighboring radar "shadow" that can be used to estimate iceberg volume or size (Larsen et al. 1978).

Iceberg detection algorithms using the ERS-1 SAR (C-band, VV polarized and 23 degree fixed incidence angle) demonstrated that 100 meter data could be used to detect even Arctic and North Atlantic icebergs with great success under "optimal conditions" (Willis et al.1996). Optimal conditions are those with wind speeds below 5 meters/sec and no sea ice or land within the image. At 100 meter spatial resolution, ERS-1 imagery detected 100% of large icebergs (120-200m width), 90% of medium size icebergs (60-120m width) and approximately 40% of small icebergs (15-60m width) (Willis et al. 1996). It is important to note that the less than desirable detection rate of small icebergs is a significant problem since small icebergs, bergy bits and growlers present the greatest danger to maritime shipping in that they are extremely difficult to detect with shipboard surface search radars. It was noted however that the SAR's iceberg detection capabilities decreased significantly with increasing wind speeds. Willis et al (1996) stated that iceberg detection using space-borne SAR's would be most effective with the following preferred radar parameters: as high frequency instrument as possible, horizontal polarization and large incidence angles. With this knowledge, the IIP and CIS are presently conducting research evaluating the utility of Radarsat SAR data for iceberg detection. Radarsat operates a C-band instrument, HH polarization, wide swath widths (up to 500km), variable incidence angles (20-60 degrees) and almost daily coverage in the high latitudes.

As described above, iceberg detection using EOS data is heavily dependent on iceberg size and surrounding environmental conditions. In the southern hemisphere, large tabular icebergs routinely calve from the numerous ice shelves in the Antarctic. Due to the enormous numbers of icebergs in this region and the absence of "in-situ" ground truth information, only very large icebergs (typically exceeding 10 nautical miles along the long axis) are detected and routinely mapped. In most cases, these icebergs are detected and tracked using AVHRR and OLS visible/infrared imagery. Large iceberg calving events are typically detected by significant changes in the ice shelf boundaries. Once within the sea ice pack, albedo similarities between icebergs and sea ice make detection and tracking difficult. Under certain conditions, visible and infrared imagery do show characteristic iceberg signatures. These signatures include leeward open water areas resulting from iceberg movements at a different velocity or direction than that of the surrounding sea ice (Strübing 1974). Surface temperature differences can also distinguish thicker bergs (up to 250m in freeboard) from the surrounding sea ice pack. The former effect is based upon the findings that larger icebergs with deep keel drafts are driven primarily by ocean currents (Gustajtis 1979) vice surface winds for sea ice.

c) *Hazard Type*:	Shorefast, Lake and River Ice Break-up
User Level:	International, Regional, and National
Disaster Mgmt Category:	Mitigation/Preparedness/Relief (surveillance, detection, Warning and damage assessment)
Operational Status:	Operational for navigable areas of the NSR, research with demonstration status in other selected Arctic coastal areas.

As described in the previous sea/lake ice section, data from EO satellites are critical for sea ice/lake ice hazard monitoring. Shorefast ice is defined as sea/freshwater ice that is attached to the coastline. River ice is a type of shorefast ice that forms in many estuarine systems in the polar regions. Human activities, such as Great Lakes ice fishing and whale hunts by Arctic indigenous people, use the stable lake or shorefast ice as a "platform" to conduct these endeavors. In the archipelagoes of the northern part of the Baltic Sea the fast ice in between is used for local car traffic, and also as a protected area (e.g. a 10m navigation channel runs along the southern coast of Finland) against ice pressure at sea. Unpredicted break-up of these ice types can threaten the safety of lives and property. In contrast, river ice break-up poses a hazard but typically only to vessels operating in the river. River break-up is usually an event of short duration but characterized by hazardous destructive forces. Human settlements are typically threatened only by associated flooding resulting from ice jams.

Visible and infrared EOS data are effective in providing general information on the location of shorefast boundaries. The shear zone caused by moving pack ice adjacent the fixed shorefast ice is often quite distinct in AVHRR/OLS imagery. Thickness information must however be obtained from "in-situ" measurements (ice cores) or estimated by freezing degree day (air temperature) models. Space-borne SAR systems are the preferred data source to mitigate and assess the effects of this ice hazard. SAR imagery is high resolution and not affected by clouds and darkness. Thus, these data are ideal for characterizing and monitoring the shorefast, lake and river ice. Unfortunately, what is really needed is a better understanding of the environmental processes that cause the break-up of this ice. Research highlighting case studies that couple EOS data with "in-situ" meteorological/oceanographic observations are needed to enhance the preparedness and capabilities of ice services to issue accurate forecasts. The NOAA Alaskan Demonstration Project is presently making high resolution Radarsat SAR-based products coupled with coincident ancillary environmental data available to state regulatory agencies (Alaska River Forecast Office) responsible for monitoring ice break-up in the Yukon River system (Lunsford 1998). Prototype products such as advisories predicting the break-up of shorefast ice are now being issued by CIS for the Arctic Bay and Pond Inlet areas of the Canadian Arctic. Arctic and Antarctic Research Institute (AARI) operational provides forecasts of fast ice breakup for navigable areas of the Northern Sea Route including estuaries, e.g. March forecast of fast ice breakup in June for Vilkitskii Strait.

PRODUCTS AND SERVICES

a) National Ice Information Services

A detailed description of all eighteen national ice services (Appendix B) can be found in WMO publication No. 574 "Sea Ice Services in the World". This publication is available as hardcopy from the WMO Secretariat or as a softcopy from the WMO/IOC Global Digital Sea Ice Data Bank website (http://www.aari.nw.ru/gdsidb/pub/WMO-574.pdf). In general, national sea ice services provide a diverse suite of digital and analog ice guidance products in support of mission planning, operations and research in the ice-covered seas in the northern and southern hemispheres. In the United States and Canada, this service is extended to the Great Lakes. Routine ice guidance products include regional and local-scale ice analyses, annotated satellite imagery, short to long-term ice forecasts, legacy ice information, ice climatologies and iceberg reports. Ice analyses typically document the date and time of data used in each analysis in a metadata narrative. Ice product formats include a) paper charts, b) simple electronic charts in GIF or Adobe Acrobat formats and c) Geographic Information System (GIS) compatible (e.g. ESRI ARC/INFO .e00 or SHAPEFILE export format) coverages. International standards for archival include the WMO digital standard for Sea Ice in GRIDed (SIGRID, SIGRID-2) formats. Almost all ice analysis charts are labeled using the World Meteorological Organization (WMO) international sea ice symbology. Additionally, many national organizations provide services available via special request. These services include Optimum Track Ship Routing (OTSR) recommendations, pre-sail ship briefings, aerial ice reconnaissance and ship rider support.

Information on North Atlantic icebergs is provided daily by the USCG IIP and CIS. The IIP distributes information on the southern and eastern extent of all known icebergs in the North Atlantic/Grand Banks region of Newfoundland. During the iceberg season (Feb-Aug), the IIP distributes information on the southern extent of all known icebergs every 12 hours. Size and time of sighting for all reported icebergs are routinely entered into an iceberg forecast model. Initialized daily with surface wind and ocean current information, the Berg Analysis Prediction Systems (BAPS) model is used to predict iceberg drift and estimated rates of deterioration. Model output is critical in predicting movement and longevity of icebergs in North Atlantic shipping lanes. CIS provides information on icebergs within the Canadian Exclusive Economic Zone year-round and collaborates closely with the IIP. Both use the same BAPS model and exchange information daily.

b) User Types

The table below lists the specific ice hazard applications and subsequent user communities that have been identified for EOS data and resulting ice guidance products.

Application	User Level	Category	Status
Sea and Lake Ice Detection for Avoidance	International, National, Regional, State	Mitigation, Preparedness	Operational
Sea and Lake Ice Characterization for Exploitation (safety, efficiency of mission)	International, National, Regional, State	Mitigation, Preparedness	Operational
Beset Vessel in Sea and Lake Ice	International, National	Mitigation, Preparedness, Response	Operational
Iceberg Detection for Avoidance	International, National	Mitigation, Preparedness	Operational, Research
Landfast, Lake and River Ice Break-up	State, Local	Mitigation, Preparedness, Response, Relief	Operational, Demonstration, Research

Sea Ice Detection for Avoidance

The majority of users interested in real-time EOS data and operational sea ice products have a basic requirement to avoid sea ice. All vessels operating near ice-covered waters are users of these data. Knowledge of the exact position of an ice edge is critical to a submarine patrolling underwater but navigating with a periscope. When under the ice, submarines need information on pressure ridging and associated keel depths. Non-ice strengthened government research vessels conducting ocean surveys will in most cases attempt to totally avoid the ice. Similarly, federal and state interest also exists in non-reinforced vessels that are part of the marine transportation, fishing, oil exploration and tourism industries.

Sea Ice Characterization for Exploitation

Knowledge on the characteristics of the sea ice cover is important to both the operational and scientific research communities. National interest lies in the operation of military vessels (e.g. submarines), Government owned icebreakers (e.g. Argentina, Canada, Finland, Germany, Japan, Russia, Sweden and the United States) and ice strengthened research vessels. Icebreaker led convoys want to know the optimum track through ice to maximize time and fuel savings. Many commercial industries have ice-strengthened cargo vessels with the same need for information to exploit the ice cover. For example, along Russia's Northern Sea Route Norilsk-class cargo vessels are capable of maintaining continuous progress through one meter of first-year ice but must avoid areas of high ice concentration under pressure or those dominated by thicker multiyear ice (Brigham 1991). Although not used specifically for exploitation purposes, other users of sea ice extent and coverage information include the international scientific community interested in long-term climate monitoring. Climate models suggest that the Arctic environment is particularly sensitive to global climate change and that sea ice (extent and thickness) is the one geophysical variable that is most sensitive to climate variability (Wadhams 1994). Accurate and complete EOS-derived records of sea ice are recognized as being extremely important to scientific research (Parkinson et al. 1987). As vessels move to Electronic Chart and Display Systems (ECDIS), ice conditions will be required in near real-time. The development and approval of international formats for display and distribution of ice information to ECDIS will increase the safety of navigation near and in ice-infested waters.

Beset Vessels in Sea Ice

Sea ice information intended to assist in the freeing of beset vessels typically receives international and national attention. Vessels that become beset in ice are typically icebreakers or ice-strengthened research vessels operating in the high Arctic or Antarctic ice packs. In the fall of 1983, for example, 15 cargo vessels and several icebreakers that were part of a Russian convoy transiting the Northern Sea Route were beset for weeks in the Chukchi Sea (Brigham 1991). In mid-February 1979 a heavy snow storm resulted in a wide jammed brash ice barrier along the German coast of the western Baltic Sea. Within hours up to 100 cargo vessels and ferries were beset in the approach to Kiel Canal. To assist these vessels in distress, national ice services are often called upon to assist their own vessels and those of other countries that become stuck in the ice. In 1997, the National Ice Center ordered Radarsat SAR imagery to assist the Argentine icebreaker, the ALMIRANTE IRIZAR whose progress was hindered by ice of the Weddell Sea near the Antarctic continent.

Iceberg Detection for Avoidance

The basic premise and mission of the IIP is to provide information on icebergs to protect vessels by ensuring safety of navigation in the North Atlantic. The IIP was formed by international mandate and is jointly funded by many countries with marine shipping interests. Specific national interest in icebergs is more elevated in those countries whose waters are more populated by icebergs. These countries include Canada (Baffin Bay, Newfoundland areas), Denmark (East and West Greenland waters), Russia (Barents Sea) and the United States (IIP area and Prince William Sound, Alaska). The increasing demand for hydrocarbons and other earth resources have stimulated interest and activity in many of these polar seas. Icebergs of all sizes pose a hazard to shipping, oil exploration and extraction activities. Other users of iceberg information include the international scientific community interested in long-term climate monitoring. Rates of iceberg production and distribution characteristics have been suggested as indicators of variations in the global climate since the polar regions are particularly susceptible to the effects of climate change (Brown et al. 1982).

Shorefast, Lake and River Ice Break-up

Users of these data can be federal or state agencies and local communities. Break-up on most rivers (like the Yukon River in Alaska) is monitored at the state level but is a federal responsibility (Canadian Coast Guard) on the heavily traveled St. Lawrence River. Federal agencies (e.g. USCG) can also become involved when navigation aides for the waterways are threatened. Fishing and hunting expeditions by local communities need information on shorefast and lake ice break-up. The user class in this hazard may also transition when individuals do become stranded on drifting ice. While local governments in some northern communities (like the North Slope Bureau in Pt. Barrow, Alaska) can provide the required coordination and resources for search and rescue efforts (ARCUS 1999), federal Search and Rescue assets are often called upon in other areas (e.g. central Canadian Arctic).

c) End User Requirements

As previously described, the operational detection of sea ice, icebergs and river/lake ice is vital to ensuring the safety of vessel operations and the commercial viability of the growing number of industries with activities in the polar regions. End user requirements for ice hazard information are quite diverse mainly due to the variability of applications. Spatial and temporal resolution of EOS data and associated ice guidance products are important to vessels that wish to avoid or exploit the ice. SAR imagery with its high resolution, wide swath, frequent revisit and all-weather capabilities is now the data of choice for many ice hazard users. Ice parameters of most frequent interest to vessels at sea include the location and size of icebergs, the location of the sea ice edge, concentration boundaries, stage of development, floe size and location and orientation of openings in the sea ice pack. Other developing applications require information on the extent of landfast, ice motion, amount of sea ice pressure ridging or topography, degree of ice compaction and the stage of decay during the summer melt season.

Generally, a ship's captain prefers to receive detailed, tactical-scale graphics or interpreted imagery rather than raw satellite images. This preference is based on the fact that expert ice analysts are found at the various national ice centers and generally not aboard ships. The greatest challenge to most national ice centers is to process the EOS data, interpret it and deliver an ice hazard product to the customer within at least 3-12 hours of acquisition. Additionally, most users desire short-term ice forecasts detailing expected changes in the ice over the next 24-72 hours.

Specific requirements for ice hazard parameters detailing present day thresholds and future objectives are listed in the table below.

Parameters	Threshold	Objective
Ice Edge Accuracy (absolute)	750 meters	50-100 meters
Ice Concentration Accuracy Ice Concentration Range	< 20% 1/10 to 10/10	< 5% 0 to 100 % (includes less than 1/10th of ice)
Ice Stage of Development (probability of typing correctly) Ice Stage of Development Range	70% Distinguish new, young, first-year and multi-year ice.	90% Distinguish 11 major gradations as defined in WMO nomenclature, between river, lake and sea ice (fresh and salty water)
Fast Ice Boundary Forms of Floating ice	Same as for ice edge 50-100 meters	Same as for ice edge 9 gradations as defined in WMO nomenclature
Ice Motion Accuracy Ice Motion Range	km/day 0-50 km/day	0.05 km/day 0-50 km/day
Timeliness	3-6 hours	< 3 hours
Sampling Frequency	24 hours	6 hours
Geographic Coverage	Poleward of 34^0 north and south of 50^0 south	Poleward of 34^0 north and south of 50^0 south

d) Observational Requirements

For each ice hazard application, EOS data needs have been identified. These requirements are listed in the table below.

Application	Spatial Resolution	Spatial Coverage (swath width)	Temporal Resolution	Tasking Time	Delivery Time
Sea and Lake Ice Detection for Avoidance	100m	500km	daily	72-168 hours	< 3 hours
Sea and Lake Ice Characterization for Exploitation (safety and mission effectiveness)	50m	300km	daily	72-168 hours	< 3 hours
Beset Vessel in Sea and Lake Ice	30m	150km	2x/daily	24-72 hours	< 3 hours
Iceberg Detection for Avoidance	10m	300km	daily	72-168 hours	<3 hours
Shorefast, Lake and River Ice Break-up	30m	150km	2x/daily	24-72 hours	< 3 hours

Assessment of Current and Planned Satellite Data

Earth Observation Satellites that provide data presently being used *operationally* for Ice Hazard monitoring fall into three major categories:

- Passive microwave satellites (DMSP SSM/I, OKEAN RM08) providing data used to produce coarse resolution (15-25 km) ice concentration/ice type gridded products. The SSM/I 85 GHz channel is also used to produce ice motion and ice concentration products.
- Visible/infrared satellites (TIROS AVHRR, DMSP OLS, various GOES Imager instruments) providing medium resolution (0.55-4.0 km) data.
- Active microwave satellites with Synthetic Aperture RADAR (SAR) instruments (RADARSAT, ERS-2) providing all-weather, high resolution (10-100 m). **Note**: The OKEAN Real Aperture Radar (RAR) provides 1.2 km spatial resolution data.

Planned or recently launched Earth Observation Satellites representing new sources of data (or presently available data in a research or demonstration mode) that are suitable for Ice Hazard monitoring include:

- Passive microwave satellites (DMSP SSM/IS, CORIOLIS, ADEOS-2 AMSR).
- Multi-spectral visible/infrared satellites (TERRA MODIS, ENVISAT MERIS,ADEOS-2 GLI).
- Active microwave satellites with SAR instruments (ENVISAT ASAR, RADARSAT-2 SAR, ALOS PALSAR) and scatterometers (QuikSCAT SEAWINDS, ERS-2, METOP, ADEOS-2)

Passive Microwave Satellites

The DMSP Block 5D-3/F-15 satellite carries an improved Special Sensor Microwave Imager with sounder (SSM/IS). As in previous instruments, SSM/IS measures radiances at 19, 22, 37 and 85 GHz. Most algorithms use the 19 and 37 GHz channels to extract ice concentration and ice type information. The sounder should provide coincident information on attenuation due to water vapor in atmosphere. Additionally, due to the higher spatial resolution (12.5 km) of the 85 GHz channel, some work has demonstrated that sequential SSM/I images can be used to generate ice motion estimates (Kwok et al 1998). The usefulness of the 85 GHz channel is limited by weather. CORIOLIS (United States), planned for launch in 2002 by the U.S. Navy is a passive microwave instrument with 5 bands (6.2, 10.7, 18.7, 23.8 and 37 GHz). ADEOS2(Japan), planned for mid-2001 launch by NASDA, will carry an Advanced Microwave Scanning Radiometer(AMRS), which is expected to provide a spatial resolution of less than 5 km.

Multi-spectral Visible/Infrared Satellites

TERRA (United States), launched in December, 1999 by NASA (as part of the Earth Observation System (EOS) program), carries the Moderate Resolution Imaging Spectrometer (MODIS) instrument. MODIS gathers high-quality data in 36 channels covering the visible, shortwave and longwave infrared bands (0.4-14 um). Taking advantage of the high radiometric resolution, NASA's MODIS Instrument Science team has developed the ICEMAP algorithm to produce an automated daily global sea ice extent map (by swath) at a 1 km spatial resolution (Riggs et al, 1999). The ICEMAP algorithm is based on the normalized difference between surface reflectance in the visible band and a shortwave-infrared band. Sea ice will also be mapped using emitted longwave thermal radiation. The Ice Surface Temperature (IST) algorithm is calculated using a split window technique method developed with AVHRR data (Key et al, 1997). Daytime gridded sea ice products will be produced using the ICEMAP/IST techniques while night-time products will be produced using only the IST technique. Data are presently being produced in the research mode with plans for operational use by national ice centers in late 2000/early 2001.

ADEOS-2 (Japan), planned for a mid-2001 launch by NASDA, will carry a multi-spectral Global Imager (GLI) instrument. The GLI, like MODIS, will have 36 channels that can be exploited to produce an automated sea ice product. ENVISAT is planned for a fall 2001 launch date by ESA and will carry a multi-spectral MERIS instrument.

Active Microwave Satellites

a) Synthetic Aperture Radar Satellites

- ENVISAT (Europe), planned for end-2001 launch by ESA, will carry an Advanced Synthetic Aperture Radar (ASAR) instrument. ASAR is a C-band, dual polarized instrument with beam steering (15-45^0 incidence angle) that allows collection of data in several different modes. Data collected in the standard mode will have a 100 km swath and 30 m spatial resolution, while the wide mode will have a swath of 405 km and 100 m spatial resolution. The latter mode is ideal for sea ice monitoring. It is also believed that alternating polarization will give improved ice edge/water discrimination over earlier single polarization SAR's (ERS-1/2 VV polarization; Radarsat-1 HH polarization). Cross polarization data are expected to be particularly useful in estimating topography and ice type discrimination (ESA, 1998).
- RADARSAT-2 (Canada), planned for mid-2003 launch by CSA, will carry an advanced C-band SAR characterized by quad polarization, beam steering in right and left directions, an increased downlink capability and a fine resolution (3 meter) mode in addition to all the same operating modes as Radarsat-1.
- ALOS (Japan), planned for a mid-2003 launch by NASDA, will carry a Phased Array type L-band SAR (PALSAR) with a cross-track pointing capability from 18-55^0 incidence angle and a ScanSAR mode with a 350 km swath and 100 m spatial resolution. ALOS will depend on two Data Relay Transmission Satellites (DRTS) and X-band downlink to ground stations for real-time data delivery to operational users.

b) Scatterometer Satellites

- QuikSCAT (United States), launched in June of 1999 by NASA, carries the SEAWINDS scatterometer. SEAWINDS is a specialized Ku band (13.4 GHZ) microwave radar that was designed to measure ocean-surface winds but can also be used to monitor ice over its 1,800 km swath. Using data from the NASA Scatterometer (NSCAT) mission, Long and Drinkwater (1999) have demonstrated that ice images with spatial resolutions of 8-10 km can be created using the Scatterometer Image Reconstruction with Filtering (SIRF) algorithm. Although the nominal resolution of the QuikSCAT SEAWINDS sensor is 30x50 km it is believed that similar resolution images can be created from QuikSCAT data.

- ERS-2 (Europe), launched in 1995 by ESA, carries a C-band scatterometer that can be exploited to map sea ice. Research and development by the Norwegian Meteorological Institute for the proposed EUMETSAT Ocean and Sea Ice Application Facility (O&SI SAF) is using the ERS-2 scatterometer data to map sea ice on a demonstration basis (Breivik et al, 1999). These data are combined with AVHRR and SSM/I data to produce ice maps with 10 km spatial resolution. METOP (Europe), planned for launch in 2003, will carry a C-band Advanced Scatterometer (ASCAT).
- ADEOS-2 (Japan), planned for a mid-2001 launch by NASDA, will carry SEAWINDS-2, a Ku band scatterometer that also can be used to generate ice all-weather, moderate resolution ice images. Like QuikSCAT, these data would serve as complimentary data sets to the coarser resolution passive microwave and high resolution SAR data to produce more accurate global-scale ice maps ideal for mission planning and climate research.

Future Improvements to Consider

As previously described, EOS data play an important and critical role in the mature application of operational sea ice mapping. The role of EOS data in iceberg detection and monitoring remains in the research and evaluation phase. Possible areas for improvement in sea ice mapping can be divided into four categories: *methodology, science, technology and data/product management.*

***Methodology*:**

- International Collaboration: While the WMO/IOC Joint Technical Commission on Oceanography and Marine Meteorology (JCOMM) has a Sea Ice Expert Panel that provides good international collaboration on standards for sea ice services, there is a need for increased cooperation with other national ice services on a more operational basis. The International Ice Chart Working Group (IICWG) was formed for this purpose and had its 1st meeting in October, 1999 in Copenhagen, Denmark, and continues to meet annually. This group will focus on improving the exchange of satellite data and products and initiating cooperative training activities. On a regional basis these activities have existed such as the Baltic Sea Ice Meeting (BSIM) since 1925 and the Joint Ice Working Group (U.S./Canada) since 1986.
- Access to EOS Data: New and updated mechanisms to improve access to satellite data should include satellite acquisition tools (and policies) that shorten time to schedule satellite acquisition of data and a shorter payload planning process for future satellites.
- Data Fusion Techniques: Recent studies indicate that substantial improvements in the quality of ice information derived from algorithms using EOS data can be achieved by using ancillary data and data fusion techniques. For example, Steffen (et. al., 1992b) stated that data assimilation and artificial intelligence (AI) methods offer the greatest promise for resolving ambiguities in passive microwave ice algorithms.
- Standard Product Formats: All national ice centers should produce standard digital formatted products (ice analysis graphics; annotated (interpreted) imagery and ice forecasts) that are user-friendly and GIS-compatible. This standardization effort should be directed at *operational customers* and separate from WMO-approved data archival formats (SIGRID-1/2). FGDC SDTS and IHO S-57 formats show promise but have gained little acceptance by the user community. Additionally, common digital coastlines are important for seamless exchange of information between national ice centers.

***Science*:**

- EOS Data Algorithms: New or improved sea ice/iceberg detection and sea ice classification algorithms are needed. Possibilities include developing an "expert" or AI system that classifies SAR data into ice types, SSM/I hybrid algorithms that account for natural variations in brightness temperatures associated with regional inhomogeneities of sea ice, SSM/I 85 GHz ice motion products, an ice/no ice cloud-masked visible/infrared product and a SAR-based iceberg detection algorithm.

- Ice Forecasting Models: Develop and implement regional (higher resolution) coupled ice/ocean/atmosphere forecasting models to improve sea ice forecasts in the Marginal Ice Zone (MIZ) and iceberg drift and ablation rates.

Technology:

- New and Improved Satellite Sensors: Use data from new sensors, such as multi-spectral radiometers and scatterometers. Improve ice mapping capabilities by taking advantage of improved sensors like SAR instruments with dual/quad polarization.
- Satellites with Multiple Instrument Payloads: Improve ice mapping capabilities through use of simultaneous data collection (for example, ENVISAT ASAR and MERIS; ALOS AVNIR-2 and PALSAR; satellite with multiple frequency SAR (L-,C- and X- bands).
- Satellite Revisit Time: Design right/left looking beam steering capability and optimum orbits to maximize revisit time and geographic coverage in ice-covered seas.
- Temporal Resolution of EOS Data: Improve delivery of processed imagery by requiring minimum real-time data processing and throughput standards at all participating ground stations. Consider use of onboard satellite data processors.
- Electronic Charts: Improve utility of ice information by producing ice analyses in electronic chart formats that can be integrated into ship chart display systems. The development and approval of international formats for display and distribution of the ice information to ECDIS will significantly increase safety of ice navigation.

Data/Product Management:

- Special EOS Data Policy: Request EOS data providers implement special data policies that allow for preferred and affordable access for national ice services and the production of ice hazard products.
- Outreach Programs: Establish outreach programs to educate customers on EOS data types, products available and the potential uses of each. Communicate to end-users the strengths and weaknesses of EOS data and ice guidance products.
- New and Improved Ice Guidance Products: Survey customer requirements to develop and implement new ice hazard products such as maps indicating state of ice decay and color-coded ice warning charts based on ship classes.
- Data/Product Dissemination: Improve efficiency of data networks through the use of state-of- the-art compression software.

The ice services are extremely dependent on the ground segment provided by satellite operators and receiving stations - e.g. the distribution of receiving stations. Likewise, affordable data continuity (e.g. SAR) is very important. Any gaps in the data between successive launches of SAR satellites could reduce the capability of many ice services.

Summary and Conclusions

It is well known that sea ice and icebergs pose a serious hazard to shipping and other maritime activities. The role of EOS data in operational ice monitoring is well documented and has grown in importance over the years. EOS data from visible/infrared sensors are readily available to all ice services but are useful only under cloud-free conditions. Passive microwave sensors can penetrate cloud cover but their effectiveness in ice monitoring is limited by coarse resolution. Active microwave sensors such as SAR's are ideal for ice mapping because of their high resolution, all-weather, wide swath ice detection capability. Investigations have also shown that these data are also valuable in their ability to quantify other ice parameters such as ice type (stage of development), ice topography and presence of open water or thin ice openings within the sea ice pack. Sea ice guidance products derived in real-time from these data are used operationally to ensure safety of navigation of non-ice strengthened vessels, maximize time and fuel savings of icebreaker lead convoys and to protect life and property associated with human activities on the ice.

In the future, new and updated EOS sensors provide great promise for improving the applications of sea ice mapping and iceberg detection. Data from multi-spectral visible/infrared radiometers and scatterometers will be used to generate automated sea ice maps. SAR satellites with right/left looking beam steering, multiple polarization modes and enhanced downlink capabilities will provide more valuable data in a shorter period of time to the end user. The coincident collection of EOS data from multiple instruments "fused" with ancillary environmental data can be used to resolve ambiguities and eliminate biases in conventional, single sensor algorithms. Data policies must exist for easy and rapid access to EOS data for ice hazard detection and monitoring. Lastly, collaborative efforts are needed between all the national ice services to ensure that EOS data are shared, that ice products are issued in standard formats and most importantly that customers are educated on the strengths, weaknesses and value of EOS data and Ice Hazard products.

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