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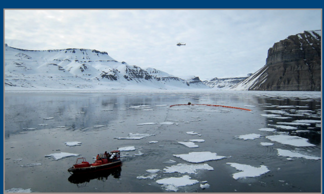
REPORT



Oil in Ice - JIP

Report no.: 15

Ice Regimes for Oil Spill Response Planning

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Preface

SINTEF has in cooperation with SL Ross Environmental Research Ltd and DF Dickins Associates LLC on behalf of the oil companies AGIP KCO, Chevron, ConocoPhillips, Shell, Statoil and Total initiated an extensive R&D program; *Joint industry program on oil spill contingency for Arctic and ice covered waters.* This program was a 3-year program initiated in September 2006 and finalized in December 2009.

The objectives of the program were;

- To improve our ability to protect the Arctic environment against oil spills.
- To provide improved basis for oil spill related decision-making:
- To advance the state-of-the-art in Arctic oil spill response.

The program consisted of the following projects:

- P 1: Fate and Behaviour of Oil Spills in Ice
- P 2: In Situ Burning of Oil Spills in Ice
- P 3: Mechanical Recovery of Oil Spills in Ice
- P 4: Use of Dispersants on Oil Spills in Ice
- P 5: Remote Sensing of Oil Spills in Ice
- P 6: Oil Spill Response Guide
- P 7: Program Administration
- P 8: Field Experiments, Large-Scale Field Experiments in the Barents Sea
- P 9: Oil Distribution and Bioavailability

The program has received additional financial support from the Norwegian Research Council related to technology development (ending December 2010) and financial in kind support from a number of cooperating partners that are presented below. This report presents results from one of the activities under this program.

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Funding Partners

R&D Partners

Cooperating Partners

SINTEF

REPORT

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Ice Regimes for Oil Spill Response Planning

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ABSTRACT

This study was undertaken for response planning purposes as part of Task 6.1 of the Joint Industry Program (JIP) "Oil Spill Contingency for Arctic and Ice-infested waters". In the case of the JIP, a more comprehensive understanding of ice conditions was seen to be necessary to successfully and more practically conduct two specific tasks:

1. tank and field testing of meso-scale oil spill response equipment
2. preparation of a generic oil spill response guide

In order to gain the insights needed by the JIP to generate realistic scenarios, the ice conditions were reviewed for nineteen regions where oil exploration and production (E&P) activities are either ongoing or planned. Using internationally accepted classification terminology to describe the ice, the immediate objective of the work became one of identifying ice regimes common to most circumpolar areas of the world.

There are some *overall* similarities in the ice conditions of the nineteen regions that have permitted grouping according to five ice regimes:

1. Arctic shallow semi-enclosed sea
2. Arctic open-sea
3. Arctic and Sub-Arctic coastal
4. Sub-Arctic estuary
5. Non-Arctic shallow sea

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1 Introduction

Planning oil spill response for marine operations in the Arctic and other cold weather regions requires detailed knowledge of the ice conditions expected to be present at a specific time of year in a particular geographical area. The consideration of ice information, together with oil and environmental data, allows “windows of opportunity” to be identified for countermeasures technologies that have a higher probability of being effective. Accurate information is essential on the ice: type, age, size, thickness, concentration, stage of growth or decay, and movement. Response systems can then be selected that not only are potentially appropriate but that can also be safely applied.

This study was undertaken for response planning purposes as part of Task 6.1 of the Joint Industry Program (JIP) “Oil Spill Contingency for Arctic and Ice-infested waters”. In the case of the JIP, a more comprehensive understanding of ice conditions was seen to be necessary to successfully and more practically conduct two specific tasks:

1. tank and field testing of meso-scale oil spill response equipment
2. preparation of a generic oil spill response guide

In order to gain the insights needed by the JIP to generate realistic scenarios, the ice conditions were reviewed for nineteen regions where oil exploration and production (E&P) activities are either ongoing or planned. Using internationally-accepted classification terminology to describe the ice, the immediate objective of the work became one of identifying ice regimes common to most circumpolar areas of the world.

It is important to note that the predominating ice features that occur in any region are, to a large extent, unique to a specific geographical location. Many factors influence the formation and movement of ice including the local climate, water depth and prevailing wind direction. Differences include seasonal variations at slightly different times and for different durations. Factors relating to recent declines in the extent of arctic ice further add to the complexities. It could be reasonably argued that any consideration of ice conditions is only relevant to a precise and individual location for a specified time period.

It should therefore not be surprising to expect potential problems in trying to apply knowledge of ice in one area to another area. For example, transferring the ice data of the high Arctic to oil spill response in the ice conditions off Sakhalin has been questioned in recent publications (De Cola et al., 2006 and Dickins Associates Ltd. 2006). Nevertheless, there are some *overall* similarities in the ice conditions of the nineteen regions that have permitted grouping according to five ice regimes:

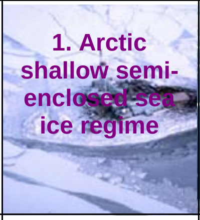
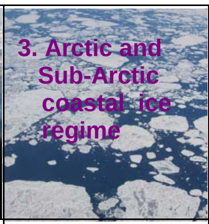
1. Arctic shallow semi-enclosed sea
2. Arctic open-sea
3. Arctic and Sub-Arctic coastal
4. Sub-Arctic estuary
5. Non-Arctic shallow sea

The five ice regimes are discussed in this report in a summarized format that includes applicable geographical areas, main features of the ice conditions, and further descriptions of the ice common to a region. Ice characteristics unique to individual locations within a region are of obvious importance and are also reported. Information is also presented on other aspects of ice, including seasonal and other variabilities. Appended data include ice classification systems, basic ice types, and ice climatology and reporting services.

2 Ice regimes

Basic features of the five ice regimes are summarized in Table 1 and then reviewed in more detail in this Section. The unique ice conditions that occur in specific areas of each region are discussed separately in Section 3.

Table 1 Summary Information for five ice regimes

	 1. Arctic shallow semi-enclosed sea ice regime	 2. Arctic open-sea ice regime	 3. Arctic and Sub-Arctic coastal ice regime	 4 Sub-Arctic estuary ice regime	 5. Non-Arctic shallow sea ice regime
Geographical areas	Beaufort Sea Chuchki Sea E. Siberian Sea Kara Sea Laptev Sea Pechora Sea White Sea	Barents Sea Greenland Sea Bering Sea	Baffin Bay & Davis Strait Labrador Sea Coast Grand Banks/ Newfoundland	Cook Inlet Gulf of St Lawrence	Bohai Bay N. Caspian Sea Japan/ East Sea Sea of Okhotsk
Ice characteristics (FY= first year ice MY = multi-year ice)					
Concentration	-8 to 9+/10 -up to 10/10 most of year	-4/10 in south -9/10 in north	4/10 to 9+/10	<3/10 to 9+/10 depends on season	- 4/10 to 9+/10 3 to 6 months -variable
Age	FY, some MY	-mostly FY -MY also possible	- FY medium -also FY thin, young, new ice	-mostly FY floes -no MY	FY or younger
Thickness	-FY 1.5-2 m -thicker pressure ridges, ice keels -MY to 4.5 m	FY 2 m MY 3-5 m	-mostly FY med.0.7-1.5 m -also FY thin.3-.7 m young .1-.3 m new <0.1 m	-wide range -mainly .7-1.2 m	-mainly thin 0.3 – 0.7 m -also medium 0.7-1.2 m
Type/size	-fast ice to 20 m depth with stamukhas, ridges, hummocks -transition (flaw) zone -pack ice -variable size -briefly ice free	-new ice, e.g. pancake and frazil -floe size Increases from ice edge -bergs in north -brash ice between floes	-floes dominate -small ice pieces 20–100 m to vast ice pieces 2–10 km -fast ice -pack ice with pressure ridges	-generally small ice pieces - pancake -brash -some fresh water ice - stamukhas	-smooth fast ice -rafting and pressure ridges - stamukhas
Movement	-mobile FY ice -slow pack ice -faster drift ice during break-up	-drifting floes usual in Marginal Ice Zone (MIZ)	-offshore pack mobile in winter -bergs drift south	-drift ice -tidal, current influences	dynamic ice further offshore

2.1 Arctic shallow semi-enclosed sea ice regime

Geographical areas

- Beaufort Sea
- Chuchki Sea
- East Siberian Sea
- Kara Sea
- Laptev Sea
- Pechora Sea
- White Sea

Figure 1 Freeze-up at Seal Island in the Alaskan Beaufort in mid-October with moving young ice. (Vaudrey, 2000)

Main features

- Long periods of intense cold and darkness
- High ice concentration (8 to 9+/10, up to 10/10) for most of year
- Thick (1.5 to 2 m) level ice with much thicker pressure ridges and ice keels
- Some multi-year ice
- Fast ice in water to 20 m deep
- Transition zone between fast ice and drifting floes of dense pack ice

Description of ice conditions

- Brief ice-free periods with rapid transitions through intermediate coverage of broken ice which is of short duration during freeze-up and break-up
- High pack ice concentration (8 to 9+/10, up to 10/10) is present for most of the year. Offshore sea ice in winter is thick, averaging 1.5 - 2.0 m, with thicker pressure ridges and hummocks. Some multi-year ice, up to 4.5 m thick, may be present from drift of Arctic pack.
- Ice-free periods are brief as are freeze-up and break-up when intermediate concentration of broken ice is present. Ice rapidly thickens and increases in coverage during freeze-up. Ice concentration rapidly decreases at break-up as ice floes form and drift away.
- There is extensive shore-fast ice near shore to a water depth of 15 – 20 m and pressure ridges, hummocks and stamukhas are often present. An interaction zone develops between the fast ice and drifting pack ice.

2.2 Arctic open-sea ice regime

Geographical areas

- Barents Sea
- Greenland Sea
- Bering Sea

Figure 2 Aerial view of ice in S. Greenland Sea

Main features

- Marginal Ice Zone (MIZ) develops with drifting ice
- Drifting ice floes in MIZ have ice concentration of 4/10 (in south) to 9+/10 (in north)
- Mean floe size increases with distance from ice edge
- Most ice is first-year ice; multi-year ice is also possible
- Ice thickness can be up to 2 m (first-year ice) and 3 - 5 m (multi-year ice)
- New ice, e.g., frazil and pancake ice, also present
- Brash ice occupies most areas between floes
- Occasional ice bergs in north

Description of ice conditions

- Ice exposed to open-ocean conditions at some locations produces a Marginal Ice Zone (MIZ). Drifting ice floes are the dominant feature of these regions with higher ice concentration (9+/10) in northern regions and less concentration (down to 4/10 or less) in the south. Mean floe size increases with distance from the ice edge. There is a seasonal movement of the MIZ, superimposed by locally prevailing wind conditions.

- Wave- and wind-induced break-up produces a mixture of broken floes of various sizes and smaller pieces known as brash ice. New ice such as frazil and pancake ice are also found. Brash ice occupies most of the surface area between the floes in the edge zone. For the transition zone, 5 - 65 km from the edge, the mean floe size in general increases with distance from the ice edge

- The most common type of ice is first-year ice. Multi-year ice can also be present. The ice thickness can be up to 2 m for first-year ice and 3 - 5 m for multi-year ice.

2.3 Arctic and Sub-Arctic coastal ice regime

Geographical areas

- Baffin Bay & Davis Strait
- Labrador Sea Coast
- Grand Banks / Newfoundland

Figure 3 Ice floes in Baffin Bay

Main features

- Ice concentration ranges from 4/10 to 9+/10
- Mostly first year medium ice (0.7 – 1.2 m thick) mixed with first year thin (0.3 – 0.7 m thick), young ice (0.1 – 0.3 m thick) and new ice (0 - 0.1 m thick).
- Floes are the dominant ice feature
- Ice floes range in size from 20 – 100 m to 2 – 10 km across and are repeatedly frozen together and broken apart
- Ice bergs from glaciers drift south

Description of ice conditions

- Sea ice is present for most of the year with nearly complete clearance of ice only in late summer. The ice is a mixture of mainly first year medium ice (0.7 – 1.2 m thick) with some first year thinner and younger ice also present. During the winter months, fast ice becomes well established along coasts.
- Floes are the dominant ice feature. The offshore pack remains mobile throughout the winter and the floes which range from small (ice pieces 20 – 100 m across) to vast (ice pieces 2 – 10 km across) in size are repeatedly frozen together and broken apart. A small percentage of old ice is usually present within the pack. Ice thickness is highly variable. The pack ice may contain floes of hummocked ice floes. Ice ridges up to 5 m high can develop. There are small floes near the ice edge, and larger floes in the interior of the pack.
- Icebergs are carried southwards by currents and originate from the calving fronts of tidewater glaciers in West Greenland. These can be an extreme hazard to shipping, but only about one in eight survives to enter the Grand Banks area.

2.4 Sub-Arctic estuary ice regime

Geographical areas

- Cook Inlet
- Gulf of St Lawrence

Figure 4 Ice floes in Cook Inlet-February 2006

Main features

- Ice concentration depends on location and season, ranging from less than 3/10 to 9+/10
- Wide range of ice thickness, mainly first year medium ice 0.7 – 1.2 m thick
- Drifting broken ice of generally smaller sizes
- Floes of first-year ice interspersed with a range of new ice forms, brash ice and smaller pancakes
- Some freshwater ice present

Description of ice conditions

- Ice is only present during the winter; the regions are completely ice-free in summer.
- The conditions governing ice formation, movement, and decay are complex and dynamic and greatly influenced by tides and tidal currents. Much of the ice remains broken.
- Openings between the larger, thicker floes are often choked with a mix of individual plates of ice crystals floating in the water (frazil), combining with ice cakes created through interactions between thicker floes (brash). Freshwater ice from a river and sea ice are present in the winter.

2.5 Non-Arctic shallow sea ice regime

Geographical areas

- Bohai Bay
- North Caspian Sea
- Japan / East Sea
- Sea of Okhotsk

Figure 5 Flat ice with ridges in N. Caspian Sea in late February/ early March

Main features

- Relatively short (3 to 6 months), variable ice season
- Ice concentration ranges from 4/10 to 9+/10
- Mainly thin (0.3 – 0.7 m thick) and medium (0.7 – 1.2 m thick) ice
- Rafting and pressure ridges present
- Stamukhas present in some locations

Description of ice conditions

- These areas only have ice present for 3 to 6 months of the year and are completely ice-free in summer.
- All sea ice is first year ice or younger. Ice concentration is seasonally variable and can be up to 10/10 concentration, but is generally thin ice, ranging from 0.3 to 1.0 m thick. The thin ice may be smooth near the shore.
- Further offshore the ice conditions are more dynamic and thick pressure ridges and rafting of ice may occur.

3 Special Features

The unique ice conditions that occur in specific areas of each of the five regions are discussed in detail in this section.

3.1 Arctic shallow and semi-enclosed sea ice regime

Beaufort Sea

The ice conditions in the Beaufort Sea have been studied extensively in relation to oil spill response, (e.g., Dickins, 1992, Dickins and Buist, 1999, SL Ross / Dickins Associates / Alaska Clean Seas, 2003 and Dickins Associates, 2004).

Figure 6 Beaufort ice hummocks

The degree of penetration of multi-year ice into the Beaufort Sea depends on the prevailing wind regime. On average, the boundary of the Arctic Pack lies from near Cape Prince Alfred south-westward to approximately 200 km north of Herschel Island and then westward approximately 200 km off the Alaska North Coast. Between the Arctic Pack and the coastal fast ice, mobile first year ice is predominant throughout the winter.

In June, melt begins in the Mackenzie Delta and an open water area also develops quickly there. Typically, Amundsen Gulf fractures in late June and the ice drift out and decay. The fast ice along the Tuktoyaktuk Peninsula fractures in early July, and by the end of the month an open water route usually develops from Mackenzie Bay to Cape Bathurst. Amundsen Gulf usually clears before August. West of the Mackenzie Delta to Point Barrow, a narrow shore or flaw lead develops in July, but the shallowness of the water and frequent onshore winds render it not navigable.

Open drift ice conditions do not develop along the coast until the first week of August and an open water route not until the first week of September. September is normally the best month for navigation in most of the Beaufort. During a cold summer, the shore fast ice along the Tuktoyaktuk Peninsula may not completely break until mid-July. These cold summers occur because north-westerly winds keep the Arctic Pack close to shore.

Chukchi Sea

The length of the ice-free season in 2003 varied at different locations in Chukchi Sea.

Table 3 Ice seasons in the Chukchi Sea

Location	Length of ice-free season (days)	Ice present (days)
Proliv Longa	55	310
Point Barrow	65	300
Bering Strait	171	194
Central Chukchi Sea	142	223

East Siberian Sea

Duration of the 2003 ice-free season varied at different locations in the E. Siberian Sea.

Table 4 Ice seasons in the East Siberian Sea

Location	Length of ice-free season (days)	Ice present (days)
Proliv Dmitriya Lapteva	26	339
Proliv Sannikova	35	330
N coast of Ostrov Kotel'nyy	45	320
N coast of Ostrov Vrangelya	29	336
Pevek	32	333
Ayon	49	316
Central East Siberian Sea	37	328

Kara Sea

The Kara Sea is shallow; large areas have a depth of less than 60 m. Fast ice is a feature of the Kara Sea (Sandven et al., 2001). Fast ice formation in the Kara Sea usually starts during October and it forms in the bays and along the coast. Maximum development of fast ice occurs in shallow waters with depth up to 20-25 m. At steep coastlines with deeper waters, the fast ice belt is narrow or absent. The photo at right was taken during a 2006 cruise (Sandven et. al. 2003).

Figure 7 Kara sea ice November'03

Laptev Sea

In June, the ice extent can sporadically reach values as low as 90% of the total area of the Laptev Sea, but almost every year it is above 95%. The south Laptev Sea is now likely to be totally free of ice in July. During an "average year," sea ice is 'exported' from the Laptev Sea through its northern and eastern boundaries, with maximum and minimum 'export' occurring in February and August, respectively. Sea ice was 'exported' into the East Siberian Sea mostly in summers.

Pechora Sea

The land fast ice zone in the Pechora Sea may extend 10-15 km offshore, reaching depths of 12-15 m. The maximum average thickness of the sea ice in the eastern part of the Pechora Sea is 1.1 m, but the absolute maximum is 1.6 m. The frequency of ice ridges increases from the shore to the external fast ice boundary and from the west to the east. Fast ice is not steady and fracturing occurs very often in winter. This may lead to the formation of hummock fields with as much as 60-80% of the sea surface being covered by ridges. The level ice thickness reaches 0.8 to 1.1 m. In the boundary of fast ice and drift ice zones, extensive hummocking takes place and grounded ridges (stamukhas) are formed. The ice conditions in the eastern part of the Pechora Sea are more severe than in the western part. In particular, the average duration of the ice season in the west is 185 days, while in the east it is 240 days (maximum 300 days).

3.2 Arctic open sea ice regime

Barents Sea

The most common type of ice in the Barents Sea is first-year ice. The ice thickness can be up to 2 m for un-deformed first-year ice and 3-5 m for multi-year ice. Multi-year ice floes have been observed on several occasions, but seldom south of Hopen Island. The ice conditions in the Barents Sea are well known to be affected by the prevailing atmospheric conditions (Sorteberg and Kvingedal, 2006).

Figure 8 Maxa Bay, Russia

The length of the ice-free season in 2003 varied at different locations in the Barents Sea.

Table 5 Ice seasons in the Barents Sea

Location	Length of ice-free season (days)	Ice present (days)
Around Bjørnøya	244	121
E coast Edgeøya	83	282
Nordkapp (Nordaustlandet)	61	304
Zemlya Frantsa Iosifa (approximately 80°N)	59	306
W coast N Novaya Zemlya (74°N–76°N)	191	174
W coast S Novaya Zemlya (71°N–73°N)	209	156
Central Barents Sea (72°N–76°N, 30°E–45°E)	286	79
Pechorskoy More	177	188

Greenland Sea

Multi-year ice in the Greenland Sea originates from the central Arctic Ocean and has spent one or more years circulating in this region before entering the Greenland Sea though Fram Strait. It is generally thick, highly deformed ice (Mikkelsen et al., 2001). Due to the dynamic nature of the Greenland Sea, numerous leads in the ice are formed during the winter. Fast ice is found only near the coast of Greenland and stays in place throughout the winter. It normally melts or breaks out in the summer.

Figure 9 Greenland ice July'06 (NASA)

Ice in the Greenland Sea is exposed to the open ocean on its eastern flank and thus has a much greater freedom of movement than that of ice in the semi-enclosed Seas in the Arctic Ocean. This exposes the ice to the turbulent action of the winds, waves and currents and therefore even in winter it rarely takes the form of a solid sheet, but is usually found in a much fractured state. Wave and wind induced break up leaves the ice as a mixture of broken floes and smaller pieces known as brash. New ice such as frazil and pancake ice are also found within this zone.
The only area in the Greenland Sea where new ice forms away from the east Greenland Continental Shelf, i.e. in deep water, is the Odden, or 'Isodden', region. This region is very exposed to the open ocean on three sides, the north, south and east. Consequently ice formed there rarely forms into large floes but due to the constant wave action the ice remains as small floes, less than 2 m in diameter, or pancake ice.

Bering Sea

Most of the sea ice forms in the northern portions of the Bering Sea shelf and is then blown southward due to the prevailing NNE winds. Ice melts at the edge when it moves into an area of water which is warmer than the freezing point. The photo at right was taken during a cruise in May 2006 (NOAA).

The melt conditions in the eastern Bering Sea have altered during the last thirty years. There were three distinct periods: 1972-1976 (cold), 1977-1988 (warm) and 1989-2001 (cool). During the cold period, ice extended south to St. Paul Island and stayed there for a month or more.

Figure 10 Bering pack ice

The climate changed dramatically from cold to warm in the Bering Sea in 1977 and in the warm period, from 1977-1988, the ice did not reach as far south and stayed in the southern area for 2-4 weeks less than it did in the previous period.

In the cool period from 1989 to 2001, sea ice again moved to the south, but it came and went very quickly. In the northern Bering Sea ice still remains late in the spring.

Table 6 Ice seasons in the Bering Sea

Location	Length of ice-free season (days)	Ice present (days)
N Bering Sea (between St Lawrence Is. and Bering St.)	198	167
N Bering Sea (immediately S of St Lawrence Is.)	211	154
Bristol Bay	284	81
Anadyrskiy Zaliv	180	185

3.3 Arctic and Sub-Arctic coastal ice regime

Baffin Bay

There are three major factors controlling the ice regime in Baffin Bay as outlined below:

Figure 11 Entrance to Hudson Bay

1. A relatively warm north-flowing current along the Greenland Coast. This current retard the time of ice formation in eastern Davis Strait, results in earlier spring break-up along the Greenland Coast to Cape York, and provides an early access route into "North Water".
2. A cold south-flowing current along the Baffin Island Coast. This water current results in early ice formation along the Baffin Island Coast, delayed spring break-up in the same area and a southward extension of ice-covered waters far beyond the limits of Davis Strait.
3. A major polynya in Smith Sound at the north end of Baffin Bay known as the "North Water". This polynya is maintained by northerly winds, water currents, and an ice bridge in the northern part of Smith Sound. Vertical mixing of the water column may also contribute to the formation of the "North Water". The "North Water" polynya which develops every year is always evident even during calm periods when it may be briefly covered with new or young ice.

Davis Strait

Many storms affect the area, and ice ridges up to 5 m high can easily develop under pressure caused by winds and currents. As a rule of thumb, ice keels are in the order of three times the vertical extent of associated ice ridges. Westerly winds are frequent so a flaw lead develops, while along the outer edge the ice organises into strips, patches and belts. In periods of persistent east to northeast winds, the ice compacts near the coast and ice deformation processes can be very intense. The photo at right was taken in March 2002 by Jacques Descloitres, MODIS Land Rapid Response Team, NASA.

Figure 12 Davis St. satellite photo

3.4 Sub-Arctic estuary ice regime

Cook Inlet

Semi-diurnal tides exceed 10 m and tidal currents exceed 4 knots. Tidal currents cause ice to converge in one area while diverging in another. Temperature, tide, and wind variations create a continuously changing distribution of floe sizes and ice thicknesses. Beach ice is composed of frozen mud exposed to the air by the ebbing tide. At flood tide, water in contact with the frozen mud also freezes.

Figure 12 Cook Inlet February 2006

Stamukhi are comprised of beach ice which has broken free, been deposited higher on the mud flats and frozen to the underlying mud. Ice floes floating toward the beach are caught on top of the higher piece of ice and as the tide recedes, the overhanging pieces break off, leaving a stack of layered ice. Estuary ice forms in estuaries and river ice in rivers: both are comprised of freshwater. River ice is much harder than sea ice and is unaffected by tidal action until spring break-up

Gulf of St Lawrence

The variation in ice conditions in the Gulf of St Lawrence are well documented and forecast (Canadian Ice Service, 2006). Ice thickness rarely exceeds the grey and grey-white stage in the Gulf during January with new ice predominating along the lee side of landmasses, particularly the north shore of the Gulf of St. Lawrence. River ice is shown in Figure 13 (Morse et. al. 2003) Scattered floes of fresh water ice and “batture” floes drift out of the St. Lawrence River into the Gulf of St. Lawrence throughout the ice season.

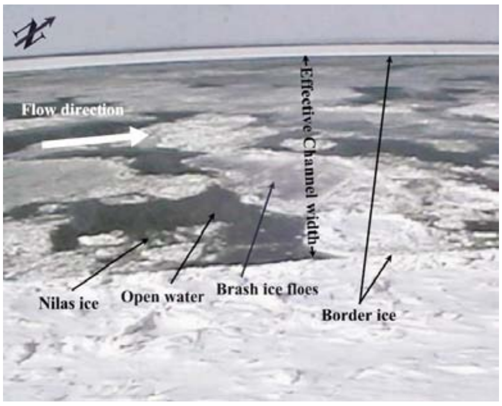


Figure 13 St. Lawrence River ice

“Batture” floes are large thick floes of mostly river ice that form on the upstream side of shoals in the St. Lawrence River when cold weather precedes the neap tide. The thickest ice in the Gulf of St. Lawrence is found in a triangle between the Magdalen Islands, P.E.I and Cape Breton Island, where pressure and ridging are also common. The thinner ice in the Gulf is usually found along the south facing shorelines of the north coast of the Gulf and along the south coast of Anticosti Island. These thinner ice areas form an important link in the shipping channel into the St. Lawrence River in winter

3.5 Non-Arctic shallow sea ice regime

North Caspian Sea (AGIP KCO, 2007)

Most of the Northern Caspian Sea is very shallow with a water depth ranging from 2 to 9 meters. The average water depth is 4.4 m. The northern sector covers approximately 25% of the total surface area of the sea but holds only 0.5% of the sea's water volume. The main source of water into the Caspian Sea is from the Volga River with about 80% of the total in-flow. Water level changes are common occurrences in the North Caspian, Sea induced by the wind drag on the water with a typical range of +/- 1 m. There are no significant tidal fluctuations and as a result the currents are wind induced.

Figure 14 A platform in N. Caspian

Because the North Caspian is near the southerly limit of ice formation, the conditions from year to year can vary considerably depending on weather patterns. Initial ice builds up in the shallow waters of the north-eastern part. Mid-winter in an average year ice extends just south of Kulali Islands with most of the areas to the north fully covered with ice. In a mild winter, the ice thickness may be limited to about 35 cm, whereas in an extreme winter, ice to 90 cm can be expected

Close to shore, ice in the Caspian Sea is smooth like river or lake ice and remains locked to the shore for much of the winter. The 'land fast' area is mainly along the coast from West of Ural to South of Kairan. This area is stable through most of the winter due to shallow water and area of ridges in its outer perimeter, anchoring the ice cover. Further offshore the ice conditions are more dynamic, and areas of pressure ridges and rafting is a common occurrence. Due to a generally thin snow cover, or even lack of it, rafting consisting of multiple layers is one of the characteristics of the North Caspian.

A common ice feature in the shallow Caspian Sea is grounded "mountains" of ice which are called stamukha. In the Kashagan area these may occur every few kilometres. Stamukha can be up to 200 m in length and are sometimes over 15 m high relative to the surrounding ice. Another ice process commonly seen is the gouging (or scouring) of the sea floor by grounded ice ridges which are pushed by the surrounding ice.

Northeast Sakhalin

The annual pack-ice regime is highly dynamic and variable (Sakhalin Energy, 2006). Tidal current superimpose circular ice movements and the average ice speed is expected to be 0.5 m/s, but speeds over 0.8 m/s can be reached 10% of the time. Level ice thickness is over 1.5 meters and ice ridges can be up to 30 m thick. The maximum ice concentration is reached in the middle of March; 80% of the total area is covered by sea ice. During the most severe winters the ice cover occupies up to 99% of the total sea water area, and in warm winters around 65%. In June, the average ice cover is about 2%.

4 Variation in ice conditions

4.1 Temporal variations

The ice conditions at any of the specific locations reviewed in Section 3 vary according to several different time scales:

- On a global and relatively long-term basis, it is known that the total area of ice in the Arctic Ocean has decreased and that this decrease has become more rapid in recent years. It is also thought that the average ice thickness in the Artic Ocean has also decreased in recent times (Richter-Menge et al., 2001), leading to a large decrease in volume of the ice (Rothrock and Zhang, 2005). There is currently great concern on the possible effects of global warming on Arctic ice conditions (Gerdes and Köberle, 2006). See Figure 15.

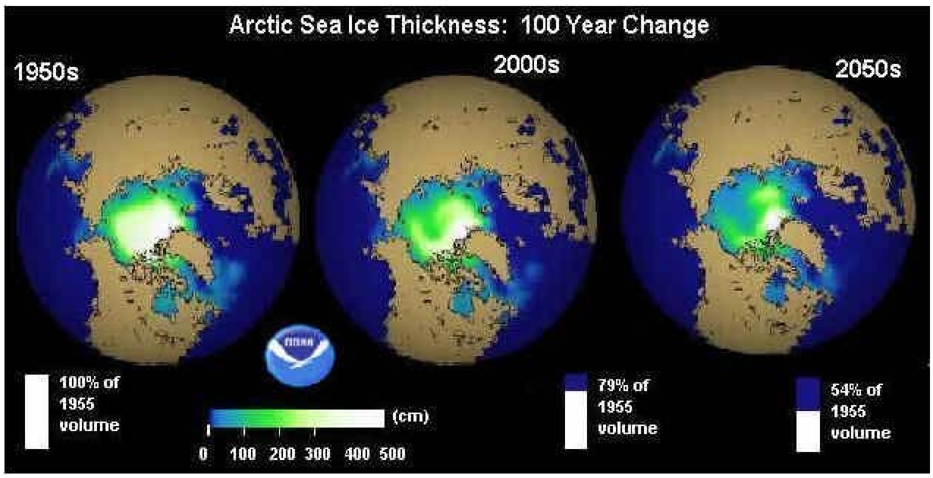


Figure15 Declining arctic ice (NOAA 2007)

- On a large scale, ice conditions at a particular location vary on a seasonal basis. There are discrete phases of freeze-up in the late autumn / early winter, persistence of ice during the winter and spring, ice-melt and clearance in summer and essentially open water conditions in the autumn. Although the precise dates of the onset of freeze-up and ice-melt vary from year to year because of variations in the prevailing meteorological conditions, there are known seasonal trends.
- On a more localized and short-term basis, ice conditions at a particular location can vary over much shorter periods of time under the influence of the prevailing winds, tides and currents. Pack ice on the sea will drift under the influence of the wind. These variations are much less predictable.
- In addition to the prevailing ice conditions caused by the air and sea temperatures plus wind and currents, the very localized ice conditions near any oil E&P activities may be modified by those activities. The use of artificial islands, ice-strengthened supply vessels, or ice breakers in support of E&P activities may alter the localized ice conditions.

4.2 Seasonal variations

Ice conditions at a particular location will vary with the season:

Freeze-up in autumn

Sea ice will start as frazil ice (ice crystals suspended in the water) as the air and sea temperatures decrease. The new ice will then develop through pancake ice (in rougher conditions) or nilas (in calmer conditions).

Subsequent development and thickening of the ice throughout the winter

Prolonged exposure to the low winter temperatures will result in a well-known sequence of increasing ice thickness from new ice (<10 cm thick), eventually up to thick first-year ice (>1.2 m – 2 m thick).

Sea ice can be broadly divided into fast ice (ice attached to land) and pack ice (ice on the sea). The extent of fast ice depends on the sea depth and characteristics of the coastline.

Pack ice will be separated from fast ice because of the effects of tides and currents. Pack ice drifts under the influence of wind and currents and forms ice floes composed of various sizes of floating ice that are dictated by the prevailing conditions. The pack will vary in ice concentration on the sea surface as the ice floes drift apart or are concentrated together by changes in the wind direction. New ice will form on the leads that open up between ice flows, but there may also be areas of open water caused by water up-wellings (polynas) or recurrent tidal breaks. Floes of ice that are compressed together will be deformed and this will cause ridges and hummocks of ice to be formed. Pack ice floes may drift far from the location where they formed because of the water circulation patterns within the Arctic Ocean and the influence of prevailing seasonal weather patterns caused by atmospheric pressure systems.

Break-up and melt of the ice in late spring

As temperatures rise, the ice will stop growing (increasing in thickness). Will warm and eventually will start to melt. Melt-water forms puddles on top of the ice and brine channels within the ice open up and the brine drains out leading to the ice losing strength and becoming ‘rotten’. Larger ice floes will survive longer in the warmer conditions than smaller ice floes and may drift further south.

In true Arctic areas, some of the ice will survive for more than one season and will become second-year or multi-year ice. Multi-year ice is much harder (and of lower salinity) than first-year ice and can increase in thickness to 3 m or more. Multi-year ice is transported from the Polar pack into the more southerly Arctic seas by the water circulation of the Arctic Ocean and can be transported between these seas and some multi-year ice may drift out even further south via the Barents, Greenland and Bering Seas. In sub-Arctic areas only first-year ice is formed and will not survive for more than one season.

Ice-free conditions in late summer

The ice will eventually clear from a particular location, either by melting or by the ice floes drifting from the location to somewhere else. There is then a period of ice-free water. In true Arctic areas some ice will remain throughout the summer and become incorporated as multi-year ice in the new ice that forms as winter approaches.

The timing of the onset and duration of these phases depends on latitude and precise geographical location. An example for the Alaskan Beaufort Sea is shown in Table 2.

Table 2 Seasonality of ice conditions, Alaskan Beaufort Sea (Glover and Dickins, 1999)

Month	**Process**	**Ice conditions**
Oct to Nov	Freeze-up: Increasing ice thickness, but storms can disrupt the forming ice sheet.	Frazil ice and young (new to thin) first-year ice
Nov to Feb	Ice sheet forming: Winter ice temperature still decreasing and ice sheet thickening.	
Dec to Apr	Stable solid ice thick enough to support vehicles	Late Dec: 1 m thick Apr: 1.5 – 2.0 m thick
Apr to May	Winter ice to melt: Ice temperature rising with brine drainage and ice becoming rotten	Thickness is stable.
May	First snow melt	
June	Melt pools Final deterioration of fast ice	
June and July	Break-up and ice clearing	Early July: 7 – 9/10 Late July: less than 3/10
Aug to Oct	Ice-free	

5 References

AGIP KCO (Rune Nilsen). 2007. Technical Note: General summary of North Caspian ice climate.

AIRSS (Arctic Ice Regime Shipping System) Pictorial Guide. TP14044E. 2003 CHC (Canadian Hydraulics Centre) / Transport Canada

Allen, A. A. and W. G. Nelson. "Oil Spill Countermeasures in Landfast Sea Ice." *Proceedings, 1981 Oil Spill Conference: Prevention, Behavior, Control, Clean-up:* American Petroleum Institute, Atlanta, 1981.

Canadian Ice Service / Environment Canada. 2006. Seasonal Outlook: Gulf of St. Lawrence and East Newfoundland Waters. Winter 2006-2007

DeCola, Elise, Tim Robertson, Sierra Fletcher and Susan Harvey. 2006. Offshore Oil Spill Response in Dynamic Ice Conditions: A Report to WWF on Considerations for the Sakhalin II Project. Alaska, Nuka Research

DF Dickins Associates Ltd. 2004. Advancing Oil spill Response in Ice Covered Waters. prepared for Prince William Sound Oil Spill Recovery Institute Cordova, Alaska *and* United States Arctic Research Commission Arlington, Virginia and Anchorage, Alaska

Dickins Associates Ltd. 2006. Preliminary Review Comments on "Offshore Oil Spill Response in Dynamic Ice Conditions: A Report to WWF on Considerations for the Sakhalin II Project" May 30, 2006

Dickins, DF. 1992. Behaviour of Oil Spilled at Sea (BOSS): Oil-in-Ice fate and Behaviour.

Dickins, DF and Ian Buist. 1999. Countermeasures for ice covered waters. Pure Appl. Chem., Vol. 71, No. 1, pp. 173–191, 1999.

Gerdes, R and Cornelia Köberle. 2006. Comparison of Arctic sea ice thickness variability in IPCC climate of the 20th century experiments and in ocean-sea ice hind-casts POAC'01 August 12-17, 2001 Ottawa, Ontario, Canada

Glover, NW and David Dickins. 1999. Oil Spill Response Preparedness in the Alaska Beaufort Sea 1999 International Oil Spill Conference, Seattle, WA

Mikkelsen, Naja, Preben Gudmandsen and René Forsberg. 2001. Studies of sea-ice conditions north of Greenland: results from a pilot *GRASP* initiative on the extension of territorial limits into the Arctic Ocean. *Geology of Greenland Survey Bulletin* 189, 127–131 (2001)

Morse, B. Hessami, M and C. Bourel. 2003. Characteristics of ice in the St. Lawrence River. Canadian Journal of Civil Engineering, Vol 30. pp766-774.

National Oceanic and Atmospheric Website (NOAA)

Richter-Menge, J and M. Hopkins, R. Lindsay, H. Melling, D. Perovich, I. Rigor, T. Tucker, A. Thorndike, J. Zhang. 2001. SEA ICE THICKNESS: THE GREAT INTEGRATOR. Large Scale Observations: a SEARCH workshop. November 27-29, 2001, Seattle, WA http://www.epic.noaa.gov/SEARCH/obs/workshop

Rothrock, DA and J Zhang (2005). "Arctic Ocean Sea Ice Volume: What Explains Its Recent Depletion?". *J. Geophys. Res.* 110 (C1): C01002.

Sandven, S, K. Kloster, Lundhaug, K.M., Dalen Ø, Alexandrov, V. and L. Bobylev. 2001. Study of fast ice in the Pechora and Kara Sea coastal region: Plan for work in AMETHYST project 2001-2002.

Sandven, S., Alexandrov, V. And K. Kloster. 2003 Service Demonstration in the Kara Sea 12 June-5 July 2003. Nansen Environmental and Remote Sensing Centre, Norway and Nansen International Environmental and Remote Sensing Centre, Russia.

Sakhalin Energy. 2006. SAKHALIN II: SUMMARY OF OIL SPILL RESPONSE IN ICE CONDITIONS September 2006. 35 Dzerzhinskogo St.,Yuzhno-Sakhalinsk,693020, Russian Federation

S.L. Ross Environmental Research Limited. 1983. Evaluation of Industry's Oil Spill Countermeasures Capability in Broken Ice Conditions in the Alaskan Beaufort Sea. Prepared for Alaska Department of Environmental Conservation. 1983.

SL Ross Environmental Research Ltd. and DF Dickins Associates Ltd. and Alaska Clean Seas. 2003. TESTS TO DETERMINE THE LIMITS TO *IN SITU* BURNING OF THIN OIL SLICKS IN BROKEN ICE. Report to the U.S. Minerals Management Service (MMS)

Sorteberg, A. and Børge Kvingedal. 2006. Atmospheric Forcing on the Barents Sea Winter Ice Extent. JOURNAL OF CLIMATE VOLUME 19. pp 4472 – 4784.

Timco, G.W. and I. Morin. 1998. Canadian Ice Regime System Database. Proceedings of Eighth (1998) International Offshore and Polar Engineering Conference Montreal, Canada, May 24-29, 1998 Proceedings ISOPE'98, Vol. II, pp 586-591

Timco, G.W. and I. Kubat. 2001.CANADIAN ICE REGIME SYSTEM: IMPROVEMENTS USING AN INTERACTION APPROACH Proceedings of the 16th International Conference on Port and Ocean Engineering under Arctic Conditions

Timco, G.W., R.M.W. Frederking and V. M. Santos-Pedro. 1997. A Methodology for Developing a Scientific Basis for the Ice Regime System. Proceedings 7th International Offshore and Polar Engineering Conference, ISOPE'07, Vol. 2, pp 498-503, Honolulu, USA, 1997.

Van Leeuwen, B. 2002. ENGINEERING APPROACH TO WATER LEVEL UNCERTAINTIES. Chapter 9, Proceedings of the 1st Workshop on the Caspian Sea, PHAJ

APPENDIX

A1. Overview

This Appendix contains descriptions of the sea ice that occurs in circumpolar areas and other regions with seasonal ice, information on the classification systems used to define ice conditions, and summaries of ice climatology and reporting services.

Background information on the most widely used ice classification system, namely, the code developed by the World Meteorological Organization (WMO), is the primary focus of this Appendix. WMO's so-called *Egg Code* is reviewed in Section A5, including the variables used to describe sea ice -- both in numerical terms and as illustrations (Figures A.1, A.2 and A.3). Section A5 also contains brief narrative descriptions of the various codes.

The WMO ice classification system was applied in this study to the review of the ice regimes relevant to the oil companies involved in the JIP so that all documentation was consistent. The overviews so produced should provide guidance not only understood by all participants but also useful in selecting specific ice conditions/scenarios for equipment tests and the response guide.

Table A.1 shows a reporting form that could be distributed to, and further used by, the JIP participants to more specifically define (or confirm) the predominant ice conditions in the areas where they have major interests.

Table A.1 Proposed report form of predominant ice conditions in a given area/location

Area/location	<Specify name of location>			
Filled in by	<Company>	<Signature>	<Date>	
Season	**Ice concentration**	**Stage of development [a]**	**Ice form [a]**	**Comments [b]**
<Specify month or range of months>	<Give range in tenths as described in Figure A.10>	<Use WMO nomenclature as listed in Figure A.11>	<Use WMO nomenclature as listed in Figure A.11>	<Include comments as needed>

[a] *Specify one predominant type, or list the most predominant in order of descending prominence.*
[b] *Comments may be used to indicate factors that are not included in the WMO ice code such as movement of ice – drift ice, fast ice, and deformation of ice – ridging and rafting)*

A2. The concept of 'ice regimes'

The World Meteorological Organization (WMO) classification system used for sea ice mapping was developed mainly to assist ship traffic through sea areas where ice is present. The WMO classification is based on three visually observable conditions or properties of ice:

1. Ice concentration on the sea surface (0/10, ice free through to 10/10 consolidated ice).
2. Stage of development and thickness (from new ice <10 cm thick to thick ice >1.2 m thick).
3. Form of ice (from pancake ice a few centimetres across up to vast ice floes 2 to 10 km long).

Combinations of these properties can be used to describe the ice regime at a particular location and time. When oil spill response in ice is considered, other conditions may be of equal importance, namely decay (melting, wave erosion), deformation of ice (ridging and rafting) and ice movement (ice drift).

The concept of ‘ice regimes’ has been used in the AIRSS (Arctic Ice Regime Shipping System) to relate the suitability of vessels for use in the Canadian Arctic (AIRRS, 2003). The ‘ice regime’ in the AIRSS Regulatory Standard is defined by the WMO classification system, plus an assessment of the Stages of Decay which are classified as ‘No Melt’ (winter), ‘Snow Melt’, ‘Ponding’, ‘Thaw Holes’ (drainage) and ‘Rotten’. Ice Roughness is also taken into account. Each of these factors is assigned a numerical value (either positive or negative) and the totalised value is related to ship ice class in a series of tables (Timco et al., 1997).

AIRSS takes into account a vessel's ability to travel safely in all types of ice conditions. Because different vessels have different capabilities in ice-covered waters, each vessel is assessed and assigned to a Vessel Class. This rating reflects the strength, displacement and power of the vessel. The relative risk of damage to a vessel by different types of ice is taken into account using "weighting" factors, called Ice Multipliers (Timco and Morin, 1998).

Although the AIRSS system is a comprehensive way of categorising ‘ice regimes’, its use is specific to vessel ice classification (Timco and Kubat, 2001). This would be useful for describing the required ice classification of vessels used in oil spill response (see Table A1), but the numerical system is not easily applicable to other aspects of oil spill response in ice.

Table A2 The Ice Multipliers for AIRSS for different ice class vessels

Ice Multipliers for each Vessel Class

Ice Types			Type Vessels					CAC	
			E	D	C	B	A	4	3
MY	Multi-Year Ice		-4	-4	-4	-4	-4	-3	-1
SY	Second Year Ice		-4	-4	-4	-4	-3	-2	1
TFY	Thick First Year Ice	> 120 cm	-3	-3	-3	-2	-1	1	2
MFY	Medium First Year Ice	70-120 cm	-2	-2	-2	-1	1	2	2
FY	Thin First Year Ice								
	stage 2	50-70 cm	-1	-1	-1	1	2	2	2
	stage 1	30-50 cm	-1	-1	1	1	2	2	2
GW	Grey-White Ice	15-30 cm	-1	1	1	1	2	2	2
G	Grey Ice	10-15 cm	1	2	2	2	2	2	2
NI	Nilas, Ice Rind	< 10 cm	2	2	2	2	2	2	2
N	New Ice	< 10 cm	"	"	"	"	"	"	"
	Brash (Ice fragments)		"	"	"	"	"	"	"
	Bergy Water		"	"	"	"	"	"	"
	Open Water		"	"	"	"	"	"	"

Ice Decay: If MY, SY, TFY or MFY ice has Thaw Holes or is Rotten, add 1 to the IM for that ice type.

Ice Roughness: If the total ice concentration is 6/10s or greater and more than one-third of an ice type is deformed, subtract 1 from the IM for the deformed ice type.

A3. Nature of data applied to characterize sea ice

According to WMO publication 574 on sea ice information services in the world, broad knowledge of the extent of sea ice cover depends on instrument, and to a lesser extent, visual observations. The instrument observations are made by conventional aircraft and coastal radar, visual and infra-red airborne and satellite imagery, and more recent techniques, such as passive microwave sensors, laser airborne profilometer, scatterometer, side-looking (airborne) radar (SLAT/SLR) or synthetic aperture radar (SAR, satellite or airborne).

Earth-orbiting meteorological satellites are now the most important and predominant mode of observing sea ice – but there are some restrictions. Satellite coverage may be broad at low resolution or cover a narrow swath at high resolution. In the latter case, data from a particular location may be obtained only at temporal intervals of several days. In general, most meteorological satellites provide complete coverage of Polar Regions once or twice a day. The satellites provide visible and infrared imagery with resolution of 250 m – 1 km, and passive microwave or scatterometer data at resolutions of 6 – 70 km. Visible and infrared data do not have cloud-penetrating capability, while microwave data are practically cloud independent. Active microwave SAR data have much better ground resolution, but a reduced coverage due to narrow swathes and greater revisit times. Figure A1 is an example of satellite imagery of ice.

Manual or visual interpretation of imagery from visible and infrared sensors requires a certain amount of skill, and interpretation of SAR images may be even more difficult. Therefore, in recent years automated digital processing techniques have been developed to aid in the interpretation of satellite data. While space-borne sensors can provide precise data on the location and type of ice boundary, ice concentrations and the presence or absence of leads, less accurate information is provided on the sea ice stages of development, stages of ice melting and ice surface roughness. Ice drift over approximately 12-24 hour intervals can often be determined through use of imagery from sequential orbits.

The following excerpt from WMO publication 574 provides the official definition of the various ice parameters (Section A4). In the subsequent section (A5), these descriptions are supplemented with definitions and pictures of the ice codes used in ice maps (the Egg Code).

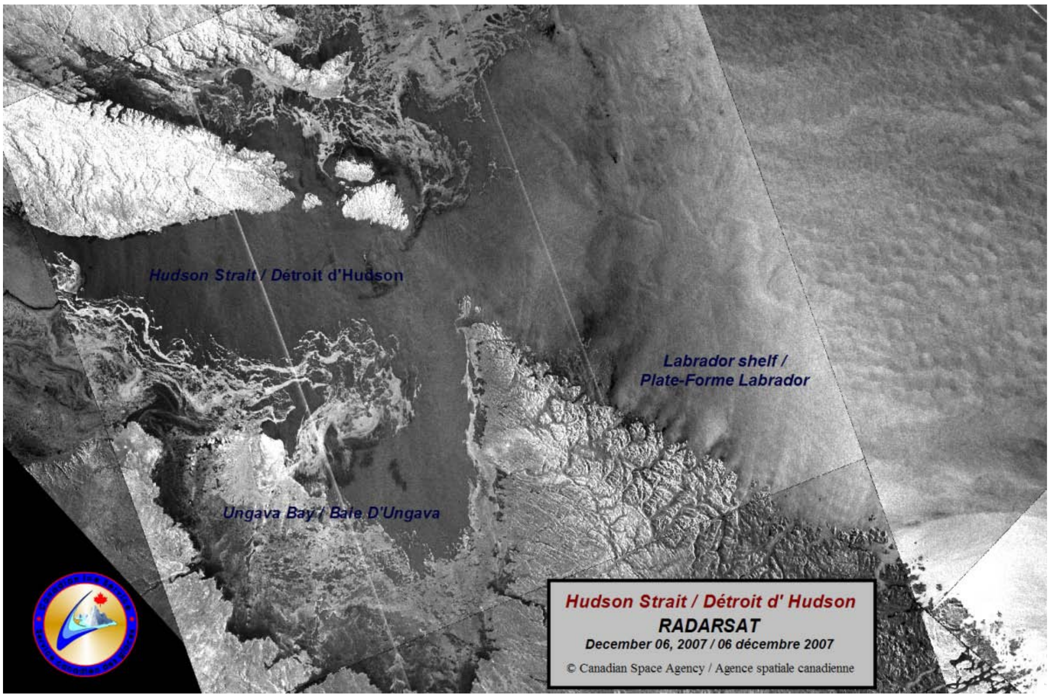


Figure A1 Canadian satellite imagery of ice - December 2007

A4. Ice development stages and types

The nature of sea ice

Several forms of floating ice may be encountered at sea. The most common is that which results from the freezing of the sea surface, namely sea ice. The other forms are river ice and ice of land origin. River ice is encountered in harbours and estuaries where it is kept in motion by tidal streams and normally presents only a temporary hindrance to shipping. Ice of land origin in the form of icebergs is discussed separately below.

Both icebergs and sea ice can be dangerous to shipping and always have an effect on navigation. Sea ice also influences the normal processes of energy exchange between the sea and the air above it. The extent of sea ice cover can vary significantly from year to year and has a great effect both on adjacent ocean areas and on the weather over large areas of the world. Its distribution is therefore of considerable interest to meteorologists and oceanographers.

Formation and development of sea ice.

Ice less than 30 cm thick


Figure A.2 Frazil ice

The first indication of ice formation is the appearance of small ice spicules or plates in the top few centimetres of the water. These spicules, known as frazil ice, form in large quantities and give the sea an oily appearance. As cooling continues, the frazil ice coalesces to form grease ice, which has a matt appearance. Under near-freezing, but as yet ice-free conditions, snow falling on the surface may result in the sea surface becoming covered by a layer of slush. These forms may be regrouped by the action of wind and waves to form shuga. All are classified as new ice.

With further cooling, sheets of ice rind or nilas are formed, depending on the rate of cooling and on the salinity of the water. Ice rind is formed when water of low salinity freezes into a thin layer of brittle ice which is almost free of salt. Ice rind may have thickness up to 5 cm. At the same time when water of high salinity freezes, especially if the process is rapid and the wind is very light, the ice has an elastic property which is characteristic of nilas. Nilas is subdivided, according to its thickness, into dark and light nilas; dark nilas reach thickness of 5 cm, while light, more advanced stage reaches a maximum thickness of 10 cm. Ice rind, dark and light nilas may be referred to as nilas ice.


Figure A.3 Nilas ice

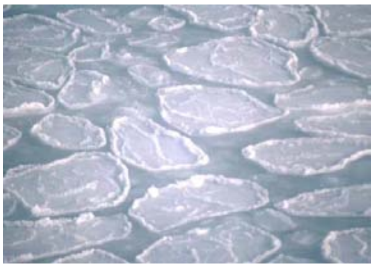


Figure A.4 Pancake ice

Pancake ice may form in the boundary between two water layers of different salinity - the lower layer with a high salinity has a temperature below the freezing point of the upper layer of lower salinity. Eventually the pancakes will surface due to buoyancy forces. 'False' pancake ice may be formed by the breaking up of nilas or ice rind due to the action of wind and waves. It must be noted that the process of pancake ice formation still requires investigation due to lack of observations.

Ice rind, nilas or pancake ice may thicken into grey ice and grey-white ice, the former having thicknesses of 10-15 cm and the latter attaining thicknesses up to 30 cm. These forms of ice are referred to collectively as young ice. Rough weather may break this ice up into ice cakes, pancake ice, or floes of varying size.

Ice 30 cm - 2 m thick

The next stage of development is known as first-year ice (FY) and is subdivided into thin, medium and thick categories. Thin first-year ice has a thickness of 30-70 cm and is subdivided according to its thickness into thin first-year ice first stage (30-50 cm) and thin first-year ice second stage (50-70 cm). Medium first-year ice has a range of thickness of from 70 to 120 cm while in polar areas thick first-year ice may attain a thickness of approximately 2 m at the end of the winter.

Figure A.5 Thin first year ice

Old ice

Thick first-year ice may survive the summer melt season and is then classified as old ice (MY). This category is subdivided into second-year and multi-year ice depending on whether or not the floes have survived one or more summers. The thickness of old ice is normally in the range 1.2 to 5 m or more prior to the onset of the melt seasoning. Old ice may often be recognized by a bluish surface colour in contrast to the greenish tint of first year ice.

Figure A.6 Thick first year ice

Decay of sea ice

During the winter the ice usually becomes covered with snow of varying thickness. While this snow cover persists, almost 90% of the incoming radiation is reflected back to space. Eventually, however, the snow begins to melt as air temperatures rise above $0^{o}C$ in early summer and the resulting fresh water forms puddles on the surface. These puddles absorb (instead of reflect) about 90% of the incoming radiation and rapidly enlarge as they melt the surrounding snow or ice. Eventually the puddles penetrate to the bottom surface of the floes and are known as thaw holes. This decay process is characteristic of ice in the Arctic Ocean and seas where movement is restricted by the coastline or islands. Where ice is free to drift into warmer waters (e.g., the Antarctic and the Labrador Sea) puddling is less prevalent and decay is accelerated by wave erosion as well as warmer air and sea temperature.

Movement of sea ice

Sea ice is divided into two main types according to its mobility. One type is drift ice, which is continually in motion under the action of wind and current stresses; the other is fast ice, attached to the coast or islands, which does not move.

Wind stress in the drift ice causes the floes to move approximately in a downwind direction. The rate of movement due to wind drift varies not only with the wind speed, but also with the concentration of the drift ice and the extent of deformation (see below). In very open ice (1/10-3/10) and open ice (4/10-6/10) there is much more freedom to respond to the wind than in close ice/pack ice (7/10-8/10) and very close (9/10-10/10) where free space is very limited. No water is visible within the compact ice (10/10) or consolidated ice (10/10) where the floes are frozen together. 2% of the wind speed is a reasonable average for the rate of ice drift caused by the wind in close ice, but much higher rates of ice drift may be encountered in open ice. Since it is afloat, a force is exerted on drift ice by currents that are present in the upper layers of the water, whether these are tidal in nature or have a more consistent direction due to other forces. It is usually very difficult to differentiate between wind- and current-induced ice drift but in any case where both are present the resultant motion is always the vector sum of the two. Wind stress normally predominates the short term movements, particularly in offshore areas, whereas the average long term transport is dominated by the prevailing surface currents.

Deformation of sea Ice

Figure A.7 Beaufort hummocks

Where the ice is subjected to pressure its surface becomes deformed. In new and young ice this may result in rafting as one ice floe overrides an adjacent floe; in thicker ice it leads to the formation of ridges and hummocks according to the pattern of the convergent forces causing the pressure. During the process of ridging and hummocking, when pieces of ice are piled up above the general ice level, large quantities of ice are also forced downward to support the weight of the ice in the ridge or hummock. The underwater parts may be termed respectively ice keel and bummock.

The draught of a ridge can be three to five times as great as its height and these deformations are thus major impediments to navigation. Freshly-formed ridges are normally less difficult to navigate than older, weathered and consolidated ridges.

Icebergs

Figure A.8 Arctic ice berg

Icebergs are large masses of floating ice derived from glaciers. The underwater mass and draught of a berg, compared with its mass and height above water varies widely with different composition and shapes of bergs. The underwater mass of an Antarctic iceberg derived from a floating ice shelf is usually less than the underwater mass of icebergs originating from Greenland glaciers. A typical Antarctic tabular berg, of which the uppermost 10-20 m is composed of old snow, will show one part of its mass above the water to five parts below.

The above water/below water ratio for an Arctic berg, composed almost wholly of ice with much less snow is generally smaller, namely, one to seven. However, because of their irregular shape, the latter icebergs have a height-to-draught ratio averaging 1:3.

Icebergs diminish in size in three different ways: by calving, melting and combined melting plus erosion caused by wave action. A berg is said to calve when a piece breaks off; this disturbs its equilibrium, so that it may float at a different angle or it may capsize. Large underwater projections, which may be difficult to observe, are a usual feature of icebergs in any state. In cold water, melting takes place mainly at the water line while in warm water a berg melts mainly from below and calves frequently. It is particularly dangerous to approach a berg in this state for it is unstable and may fragment or overturn at any time. There are likely to be many growlers and bergy bits around rapidly disintegrating icebergs, which form a particular hazard to navigation. Weathered bergs are poor reflectors of radar pulses and cannot always be detected by these means. Their breakdown fragments - bergy bits and growlers - are even more difficult to detect with ships' radar for the background clutter from waves and swell often obscures them. These smaller fragments are especially dangerous to shipping for, despite their low profile they represent sufficient mass to damage a vessel, which comes into contact with them at normal cruising speed. Some growlers consisting of pure blue ice hardly break the sea surface and are extremely difficult to detect.

A5. WMO's system of sea ice classification - the "Egg Code"

The following illustrations of ice codes are from MANICE, *Manual of Standard Procedures for Observing and Reporting Ice Conditions*, Canadian Ice Service – Environment Canada http://ice-glaces.ec.gc.ca

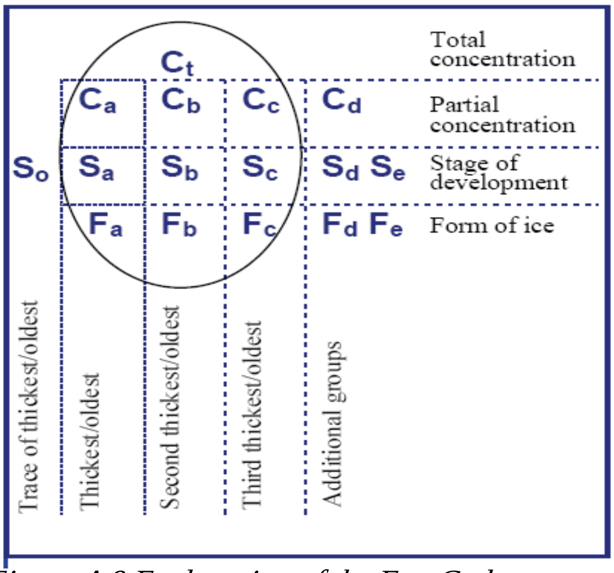


Figure A.9 Explanation of the Egg Code

Note that a set of one digit numbers is used to characterize concentration (C_a, C_b, C_c), stage of development (S_a, S_b, S_c) and form of ice (F_a, F_b, F_c) from the thickest/oldest to the less thick/younger ice.

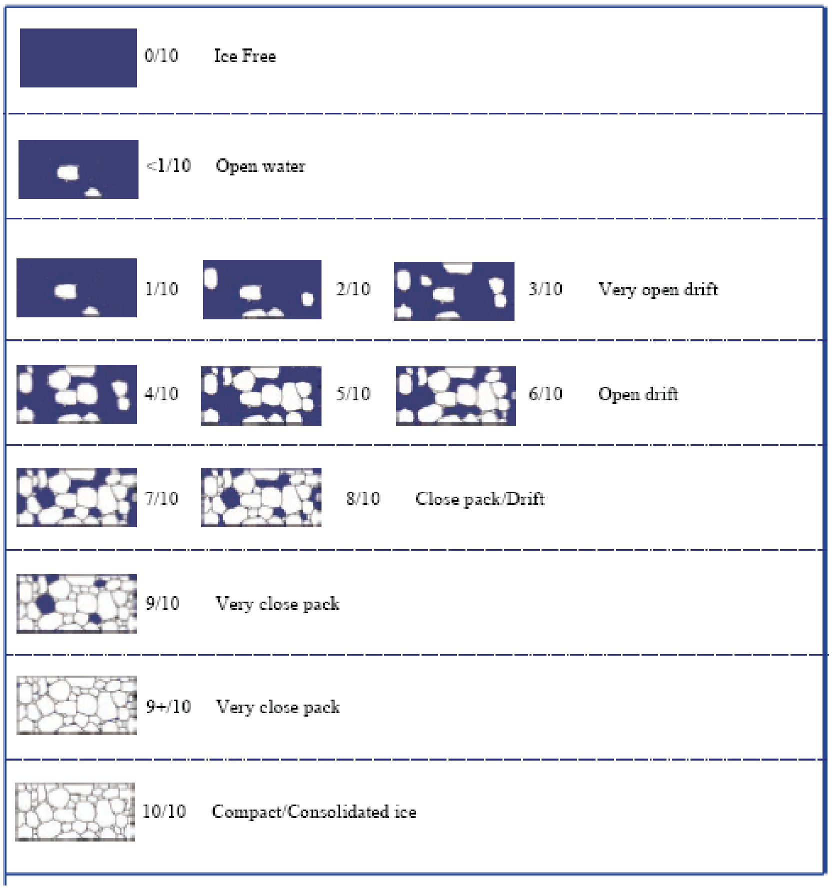


Figure A.10 Illustration of ice concentrations

Ice codes for stage of development and form of ice

Stage of development (S_a, S_b, .)

Egg coding for SEA ICE stages of development
Egg Code section 3

Description	Image	Thickness	Code
New ice		<10 cm	1
Nilas, Ice rind		0–10 cm	2
Young ice		10–30 cm	3
Grey ice		10–15 cm	4
Grey-white ice		15–30 cm	5
First year ice		= or >30 cm	6
Thin first-year ice		30–70 cm	7
Thin first-year ice, first stage		30–50 cm	8
Thin first-year ice, second stage		50–70 cm	9
Medium first-year ice		70–120 cm	1.
Thick first-year ice		>120	4.
Old ice			7.
Second-year ice			8.
Multi-year ice			9
Ice of land origin			▲
Unknown, undetermined			X

Form of ice (F_a, F_b,..)

Egg coding for floe sizes
Egg Code section 4

Description	Image	Width	Code
Pancake ice			0
Small ice cake, brash ice		<2 m	1
Ice cake		2-20 m	2
Small floe		20–100 m	3
Medium floe		100–500 m	4
Big floe		500–2000 m	5
Vast floe		2–10 km	6
Giant floe		>10 km	7
Growlers* and Bergy Bits*			8
Icebergs*			9
Undetermined or unknown			X
Ice in strips			∩∪

Figure A.11 Illustrated description of ice codes for stage of development and form of ice. (To get the full size pictures, go to Environment Canada web site http://ice-glaces.ec.gc.ca . Choose e.g., English, Ice Codes, Egg Code, and Egg Code Tables and click on the thumbnail pictures.)

A6. Field guide for arctic oil spill response

The WMO ice code comprises three main parameters – ice concentration, stage of development and ice form or size, each given numerical values according to a standardized system (see Figures A.9 and A.10). A more pragmatic approach to sea ice characterisation was used in the Field Guide for Oil Spill Response in Arctic Waters (ref).[1] In the Field Guide, stages of ice development are defined in terms of seasons – open water, freeze-up, frozen conditions, and break-up – each comprising certain possible ice forms (ice floes, broken ice, frazil/grease ice, slush, pancake ice, brash ice, ice hummocks, melt pools, leads). Different locations of oil are considered for the various seasons – oil on sea surface, oil between broken ice, oil under ice, submerged oil, and oil in melt pools as illustrated below. It should be noted that some of the terms used here to define ice conditions are not included in the WMO classification system.

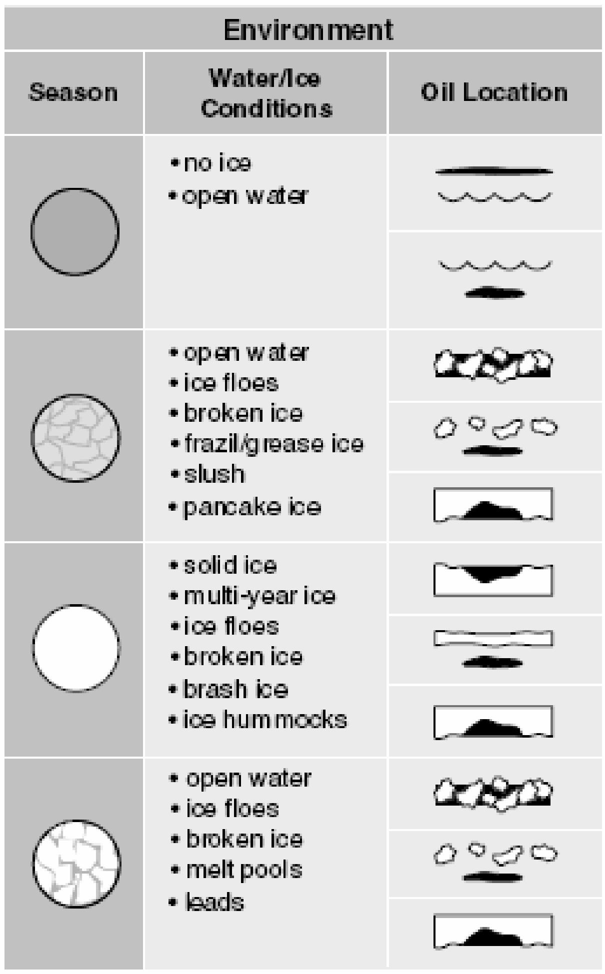


Figure A.12 Ice conditions as defined in Field Guide for Oil Spill Response in Arctic Waters.

[1] The Field Guide was prepared for the Emergency Prevention, Preparedness and Response Working Group (EPPR) within the Arctic Environmental Protection Strategy (AEPS) which was adopted by Canada, Denmark/Greenland, Finland, Iceland, Norway, the Russian Federation, Sweden and the United States through a Ministerial Declaration at Rovaniemi, Finland in 1991.

A.7 Sea ice reporting and ice climatology

Ice reports and forecasts

WMO's publication 574 on sea-ice information also includes descriptions of regional and national practices on sea ice reporting and forecasts. Countries with severe seasonal ice conditions generally provide ice maps on a daily to weekly based on analysed satellite imagery and supplementary information from aircrafts and vessels (Figure A.13). In some countries, ice forecasts are made typically 5 to 7 days in advance using numerical sea ice models, and contain fields of ice thickness, concentration and velocity, location of ice edge and ice ridges (Figure A.14).

The national services of interest in the present context are as follows:

Table A.2 National Ice Services

Region and country	Main area	Main provider	Output products
Northern Hemisphere			
China	Bohai Sea	National Marine Environment Forecast centre (NMEFC)	Remote sensing image, daily analyzed ice charts, five day numerical ice formation and ice drift forecasts.
Japan	Sea of Okhutsk	Japan Meteorological Agency (JMA), Japan Coast Guard (JCG)	Analyzed ice charts and numerical ice formation and ice drift forecast twice a week
Russian Federation	Arctic area, Baltic Sea, Caspian Sea, and Okhotsk Sea.	Arctic and Antarctic Research Institute in St Petersburg (AARI), Hydro-Meteorological Centre in Moscow	General ice charts and numerical ice formation and ice drift forecasts issued weekly. Daily charts for Gulf of Finland
North-east Atlantic and Baltic Seas areas			
Denmark	Greenland waters	Danish Meteorological Institute	Analyzed ice charts updated daily to weekly for smaller areas. Summary chart for all Greenland waters once a week
Estonia	Gulf of Finland, Gulf of Riga, Baltic Sea	Estonian Meteorological and Hydrological Institute (EMHI)	Analyzed ice charts in the Baltic Ice Code issued daily. One-day forecasts produced by statistical methods
Finland	Baltic Sea	Finish Institute of Marine Research (FIMR)	Analyzed ice charts issued daily during the ice season. 54 hours numerical ice formation, deformation (ridging and rafting) and ice drift forecasts.
Germany	German Bight and Baltic Sea west of Bornholm	Federal Maritime and Hydrographic Agency (BSH)	Analyzed ice charts and 48 hour numerical ice formation and ice drift forecasts three time a

Region and country	Main area	Main provider	Output products
			week in ice season
Iceland	Icelandic waters (Greenland Strait and Island Sea)	Iceland Meteorological Office	Ship reports prepared for display on Internet (ice charts). No forecasts
Latvia	Latvian Baltic Sea, Gulf of Riga	Latvian Hydro-meteorological Agency (LHMA)	Daily plain language reports, ice charts on a less regular basis. No forecasts
Lithuania	Gulf of Riga, Gulf of Finland, the Belt Sea, and the Curonian Lagoon	Centre of Marine Research (CMR)	Daily marine bulletin, maps provided on request. Forecasts-warnings to shipping and fishing companies for the Lithuanian port and the Curonian Lagon
Norway	Atlantic part of Arctic, covering east coast of Greenland to the western coast of Siberia, with emphasis on Svalbard	Norwegian Ice Service at Norwegian Meteorological Institute (met.no)	Ice charts issued daily. High resolution ice charts for Svalbard area. Numerical forecast model tested on a preoperational basis
Poland	Baltic Sea, Kattegat and Skagerak	Institute of Meteorology and Water Management, maritime Branch	Ice charts prepared twice a week. Subjective 35-hour ice forecasts
Sweden	Gulf of Bothnia, Baltic Proper, Gulf of Finland, Gulf of Riga, the Sound and the Belts, Kattegat, Skagerak	Swedish Meteorological and Hydrological Institute (SMHI)	Analyzed ice charts issued daily. Five day numerical ice formation and ice dynamics forecasts: ice drift, ice concentration, ice deformation and amount of ridging
North America			
Canada	Arctic areas, Gulf of St. Lawrence, Great Lakes	Canadian Ice Service at Meteorological Service of Canada	Regional weekly ice charts, daily detailed ice charts for specific areas
North American Ice Service	Great lakes	US National Ice Centre and Canadian Ice Service	Weekly ice charts. 30 day forecasts/outlooks
United States	Great Lakes, Alaskan waters, West and East Arctic, Ross Sea-McMurdo Sound	National Ice Centre (NIC) supported by National Oceanic and Atmospheric Administration (NOAA), U.S. Navy and U.S. Coast Guard	Digital ice charts produced for different areas on daily to bi-weekly basis. 48 hour forecasts of the ice edge location (Arctic region)

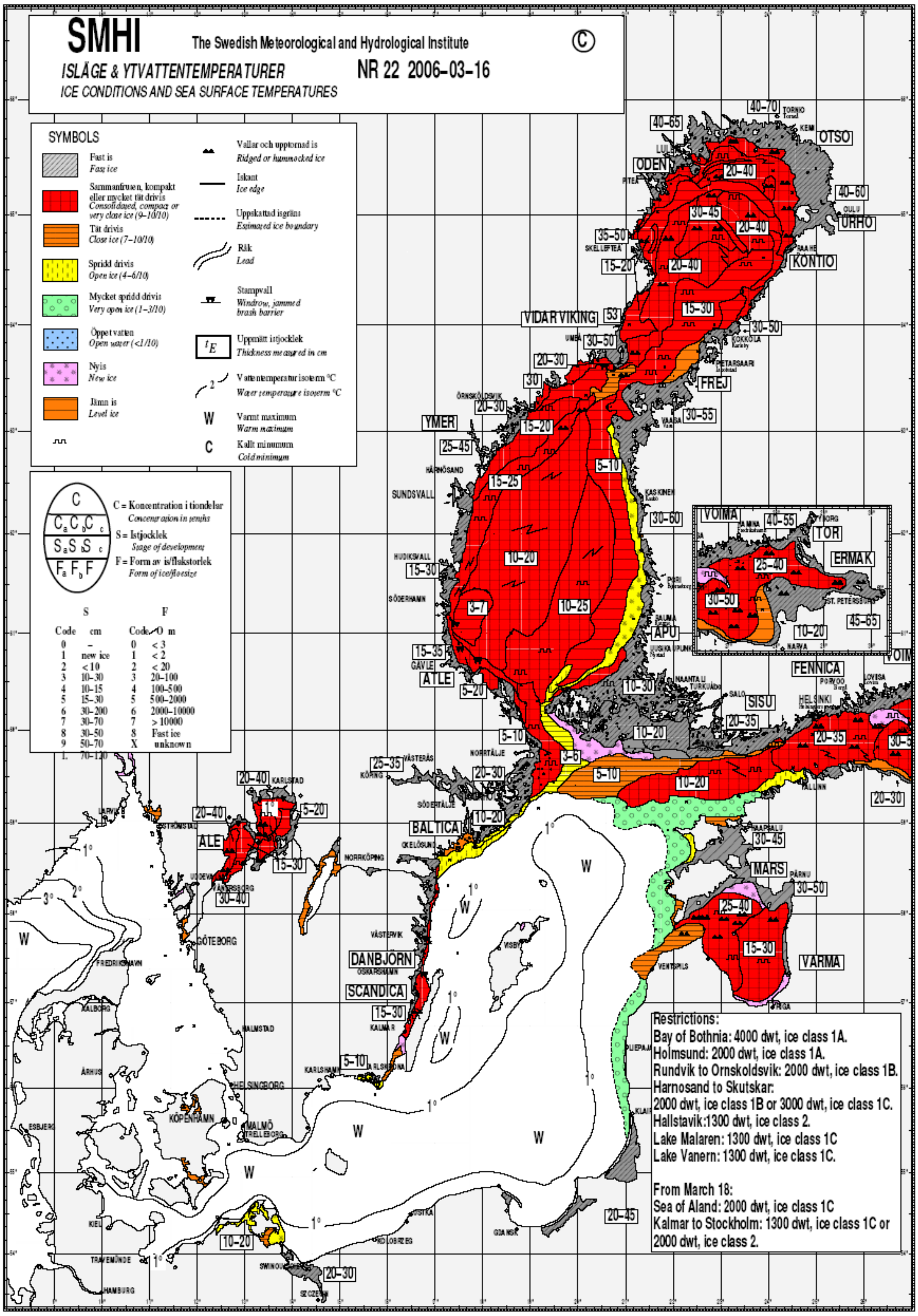


Figure A.13 Example of colour-coded ice maps issued daily by SMHI for the Baltic Sea.

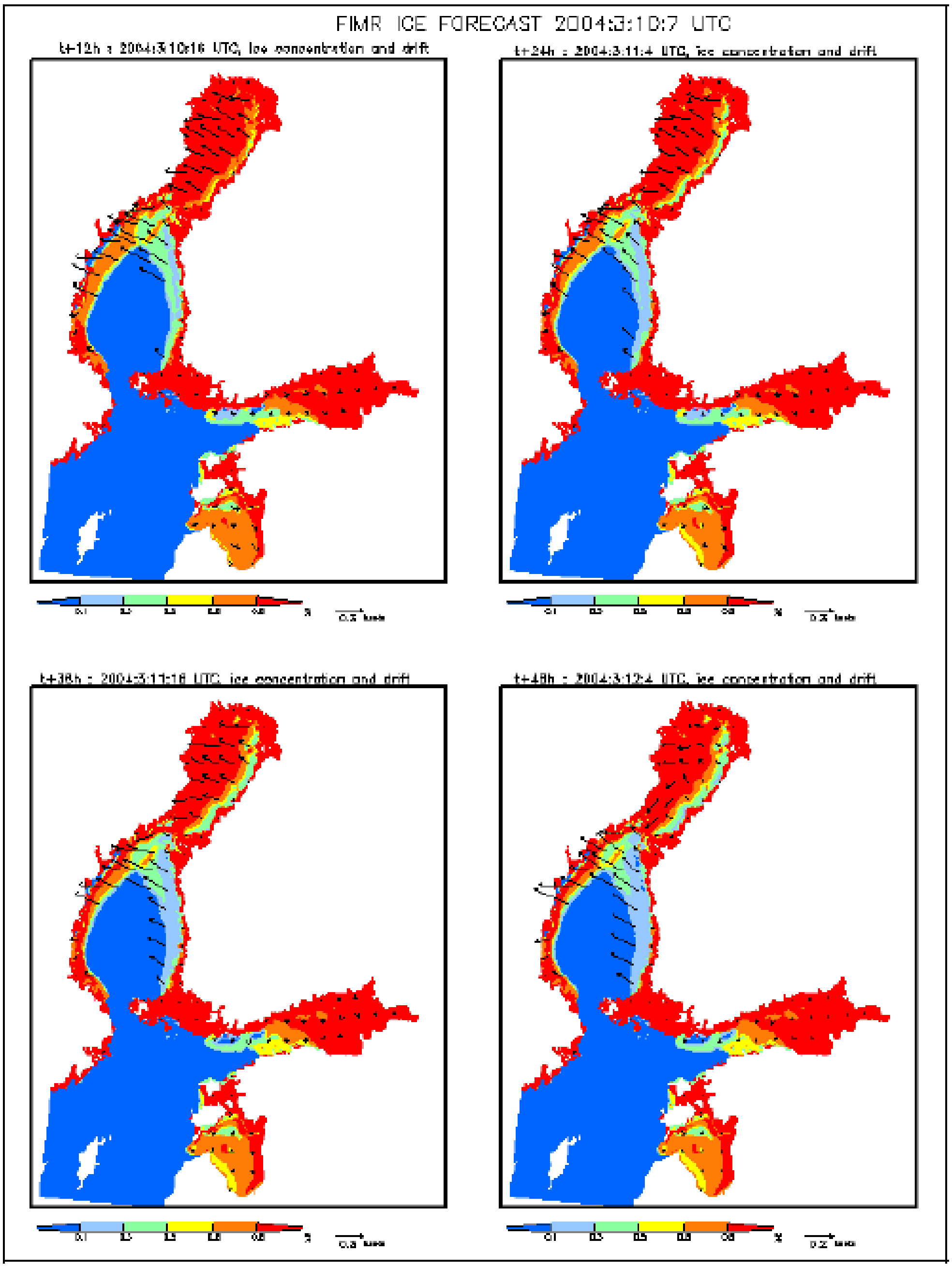


Figure A.14 Ice concentration and drift forecast for the Baltic Sea issued by the Finnish Institute of Marine Research (FIMR) for the period10-13.03.2004 (t+12h, +24h, +36h and 48h).

Ice climatology

Historical archives of weekly ice maps have been digitalized and converted to gridded form to provide a basis for risk assessments for navigation and various ice-sensitive operations (e.g. development and production of oil and gas fields). One example of such efforts is the Global Digital Sea Ice Data Bank (GDSIDB) established by the World Meteorological Organization (WMO) Commission on Marine Meteorology and developed by the Russian Arctic and Antarctic Research Institute (AARI) in cooperation with the National Snow and Ice Data Centre (NSIDC) at the University of Colorado, USA (Figure A.15). This cooperation has led to a set of three atlases on CD-ROM for arctic oceanography, sea ice, and meteorology (see http://nsidc.org/data/ewg/).

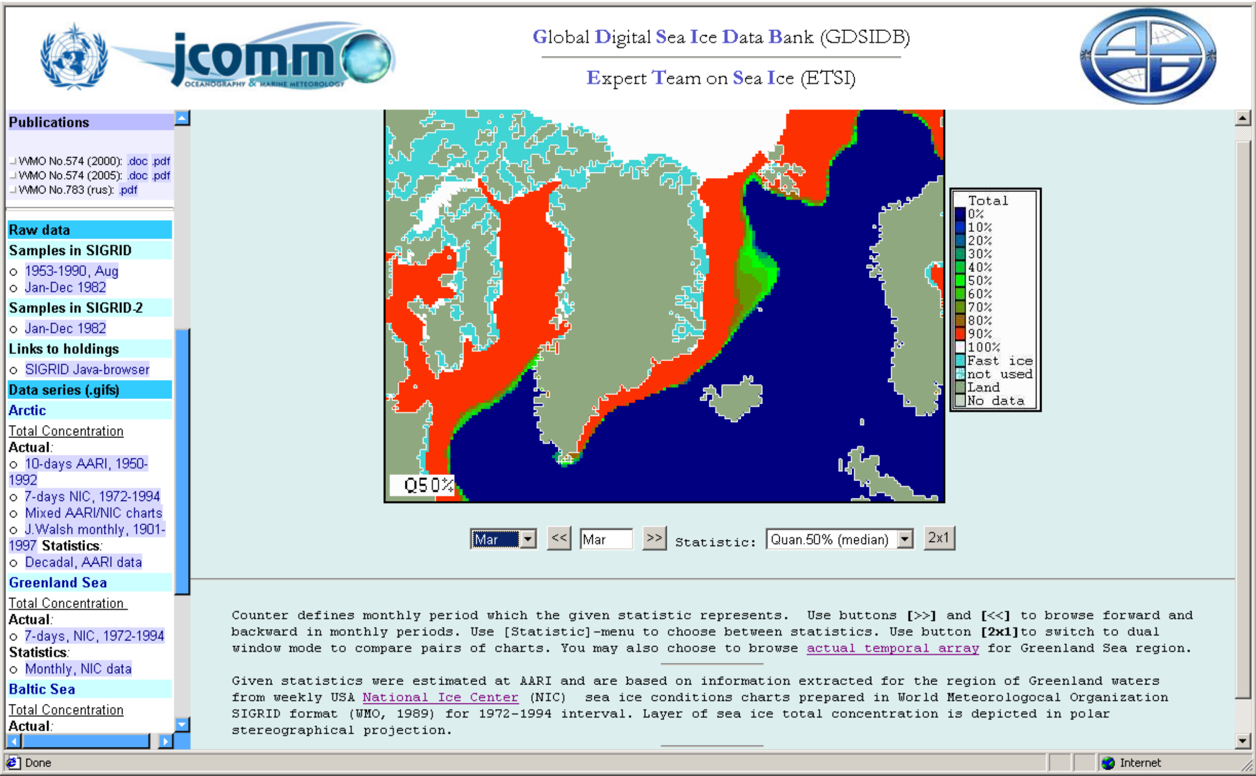


Figure A.15 Example of presentation of ice concentration statistics for the Greenland Sea prepared by AARI as a part of the GDSIDB project. The chosen map depicts gridded median ice concentrations in March based on weekly data for the period 1972 to 1994 (see http: //www.aari.nw.ru/gdsidb/).

Another example is the GIS-based Alaska Sea Ice Atlas based on weekly ice reports archived by the US National Ice Centre. The first product from this effort was the Marine Ice Atlas for Cook Inlet, Alaska. The atlas contains a chapter on the physical description of the region and general descriptions of the marine ice environment, together with a set of maps describing expected ice conditions based on statistical analysis of historical ice data (Figure A.16). Two additional chapters deal with the oceanography and climatology of the region. Informative presentations of air temperature and wind statistics on a monthly basis for a set of meteorological stations in the region are given in appendixes (Figure A.17).

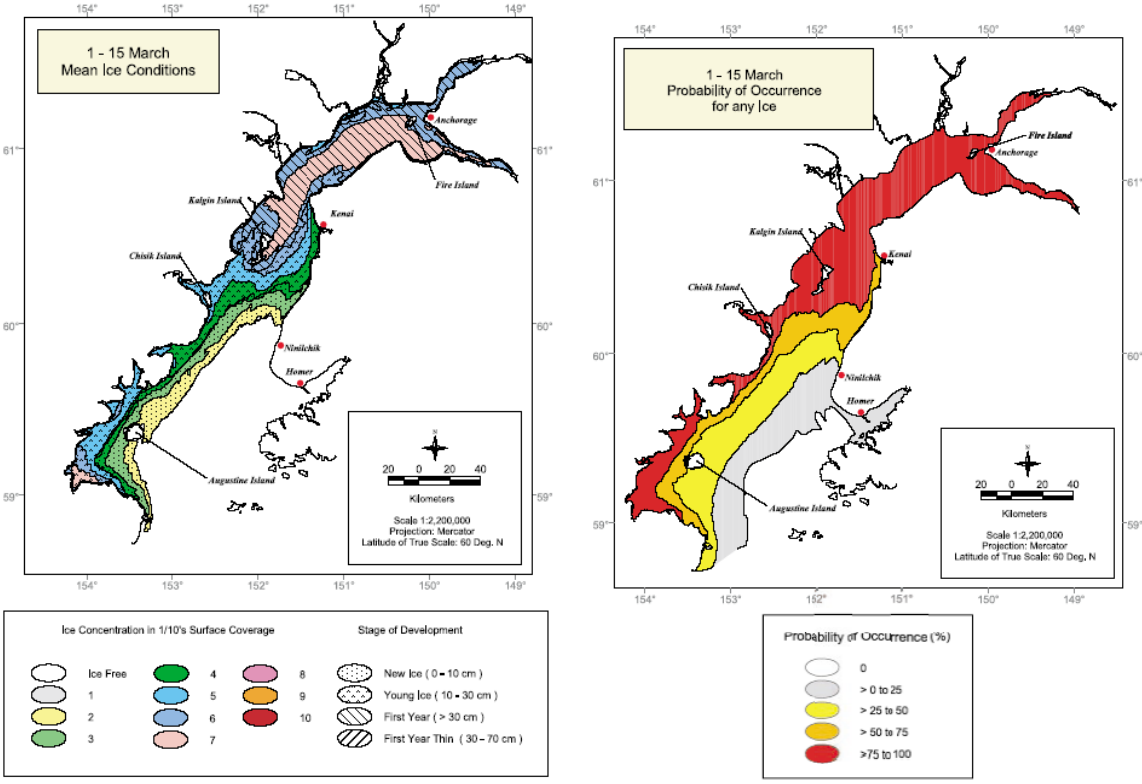
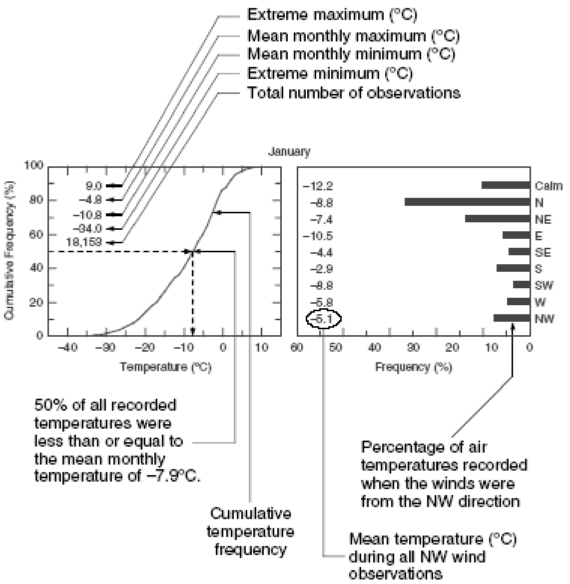


Figure A.16 *Example of presentation of expected ice conditions: Left: Colour coded mean ice concentration combined with symbols for stage of development. Right: Colour coded probability of occurrence of any ice. From Marine Ice Atlas for Cook Inlet, Alaska.*



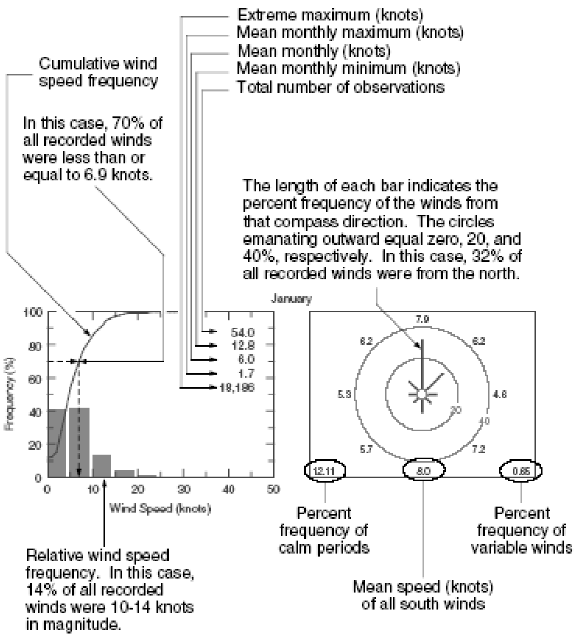


Figure A.17 Standardized presentations of climatological data in the Marine Ice Atlas for Cook Inlet, Alaska. Top: Air temperature, bottom: Wind speed.

The products of the Cook Inlet Ice Atlas have been incorporated in the *Alaska Sea Ice Atlas* which is an interactive GIS-based atlas distributed via the Internet (Figure A.18). The following description is based on the Introduction to the Alaska Sea Ice Atlas, to be found at http://holmes-iv.engr.uaa.alaska.edu. According to this introduction, the fundamental objective of the Alaska Sea Ice Atlas project is to provide government, industry, and the public with GIS-based ice-related risk assessment information for (1) navigation, (2) design of ice-resistant and ice engineering structures, and (3) oil spill prevention and response. The project is creating a state-wide GIS database of ice information, as reported by the National Weather Service, National Ice Centre, and other agencies. The ice information (concentration and stage of development) have been digitized and interpolated to grid cells with a resolution of 5 km.

In addition to the direct ice related parameters, the atlas includes time series of meteorological data from first-order coastal weather stations covering a period of 50 years (1950 – 2000), as well as gridded hind cast wind data with a resolution of 50 km based on daily average atmospheric pressure distributions archived for the 52 years from 1946 to 1997.

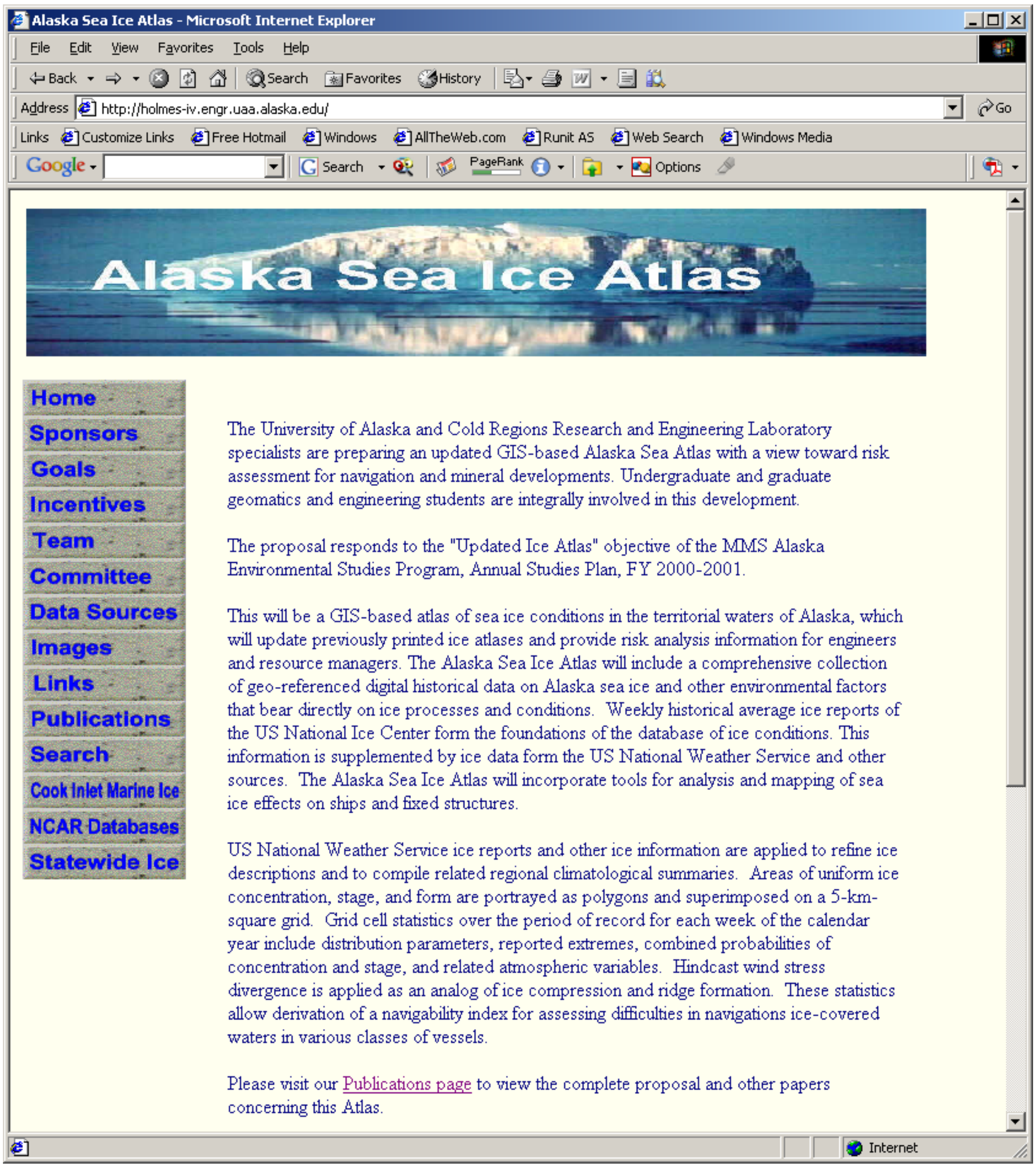


Figure A.18 Entrance page to the Alaska Sea Ice Atlas. Links on the left side connect to the major divisions of the online Alaska Sea Ice Atlas. The Atlas has two collections of interactive maps on line – one covers Cook Inlet (Cook Inlet Marine Ice) and the other the rest of the Alaska coastal waters (State-wide Ice).

The GIS application allows users to interrogate the databases via maps of adjustable scale. They will be able to investigate historical conditions and statistical parameters. Some representative cartographic products include:

- maps of average ice classification (concentration and stage),
- maps of extreme historical ice conditions,
- time series, extreme statistics, and other parameters in any grid cell,
- ice-related meteorological and oceanographic parameters including air temperature and pressure, wind speed and direction, and sea surface temperature
- superstructure icing potential, derived from sea and air temperatures and wind speed,
- potential for reduced visibility from fog or precipitation,
- hours of darkness or daylight.

In conclusion, the Alaska Sea Ice Atlas uses GIS software for practical purposes by computing user-specified geo-referenced parameters that are of primary importance to planning and design of offshore and coastal works in Alaska. The system is web-based and does not rely on paper publications. Availability of the Atlas on the Internet assures transfer of technology to the widest possible population of ice information users. It should be noted, however, that a minimum practical knowledge of GIS-applications will be required to retrieve information from the system.

With this in mind, the Atlas might prove to be a valuable tool also for assessment of various oil spill response options at a given location.