

## NRC Publications Archive Archives des publications du CNRC

### Grand Banks iceberg management

AMEC Americas. AMEC Earth and Environmental; R. F. McKenna and Associates; PETRA International Ltd.

For the publisher's version, please access the DOI link below./ Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

#### **Publisher's version / Version de l'éditeur:**

<https://doi.org/10.4224/12328812>

*PERD/CHC report; no. 20-84, 2007-05*

#### **NRC Publications Archive Record / Notice des Archives des publications du CNRC :**

<https://nrc-publications.canada.ca/eng/view/object/?id=754dda8b-6c1c-4712-bdc8-a8844324ccaa>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=754dda8b-6c1c-4712-bdc8-a8844324ccaa>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

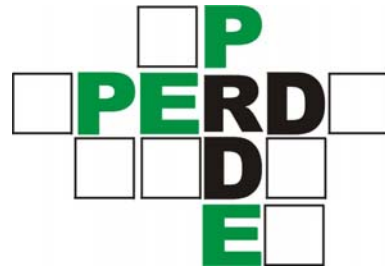
<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

**Questions?** Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

**Vous avez des questions?** Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.



## **Grand Banks Iceberg Management**

**PERD/CHC Report 20-84**

**May 2007**



# **Grand Banks Iceberg Management**

## **PERD/CHC Report 20-84**

Prepared for

Dr. Garry Timco  
Canadian Hydraulics Centre  
National Research Council Canada  
Ottawa, ON, K1A 0R6  
Canada  
[garry.timco@nrc.ca](mailto:garry.timco@nrc.ca)

Prepared by

**AMEC Earth & Environmental**  
A Division of AMEC Americas  
133 Crosbie Road  
PO Box 13216  
St. John's, NL, A1B 4A5  
Canada  
[john.mcclintock@amec.com](mailto:john.mcclintock@amec.com)

**R. F. McKenna & Associates**  
P.O. Box 372  
Wakefield, QC, J0X 3G0  
Canada  
[richard.mckenna@sympatico.ca](mailto:richard.mckenna@sympatico.ca)

**PETRA International Ltd.**  
P.O. Box 191  
Cupids, NL, A0A 2B0  
[petra@persona.ca](mailto:petra@persona.ca)

May 2007

TN07227301

## EXECUTIVE SUMMARY

This report summarizes the current state-of-the-art of iceberg management on the Grand Banks of Newfoundland on the East Coast of Canada through description of the magnitude and range of iceberg conditions, and the approaches used for iceberg detection and towing. There is presently a high standard of iceberg towing and deflection capabilities and iceberg detection frameworks in place, all implemented with generally proven ice management plans and programs.

There appear to be no major issues with iceberg towing. The long standing synthetic line tow rope method has been effective for many years. The new iceberg tow net has been demonstrated over the past three to four years to significantly improve the prospect of managing slippery or otherwise hard to tow small and medium icebergs. Greater experience with the net would improve confidence for vessel captains and industry.

Early detection of icebergs and minimizing possible gaps in the spatial, temporal, and environmental conditions coverage provided by the growing range of satellite and radar technologies together with aerial reconnaissance, remain challenges. Further quantification of these coverage parameters and the potential benefits and limitations would be valuable as input into planning and decision-making tasks. Increased operational use of satellites would improve their confidence for all stakeholders.

Resource management and decision-making including which icebergs to tow, how soon, in which directions, and for how long are perennial challenges especially with multiple fields since different operators have different needs and priorities. This is significant both from a risk mitigation standpoint, to ensure that the “best” decision can be made, and from a cost perspective so that resources are assigned for appropriate lengths of time. The use of data fusion and decision-making tools would appear to be the obvious route and good progress has been made with each. Better monitoring and assimilation of met-ocean conditions is another factor for the decision-making. The PERD iceberg sighting and iceberg management databases are good information resources and they should be maintained. The databases offer utility in a number of areas including study of past conditions and performances, for planning future activities, and possibly as input to other initiatives, such as decision-making or data fusion toolboxes and iceberg management planning aid technologies.

A suggested plan to identify outstanding iceberg management issues, that in order to solve or measurably improve require dedicated research, is presented. A descriptive list of issues is provided for initial consideration by stakeholders. It is proposed that ideally the present and target levels of performance for each are estimated to help judge the possible cost-benefit of pursuing each issue. An agreement on objectives, determination of constraints and resource requirements, and scheduling are then required followed by validation of the plan.

A timely discussion is also presented on the rapid changes in the melt and calving rate of the Greenland ice sheet in response to equally rapid air and ocean temperature warming in the last decade, and the effects of these changes on sea ice and icebergs. These environmental changes directly affect both the Labrador Sea and the Grand Banks of Newfoundland and are front and centre in the debate over global climate change.



## ACKNOWLEDGEMENTS

The project team gratefully acknowledges the assistance and contributions of the following individuals for this study who are also researchers and practitioners for Grand Banks ice management operations.

Freeman Ralph, C-CORE  
Des Power, C-CORE  
Kelley Dodge, C-CORE  
Pip Rudkin, PAL

## PROJECT TEAM

John McClintock, AMEC  
Richard McKenna, R.F. McKenna & Associates  
Chris Woodworth-Lynas, PETRA International Ltd.  
Stephen Green, AMEC  
Diana Cardoso, AMEC

## CITATION

McClintock, J., R. McKenna, and C. Woodworth-Lynas, May 2007. "Grand Banks Iceberg Management." PERD/CHC Report 20-84. Report prepared for PERD/CHC, National Research Council Canada, Ottawa, ON. Report prepared by AMEC Earth & Environmental, St. John's, NL, R.F. McKenna & Associates, Wakefield, QC, and PETRA International Ltd., Cupids, NL.

## TABLE OF CONTENTS

EXECUTIVE SUMMARY .....	I
ACKNOWLEDGEMENTS .....	II
PROJECT TEAM .....	II
CITATION .....	II
1.0 INTRODUCTION.....	1
1.1 Objectives.....	1
1.2 Background.....	1
1.3 Report Structure .....	3
2.0 ICE MANAGEMENT.....	4
2.1 Role of Ice Management.....	4
2.2 Grand Banks Iceberg Conditions.....	4
2.3 Regulatory Regime .....	11
2.4 Critical Factors in Ice Management .....	14
2.5 Ice Season Reports .....	17
2.6 Iceberg Detection.....	17
2.7 Iceberg Towing and Deflection .....	18
2.7.1 Single Vessel Iceberg Towing Procedure.....	18
2.7.2 Dual Vessel Towing.....	28
2.7.3 Water Cannon .....	28
2.7.4 Propeller (“Prop”) Washing.....	30
3.0 ICEBERG DETECTION RESEARCH .....	32
3.1 Overview.....	32
3.1.1 Range of Potential Platforms and Sensors.....	32
3.1.2 Strategic Issues .....	32
3.1.3 Tactical Issues .....	33
3.1.4 Radar Bands.....	34
3.2 Airborne Systems .....	34
3.3 Satellite Systems .....	34
3.3.1 Background .....	34
3.3.2 Operational Experience with Satellite Radar in Canada.....	35
3.3.3 Iceberg – Vessel Discrimination .....	36
3.3.4 Iceberg Detection in Sea Ice .....	36
3.3.5 Trade-off Between Resolution and Swath Width.....	36
3.4 HF Radar .....	38
3.5 Marine Radar.....	38
3.5.1 Background .....	38
3.5.2 Coherent Radar .....	39
3.6 Other Systems .....	39
3.6.1 UAV .....	39
3.7 Integration of Detection and Tracking Systems .....	40
3.7.1 Trajectory Forecasts.....	40
3.7.2 Fusion of Data from Multiple Sensors .....	40
3.7.3 Calving Forecasts.....	41
4.0 ICEBERG TOWING RESEARCH .....	42
4.1 West Greenland Towing Experience and Analysis.....	42
4.2 The PERD Iceberg Management Database .....	43
4.3 C-CORE Iceberg Net.....	48

4.4	C-CORE Iceberg Decision Making Toolbox .....	51
4.5	Dunderdale Iceberg Management Planning Aid (IMPA) .....	51
5.0	WHERE HAVE ALL THE ICEBERGS GONE? .....	52
5.1	Background.....	52
5.2	Iceberg Climate.....	54
5.2.1	Ocean Temperatures: Intermediate Water .....	54
5.2.2	Ocean Temperatures: Sea Surface.....	54
5.2.3	Air Temperature.....	55
5.2.4	Sea Ice Extent .....	57
5.3	Greenland Ice Sheet and Icebergs .....	59
5.3.1	Glacialquakes .....	61
5.3.2	Response of Individual Glaciers .....	64
5.4	Significance to Icebergs.....	66
5.5	Summary .....	68
5.5.1	Iceberg Production is Increasing .....	68
5.5.2	Iceberg Flux is Decreasing .....	68
5.5.3	The Future .....	68
6.0	OUTSTANDING ISSUES AND AREAS FOR RESEARCH.....	69
6.1	Observations.....	69
6.2	A Suggested Plan for Ice Management Issues (IMI) .....	70
7.0	REFERENCES.....	77
7.1	Personal Communications.....	77
7.2	Literature Cited .....	77
7.3	Additional Reading.....	82

### LIST OF FIGURES

Figure 1.1	Drilling Locations, Offshore Newfoundland .....	2
Figure 2.1	Major Ocean Circulation Features.....	5
Figure 2.2	Annual Number of Icebergs Crossing 48 ° N (1946-2006) (Data from: IIP, 2005) .....	7
Figure 2.3	Monthly Number of Icebergs Crossing 48 ° N (1946-2006) (Data from: IIP, 2005) .....	8
Figure 2.4	Iceberg Size Comparisons. ....	10
Figure 2.5	Iceberg Draft Estimation Graph.....	11
Figure 2.6	Relationship between the various factors for floater operations in ice environments (from Makrygiannis et al., 2006).....	14
Figure 2.7	Sample Ice Season Report Table of Contents (PAL, 2003). ....	19
Figure 2.8	Sample Daily Tactical Iceberg Plot (AMEC, 2000c) .....	20
Figure 2.9	Single Vessel Iceberg Towing .....	23
Figure 2.10	Retrieving the Tow Line, <i>West Navion</i> in Distance .....	24
Figure 2.11	Iceberg Towing by <i>Normand Jarl</i> .....	24
Figure 2.12	<i>Havila Charisma</i> Towing Iceberg F170 as Seen From the <i>West Navion</i> .....	25
Figure 2.13	Iceberg F170 Under Tow by <i>Havila Charisma</i> , <i>West Navion</i> in Background .....	25
Figure 2.14	Use of Towing Catenary to Reduce Overturning Moment of Unstable Icebergs .....	26
Figure 2.15	High Sea State Deployment of Towing Equipment.....	27
Figure 2.16	Water Cannon.....	29

Figure 2.17	Propeller Washing.....	31
Figure 4.1	West Greenland, Deflected Iceberg Size Distribution (Source: AMEC, 2002a). 42	
Figure 4.2	West Greenland Towing Complications (Source: AMEC, 2002a). ....	43
Figure 4.3	PERD Iceberg Management Database Key Parameters. ....	44
Figure 4.4	Grand Banks Iceberg Tow Methods (Data From: PERD IMDB).....	45
Figure 4.5	Grand Banks Iceberg Tows: Reason Management Ended (Data From: PERD IMDB) 46	
Figure 4.6	Grand Banks Iceberg Tow Evaluations (Data From: PERD IMDB).....	47
Figure 4.7	Concept of Iceberg Net Towing (Source: C-CORE, 2004a).....	49
Figure 4.8	Iceberg Net Schematic (Source: C-CORE, 2004a). ....	49
Figure 4.9	Iceberg Net In Use (Source: C-CORE, 2004a).....	50
Figure 4.10	Iceberg Net Storage (Source: C-CORE, 2004a).....	50
Figure 5.1	Ice extent anomaly for winter showing decrease in Arctic ice in the month of April (the month of greatest ice extent) since 1979 (National Snow & Ice Data Centre). 52	
Figure 5.2	Ice extent anomaly for summer showing decrease in Arctic ice in the month of September (typically the month with the least ice) since 1979 (National Snow & Ice Data Centre). 53	
Figure 5.3	Actual ice extent is decreasing at a rate faster than all of the combined 18 prediction models used by the Intergovernmental Panel on Climate Change (IPCC) in preparing its 2007 assessments (National Snow & Ice Data Centre). ....	53
Figure 5.4	Since 1995 spring sea surface temperature (SST) anomalies in the Labrador Sea have increased in size and since 1997 extend into Disko Bay, western Greenland (data from NASA N.O.M.A.D.S.).....	55
Figure 5.5	Number of positive degree days at 100 m and 1169 m, Jakobshavn Isbrae (from data of Thomas <i>et al.</i> 2003).....	56
Figure 5.6	Positive Degree Days (PDD) from Egedesminde, near Jacobshavn Isbrae, and Sea Surface Temperatures (SST) for the four warmest months (July – October) for the N. Atlantic and Davis Strait 50 – 65° N, 45 – 65° W (from Thomas <i>et al.</i> 2003). ....	56
Figure 5.7	Decline in Arctic sea ice extent from 1978-2005. The September trend from 1979 to 2005, now showing a decline of more than 8 percent per decade, is shown with a straight blue line (National Snow & Ice Data Center).....	57
Figure 5.8	Example of sea ice concentration (left) and sea surface temperature anomalies (right) for April 2000 (top) & 2006 (bottom). Increasing sea surface temperatures correlate with below normal sea ice concentration anomalies. (National Snow & Ice Data Center). ....	58
Figure 5.9	Map of Greenland showing the estimated volumetric increase in iceberg discharge in the decade between 1996 and 2005 (based on mass balance measurements for the entire ice sheet by Rignot and Kanagaratnam, 2006).....	60
Figure 5.10	Top: Map of Greenland showing locations of summer glacialquakes between 1993 and 2005. Summer seismicity is more than 5 x greater than in winter. Bottom: Graph showing increase in frequency of glacialquakes (green bars) against a constant background of earthquakes (grey bars). Based on Ekström <i>et al.</i> 2006; Joughin, 2006. ....	63
Figure 5.11	Retreat of the floating ice tongue of Jakobshavn Isbrae, west Greenland... 65	
Figure 5.12	Left: Surface runoff on the Greenland ice sheet draining into a large Moulin. Bottom: view of large meltwater pool. ....	67

## LIST OF TABLES

Table 2.3	Grand Banks Iceberg Length, Width and Height Statistics.....	8
Table 2.1	International Ice Patrol Iceberg Shape Classification Codes.....	9
Table 2.2	Iceberg Size Classifications.....	9
Table 3.1	Detection Systems and Supporting Platforms .....	32
Table 3.2	Radar Bands.....	34
Table 3.3	Research Projects on Satellite Radar Detection of Icebergs.....	35
Table 3.4	ENVISAT Modes, Resolutions and Swath Widths.....	37
Table 3.5	RADARSAT-1 Modes, Resolutions and Swath Widths .....	37
Table 3.6	RADARSAT-2 Modes, Resolutions and Swath Widths .....	37
Table 5.1	Estimated increase in iceberg production (km <sup>3</sup> ) of the Greenland ice sheet between 1996 and 2005 (derived from data of Rignot and Kanagaratnam, 2006).....	60
Table 6.1	Potential Ice Management Issues List.....	72

## **1.0 INTRODUCTION**

### **1.1 Objectives**

The objective of this work is to summarize the current state-of-the-art of iceberg management on the Grand Banks of Newfoundland on the East Coast of Canada, and to define outstanding research initiatives that would improve its safety and efficiency. Specific objectives are:

- to provide detailed information on the approach used for iceberg detection and towing on the Grand Banks
- to provide information on past research efforts that have been successful at improving safety and efficiency of iceberg towing
- to detail a plan that would help identify outstanding issues that should be addressed through a dedicated research program

### **1.2 Background**

The development of hydrocarbon resources on the Grand Banks of Newfoundland and in the Labrador Sea is hampered by the presence of icebergs. Production platforms, collection and offloading systems, operations, and exploration schedules are all influenced and can be affected by iceberg threat. Over the past 30 years, techniques for safely working in this environment have been developed, implemented, and refined.

There are presently three oil-producing fields in the North Atlantic: Hibernia, Terra Nova, and White Rose (Figure 1.1). The Hibernia production installation consists of a platform (concrete gravity base structure (GBS) and topsides facilities), export lines, and Offshore Loading System (OLS). The installation is located on the Grand Banks approximately 170 nautical miles (315 km) east of St. John's, Newfoundland. Towout of the GBS was completed in summer 1997 with first oil later that fall. Field development includes helicopter and supply vessel operations support. A steel-hulled Floating Production, Storage and Offloading (FPSO) design was selected for Terra Nova located 21 nautical miles southeast of Hibernia. First oil was achieved in January 2002. The third field, White Rose, located 30 nautical miles northeast of Hibernia and Terra Nova, is also being developed with an FPSO and first oil there was in November 2005. Project lifetimes are estimated to be in the range of at least 15 to 20 years. All projects are supported with shuttle tanker shipments to Newfoundland. Water depths range from about 85 m at Hibernia to 95 m at Terra Nova to 120 m at White Rose.

There is also the prospect of the development of the Hebron Field located in the Jeanne d'Arc Basin, approximately 10 km north of Terra Nova and approximately 35 km southeast of Hibernia. Drilling exploration has also been active in the Orphan Basin region north of the Grand Banks with drilling of the deep water (~2000 m) well Great Barasway from summer 2006 to winter 2007, and in the Flemish Pass (e.g., Tuckamore B-27 in spring 2003).

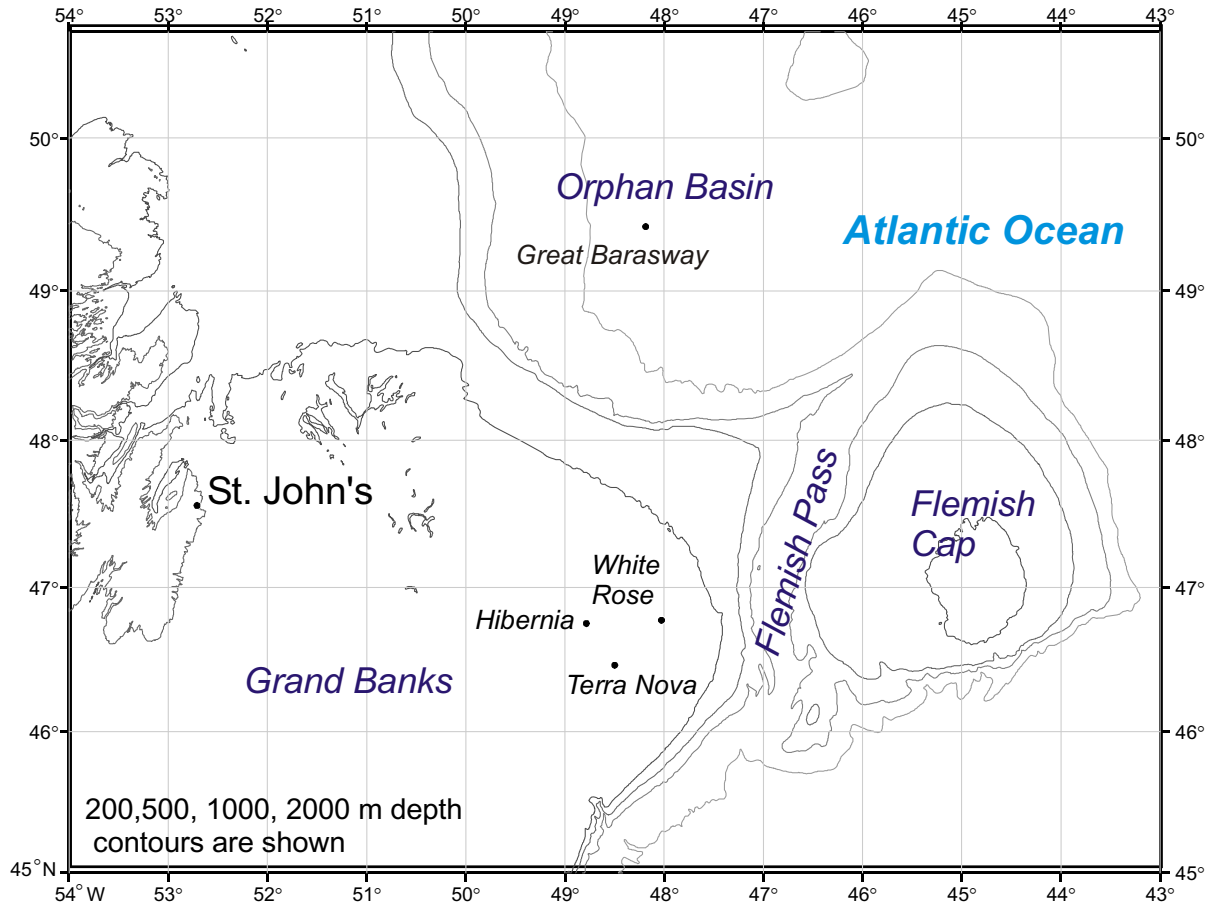


Figure 1.1 Drilling Locations, Offshore Newfoundland

Each year on the Grand Banks the potential exists for numerous icebergs, ranging from very large icebergs of mass one million tonnes or greater to small growlers. Strong winds and occasionally storm force wind and wave conditions, and frequently poor visibility in ice season can reduce visual and radar detection of icebergs and the effectiveness with which they can be towed or deflected. Being able to predict the drift trajectory of an iceberg is important for ice management planning and deployment of resources: occasionally strong and sometimes complex ocean currents and tidal patterns can make this prediction difficult. Ice management operations are carried out with support vessels for iceberg towing and deflection, onboard Ice Watch services, iceberg data management, communication, and reporting, and iceberg detection resources such as radar, fixed-wing aircraft and remote sensing satellite.

A significant body of experience has been achieved since towout of the Hibernia GBS in 1997 with Grand Banks ice management operations at Hibernia, and subsequently Terra Nova, and White Rose, carried out each year. Iceberg season on the Grand Banks traditionally lasts from April (or March) to June (or July) and the number of icebergs seen is highly variable from one year to the next. In the past 10 years this has ranged from 1380 icebergs in 1998 to none in 2006, averaging 542 each year over this recent period.

A comprehensive iceberg management program was also completed during a ten-week drilling program offshore West Greenland, in summer 2000, in which 228 iceberg targets

were tracked, and of a total of 168 confirmed icebergs, 64 icebergs were deflected. These operations, both recent Grand Banks and Greenland, have been documented in annual or end of well ice reports.

Iceberg management has also been supported and augmented by research activities. This includes the work in 1998 contracted by NRC to develop a strategy for improving iceberg management on the Grand Banks in which a complete and detailed survey of physical iceberg deflection techniques and capabilities was presented (Crocker et al., 1988). There have been numerous PERD-sponsored Canadian East Coast Ice Engineering Issues studies focusing on practical solutions to ice problems relevant to development of this area and the associated Canadian Hydraulics Centre (CHC) web site (NRC-CHC, 2007) is an excellent resource. This includes dedicated databases for iceberg sightings and iceberg management operations which have been created and are updated frequently in a collaboration of ice management service providers and stakeholders.

Significant advances in iceberg detection technologies, through platform-based radar and RADARSAT and other remote sensing technologies, and ice trajectory modelling have also been achieved through various government and industry-sponsored initiatives.

Improvements are still possible in these areas, including iceberg detection and management in high seas and in sea ice (more an issue for Labrador or north of the Grand Banks), assimilation of iceberg monitoring data and gaps, decision-making, as well as ongoing challenges of physically dealing with smaller icebergs and ones that are more difficult to manage.

For a range of present and future development scenarios, pipelines, flowlines, wellheads, and subsea tie-ins are expected to play an increasingly important role in the economic development of oil and gas on Canada's east coast, and must be protected from icebergs. These supporting installations introduce additional considerations for iceberg management.

The present report is intended to provide an up-to-date summary of both iceberg detection and iceberg towing in the Grand Banks region, outline safety and efficiency issues that remain and provide guidance on future research directions for improved iceberg management planning and operations.

### **1.3 Report Structure**

Section 2 of this report provides an overview of ice management, including description of: Grand Banks iceberg conditions, critical factors for ice management, the approaches used for iceberg detection and towing, and decision-making. Fundamental to iceberg management and possible improvements in ice operations is an understanding of the range and magnitude of conditions which may be encountered. The detection and towing strategies introduced in Section 2 are elaborated in Section 3, which details iceberg detection approaches and research including airborne, satellite, HF and marine radar, and Section 4, where additional towing techniques and research activities are described. Section 5 is a timely discussion of the rapid changes in the melt and calving rate of the Greenland ice sheet and effects of these changes on sea ice and icebergs: environmental changes directly affecting both the Labrador Sea and the Grand Banks. Section 6 presents a suggested plan intended to identify outstanding issues that in order to solve require a dedicated research program.

## **2.0 ICE MANAGEMENT**

### **2.1 Role of Ice Management**

Ice management is a required element of physical environmental programs for oil and gas exploration or production drilling operations taking place in regions in which sea ice and/or icebergs can occur.

For regulators, concerns about ice management include:

- the safe operation of platforms in the environment for which they were designed
- documentation that the operation of platforms has indeed been safe

Concerns about ice management are therefore related to verification that systems and procedures have acceptable success levels in the context of overall platform safety. This is a research area that was initiated during drilling offshore Labrador in the 1970s and continues to this day on the Grand Banks.

For operators, ice management is used to:

- ensure that the platform operates safely in the environment for which it was designed
- reduce risk to personnel, environment and assets over and above design requirements
- minimize disruptions to drilling or producing operations

Ice management is essential for drilling platforms or floating production platforms because these generally cannot operate in ice environments without some form of management support. Ice management is important for fixed platforms because substantial savings may accrue by minimizing disruptions to operations.

Present oil and gas drilling activities offshore Newfoundland are shown in Figure 1.1.

### **2.2 Grand Banks Iceberg Conditions**

The East Coast and Newfoundland can be a high traffic area for many icebergs in their journeys south from the fjords of Greenland. Icebergs are masses of fresh water ice which calve each year from the glaciers of Greenland. Icebergs are moved by both the wind and ocean currents, and typically spend one to three years traveling a distance up to 2897 km (1800 miles) to the waters of Newfoundland. The West Greenland and Labrador Currents (Figure 2.1) are major ocean currents which move the icebergs about the Davis Strait, along the coast of Labrador, to the northern bays of Newfoundland, and to the Grand Banks. Icebergs will exhibit little or no melting in sea temperatures of about 5°C or less while waves and warm air temperatures will tend to erode them in their travels. A medium iceberg (15-30 m or 32.8-49.2 ft high, 45-90 m or 147.6-295.3 ft long) will deteriorate in sea water of 4.4°C in about 10 days. Generally larger icebergs can survive until late into the summer.

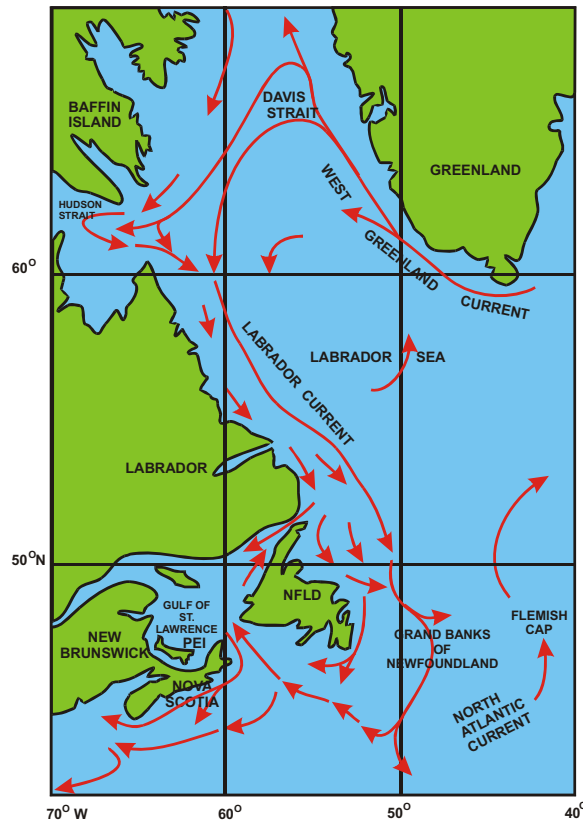


Figure 2.1 Major Ocean Circulation Features

On average, the seawater temperature on the Grand Banks is highest in August, when the temperature stratification is also the highest. Mean sea temperature in August is about 12°C near-surface, -0.2°C at 50 m depth and about -1°C at 80 m. On average, the temperature stratification is primarily limited to within 50 m depth below the water surface. Below the 50 m depth, the seawater temperature remains near zero on average all year round. The seawater temperature and stratification is at a minimum in January and February. The mean sea temperature in February is about -0.5°C near-surface, -0.4°C at 50 m depth and about -0.3°C at 80 m.

The presence of easterly and northeasterly winds can strongly influence the numbers of icebergs that make their way to the Newfoundland coast and also onto or off the Grand Banks. As witnessed in 2000 for example on the Grand Banks, local wind conditions can bring large numbers of bergs onshore from their traditional route in the Labrador Current (AMEC, 2000c, PAL, 2000). Larger icebergs have the potential to become grounded on the Grand Banks.

These factors combined with the prevailing wind directions and sea and air temperatures will determine whether and for how long the icebergs stay on the Grand Banks and along the coast. The majority of icebergs will be present from March to June or July. By August in most years, the icebergs both along the coast and offshore Newfoundland will have drifted south of the Grand Banks or melted.

### Iceberg Numbers

The U.S. Coast Guard International Ice Patrol (IIP)<sup>1</sup> has monitored the number of icebergs crossing latitude 48° N (about 30 km north of St. John's) since 1914 as part of its core purpose to promote safe navigation of the Northwest Atlantic Ocean when the danger of iceberg collision exists. This number is highly variable from one year to the next. Figure 2.2 illustrates the interannual variability in this total. In 1984 a total of 2202 icebergs were recorded crossing 48°N whereas in 2005 there were 11 and in 1966 and 2006 there were none. The largest number in the past 10 years is 1380 icebergs in 1998, although the presence of icebergs on the Grand Banks is not sufficient to impact drilling operations<sup>2</sup>.

In 1999, while there were a good number of icebergs on the East Coast, most of them actually drifted south and west through the Strait of Belle Isle at the northern tip of Newfoundland: the (Grand Banks) "south of 48° N count" was 22.

The annual average iceberg count is 543 over this recent 10-year period and the annual mean is 553 icebergs. Figure 2.3 shows the monthly mean and median number of icebergs crossing 48°N. The monthly mean ranges from 8 in August and 18 in February, to 71 in March and 90 in June, with the greatest averages in April (130) and May (143). During the main portion of the season from March to June, the median ranges from 31 in March to 70 in April.

---

<sup>1</sup> <http://www.uscg.mil/lantarea/iip/home.html>

<sup>2</sup> "The closest iceberg to the Hibernia platform was estimated to be 30 nautical miles north northwest of the site on 14 May. The iceberg was sighted during a fixed-wing aircraft surveillance flight (no size information was available, although the majority of bergs in the region (to the northwest through to northeast, east, and southeast) at the time were of the bergy bit to medium size iceberg variety. On several occasions during the spring, primarily in mid to late May, there were 20 to 40 icebergs to the northeast through to southeast, generally at a consistent 40 to 60 nautical mile range from the platform" (AGRA, 1998).



Annual Number of Icebergs Crossing 48°N (1946-2006)

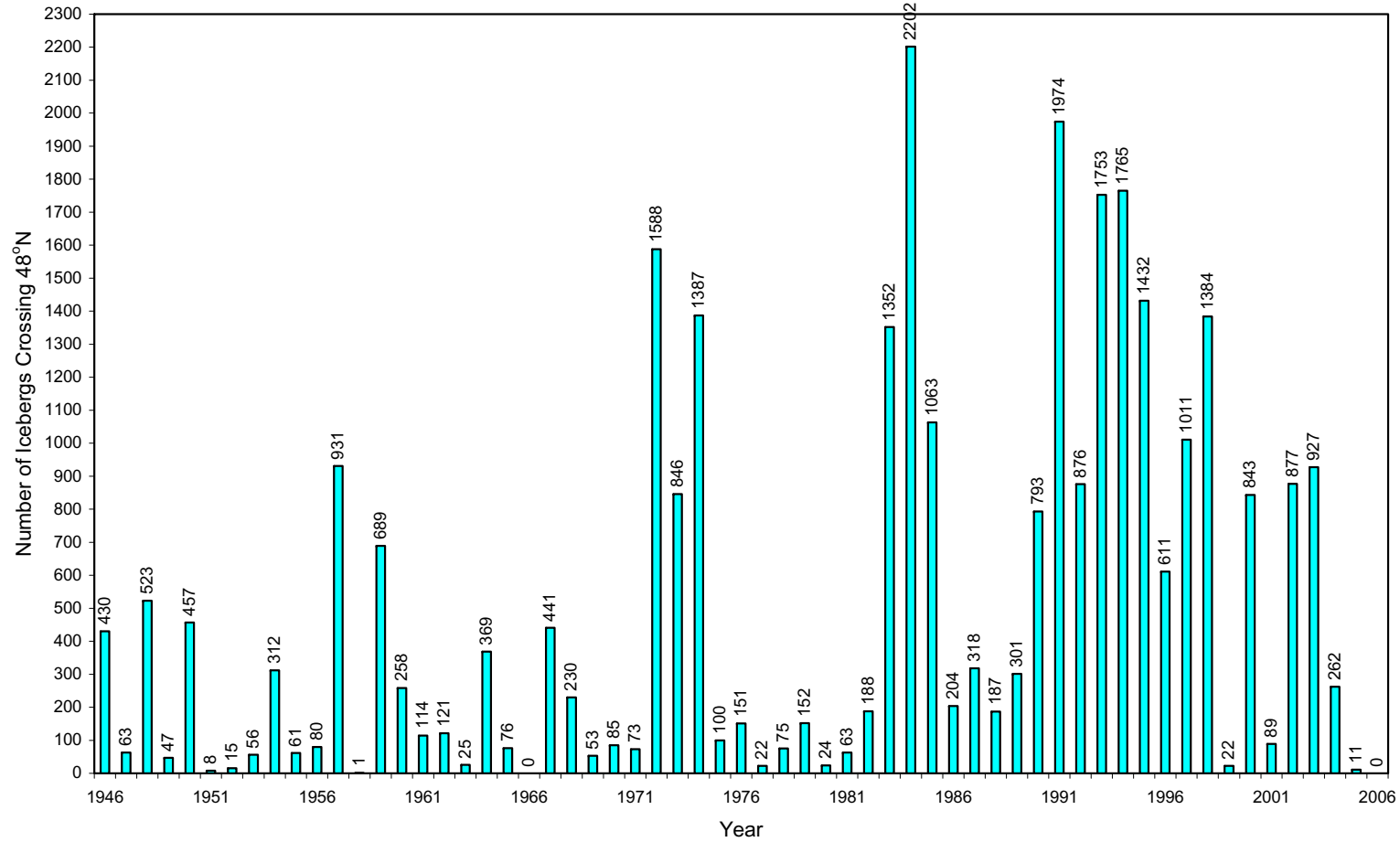


Figure 2.2 Annual Number of Icebergs Crossing 48° N (1946-2006) (Data from: IIP, 2005)

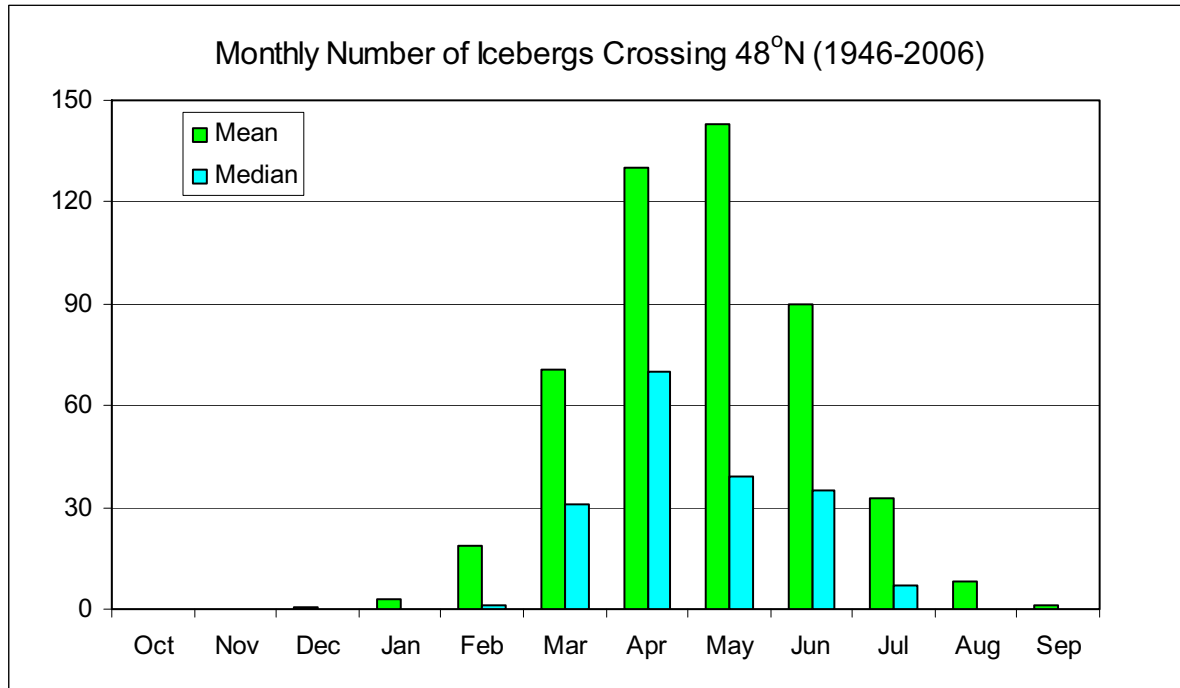


Figure 2.3 Monthly Number of Icebergs Crossing 48 ° N (1946-2006) (Data from: IIP, 2005)

Iceberg Size

For general reference, iceberg shape and size classifications in common use are presented in Table 2.2 and Table 2.3. These sizes can be better appreciated by comparing the icebergs with a variety of well-known vessels as shown in Figure 2.4. Iceberg size statistics from two significant studies and databases are summarized in Table 2.1. These include the 1988 Terra Nova Design Criteria Study (Seaconsult, 1988) and the PERD Iceberg Sighting Database (BMT Fleet Technology, 2005, Verbit et al., 2006) where the more recent PERD table entry is from a query restricting data to the recent period 1987 to 2006, and the Grand Banks region south of 49 ° N, and between 46 ° and 53 ° W, which equates to slightly over 600 observations for each of length, width, and height. For this recent entry, between about one quarter and one third of the values are measurements, the remaining being estimates.

Table 2.1 Grand Banks Iceberg Length, Width and Height Statistics

Parameter	Source	Mean (m)	Maximum (m)
Waterline Length	On-shelf, Seaconsult (1988)	61	228
	Off-shelf, Seaconsult (1988)	90	382
	PERD (1960-99)	94	
	PERD (1987-06)	67	500
Waterline Width	On-shelf, Seaconsult (1988)	41	137
	Off-shelf, Seaconsult (1988)	61	250
	PERD (1960-99)	60	
	PERD (1987-06)	41	300
Above Water Height	On-shelf, Seaconsult (1988)	16	85
	Off-shelf, Seaconsult (1988)	21	100
	PERD (1960-99)	25	
	PERD (1987-06)	14	91

Table 2.2 International Ice Patrol Iceberg Shape Classification Codes.

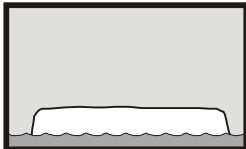
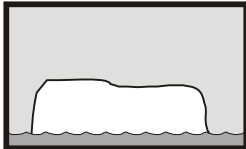

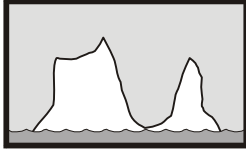
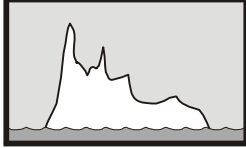
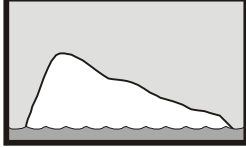
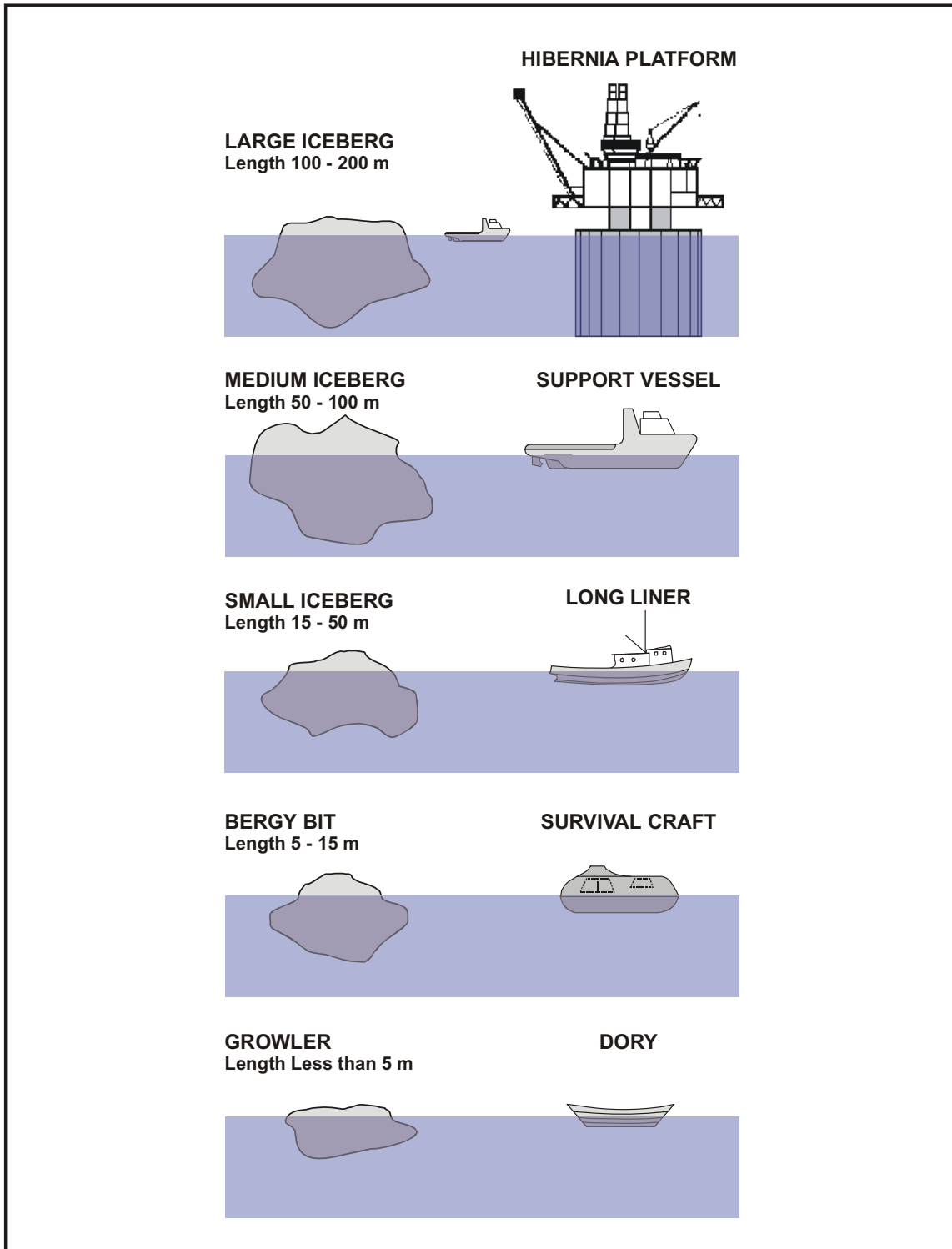
Iceberg Code	IIP Code	Comments	Illustration
Tabular	TAB	Horizontal, flat-topped with length-height ratio of 5:1 or more.	
Blocky	BLK	Steep precipitous side with almost horizontal top and with length-height ratio of 3:1 to 5:1.	
Dome Spherical	DOM SPH	Large, smooth rounded top.	
Dry Dock	DDK	Eroded such that large U-shape slot is formed with twin columns or pinnacles. Slot extends under the waterline or close to it.	
Pinnacled	PNC	Large central spire or pyramid of one or more spires dominating shape. Less massive than dome-shaped iceberg of similar dimensions.	
Wedge	WDG	A tabular iceberg which has altered its position of stability so that is now appears tilted, resembling a wedge.	
Bergy Bit Growler	BBB GGG	Masses of glacial ice calved from an iceberg. The growler is smaller than a bergy bit which is, in turn, smaller than an iceberg	

Table 2.3 Iceberg Size Classifications

Iceberg Type	Code	Mass (T)	Height (m)	Length (m)
Growler	GG	500	< 1 m	< 5 m
Bergy Bit	BB	1,400	1 - 5 m	5 - 15 m
Small Berg	SB	100,000	5 - 15 m	15 - 50 m
Medium Berg	MB	750,000	15 - 50 m	50 - 100 m
Large Berg	LB	5,000,000	50 - 100 m	100 - 200 m
Very Large Berg	VB	>5,000,000	> 100 m	> 200 m



**ICEBERG SIZE COMPARISONS**

Figure 2.4 Iceberg Size Comparisons.

Iceberg draft can be estimated from its measured maximum waterline length using the following empirical relationship:

$$D = 3.781 L^{0.63}$$

Where        D = Draft (m)  
               L = Length (m)

For example, draft or keel depth of an iceberg of length 70 m (230 ft) would be on the order of 90 m (295 ft). This relationship is displayed graphically in Figure 2.5. The expected accuracy for draft estimates is  $\pm 25\%$ . From PERD (1987-2006) the mean draft (measured or estimated) is 49 m and maximum is 185 m.

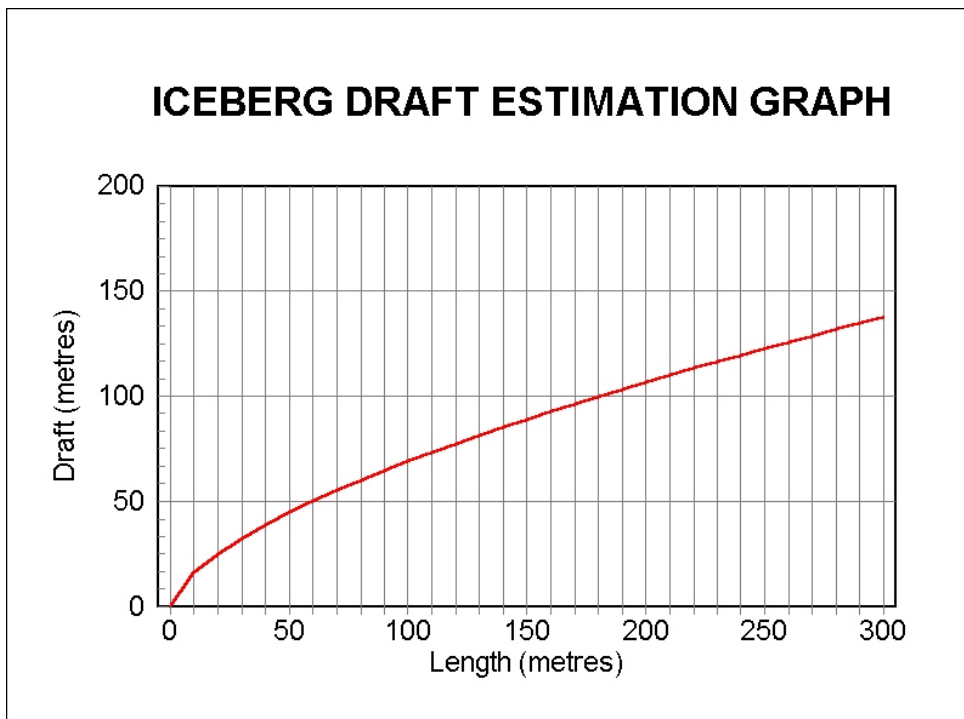


Figure 2.5 Iceberg Draft Estimation Graph

### 2.3 Regulatory Regime

The regulatory regime surrounding ice management was discussed in Crocker et al. (1999). Focus was primarily on the C-NOPB (now the C-NLOPB) regulations and Terra Nova Development Plan. Since then, significant developments have taken place in terms of the standards governing for offshore structures in ice environments and the White Rose project has now come onstream.

The C-NLOPB Physical Environmental guidelines specify the following with respect to ice management:

#### 4.0 ICE MANAGEMENT GUIDELINES A. ICE MANAGEMENT PROGRAM

*When operations are conducted in pack ice or areas of drifting icebergs or ice islands, an ice management plan will be implemented by the operator under the Contingency Planning Guidelines to ensure the safety of drilling or production operations. Since ice conditions can vary greatly from area to area, and season to season or year to year within an area, ice management plan should be tailored to the region, period, and nature of the operation. The plan should include systems for ice detection, surveillance, data reporting, collation, quality control and presentation and, where applicable, a local tactical ice forecasting component.*

*Iceberg/ice island and ice-hazard trajectory forecast service should reflect the operator's contingency plan specifications.*

*The frequency of ice-hazard/iceberg forecasts should be commensurate with the level of threat as determined from the operator's Ice Alert Procedures. The operator should also arrange for regular verification of the ice-hazard/iceberg forecasts. In any case the verification methodology should be submitted to the Regulator for approval.*

#### **B. ICE REPORT**

*Under the ice management plan, additional information above and beyond that collected under MANMAR is available. To satisfy the Regulator's safety and operational audit, East Coast Operators will report the following iceberg and/or sea ice information once daily (when applicable) to the Regulator:*

- *icebergs: time of observation, geographic position (latitude & longitude), type, source of observation, and area surveyed; and*
- *sea ice: ice boundary, type, concentration, and area surveyed.*

*Operators are expected to maintain separate logs for ice and/or ice-hazard/iceberg data. Special reports will be made to the Regulator when dictated by significant events.*

#### **C. ADDITIONAL ICE DATA**

*A summary of ice information, including any ice forecast verification statistics, will be submitted to the Regulator (as appropriate) in a separate self-contained document as part of the Final Well Report. Data in acceptable data storage media accompanying the summary should be coded in the format provided in Appendix 1B.*

The C-NLOPB also has requirements for the development of safety plans (C-NLOPB, 2002), which include the Ice Management Plan. Specific consideration is made for:

- *"that all major hazards have been identified and the risks associated with them reduced to ALARP"*
- *qualifications, competency and training of personnel*
- *changes to systems, procedures and equipment – that risk is not increased*
- *"procedures are in place to provide for effective weather forecasting, ice management"*

The Canadian standard for the design of offshore structures developed in 1992, CSA S471-92 "General requirements, design criteria, the environment, and loads" (CSA, 1992), contains the following provision for ice management:

#### **4.11 Ice Management**

*Any ice management measures contemplated in order to conduct normal operational activities around the structure shall be documented. Where ice management measures are to be used to reduce global or local design ice loads, the reliability of the procedures shall be consistent with the intended safety class for the structure or for the particular structural element.*

In 2004, the CSA standard was revised with respect to ice management provisions. The Canadian standard S471-04 "General requirements, design criteria, the environment, and loads" (CSA, 2004) for the design of offshore structures now states the following:

#### **4.11 Ice management**

*Operational procedures may be used to reduce global or local ice design loads, provided that it can be shown that, in combination with structural resistance, the intended level of safety is achieved.*

*The following points shall be considered:*

*(a) Operational procedures may include such activities as ice event detection, physical ice management,*

*disconnection of the structure, moving the structure off station, evacuation of personnel, shut-in of production, or other techniques that reduce the frequency or severity of ice impact or the consequences for personnel or the environment.*

*(b) A reliability analysis which demonstrates that the target reliability has been achieved shall be undertaken. The approach used shall be founded on documented experience whenever possible and shall reflect the uncertainty inherent in the input data and modelling techniques. The load factors presented in Table 6.3 shall be demonstrated to be adequate or shall be adjusted in order to achieve the required reliability.*

*(c) Procedures shall be well documented. Operations in accordance with such written procedures shall be undertaken throughout the operating life of the structure.*

These provisions represent a significant enhancement to those in the original S471-92 (CSA, 1992) document. More emphasis is now placed on the need for systems and procedures for which documented evidence of success is available.

A new international standard *ISO 19906, Petroleum and natural gas industries — Arctic offshore structures* is now being developed and is scheduled to be completed in late 2009. This standard will also deal specifically with ice management considerations at the insistence of Canadians involved at the working group and technical panel levels. In a recent paper outlining the development process for floaters provisions in the 19906 standard (Makrygiannis et al., 2006), specific references are made to ice management.

*"Active intervention through ice management (detection, towing, icebreaking, ice clearing etc.) may be used to alter interaction scenarios within the framework of a systematic ice alert procedure. Ice avoidance through seasonal operation, disconnection or displacement of installation may also be used to alter the interaction scenarios associated with ice actions."*

The scope of ice management activities is also seen in Figure 2.6, taken from Makrygiannis et al. (2006). Basically, ice management activities cannot be divorced from ice monitoring,

forecasting and the continuous assessment of ice risks. The ISO 19906 standard will also deal with the requirement for an ice management plan, which is a new development in offshore standards, although not in terms of Canadian regulations.

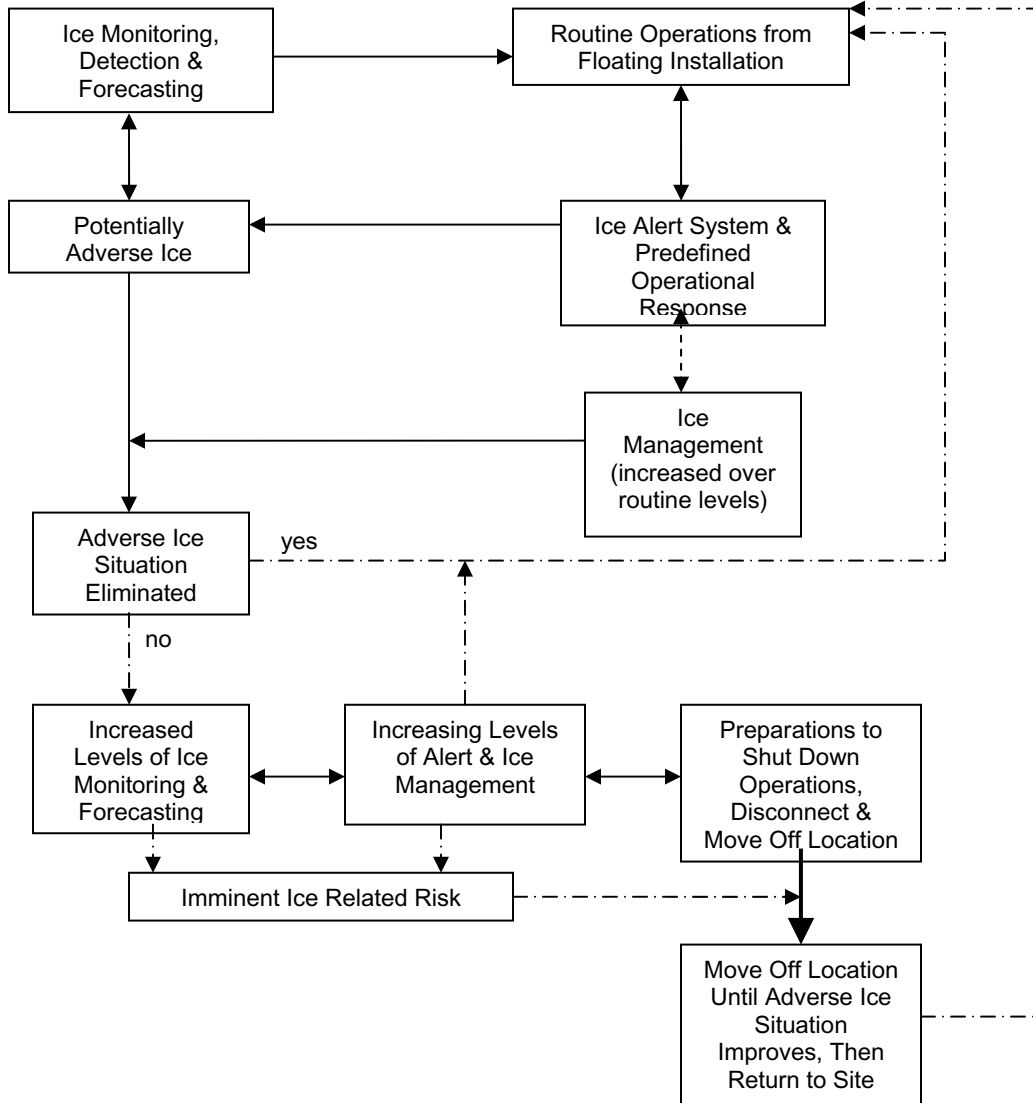


Figure 2.6 Relationship between the various factors for floater operations in ice environments (from Makrygiannis et al., 2006)

## 2.4 Critical Factors in Ice Management

This section presents a discussion of some of the generally accepted elements and considerations of ice management. In practice these are addressed through preparation of an Ice Management Program which shall describe:

- ice detection,
- surveillance,
- data collection,

- reporting,
- forecasting,
- response, roles and responsibility, and decision-making; and
- avoidance or deflection.

### Ice Management Plan

The Operator shall prepare and implement an ice management plan appropriate for the planned operations. Since ice conditions can vary greatly from area to area, and season-to-season, or year-to-year within an area, the ice management plan should be tailored to the region, period, and nature of the operation. For example, ice management is generally of particular importance for operations on the Grand Banks or West Greenland where ice severity can be high.

The ice management plan should be simple, functional, and provide guidance and a plan for action. The plan should address to some appropriate level of detail, the following critical factors:

### Operations Plan and Operating Environment

- Operations details including any or all of: rig type, mode of station keeping, drilling season, well duration, re-supply plans, crew transport plans, etc.
- Description of physical environment conditions including sea ice, icebergs, marine climatology, physical oceanography, etc. The essential elements to describe are historical sea ice and iceberg conditions.

### Ice Management Principles, Strategy, Approach

- corporate attitude towards ice management and toward risk acceptance
- strategy objectives should be defined, e.g.
  - 1- protection of crew and unit,
  - 2- allow operations with a minimum of disruption or added expense due to an ice situation.
- approach should be defined, e.g.
  - 1- iceberg monitoring (surveillance + observations + tracking + forecasts)
  - 2- ice alertness with zone definitions to determine response
  - 3- ice response: physical management such as towing and/or deflection; disconnect and departure from wellsite.

### Regional Strategic Surveillance

- seasonal outlook
- zone of interest
- opportunistic surveillance
- dedicated surveillance
- remotely-sensed surveillance
- frequency of surveillance
- detectability/target verification
- time applicability

Given the Study Area proximity there may be synergies and opportunities in conjunction with CIS aerial reconnaissance in other areas such as the Gulf of St. Lawrence or coastal Labrador. Both aerial and remotely sensed (e.g., RADARSAT) technologies are in routine use for the CIS ice monitoring and ice chart preparation activities and generally provide excellent surveillance coverage.

#### Local Tactical Surveillance and Observation

- aerial surveillance
- vessel-based surveillance
- rig-based surveillance
- detection
- ancillary information
- continuity
- roles/responsibilities

If drilling is occurring during the ice season, the required level of ice observing could likely be performed by the rig or platform weather observer or other designate, i.e., it is unlikely specific ice management personnel would be required offshore.

#### Reporting and Information Management

- reporting/recording tools
- level of automation
- quality control
- communications
- information dissemination
- data sharing

#### Determination of Risk

- incident command and control
- roles and responsibilities
- tactical ice forecasting
- definition of ice management response zones

#### Response

- safety considerations
- interaction with drilling operation
- roles and responsibilities
- physical ice management

#### Joint Ice Management

As part of ice management planning, Grand Banks Operators presently utilize a synergy with each other and the ice service groups regarding joint ice management. Practical benefits include the areas of surveillance and detection, observation, iceberg tracking, data sharing, tactical support, ice forecasting and trajectory modelling, and physical

management. Challenges do exist. A multi-installation management system is in place, involving multiple ice vessels and sensors for iceberg detection. Tankers are a consideration as well. Ice operations are centered from a single platform. Supply vessels involved in iceberg management activities managed by different operators. While ice management resources are shared, priorities of each installation are not always the same. Complete ice information is not always available to individual vessels.

### Ice Reports

As part of, or in addition to, the reporting defined in the Ice Management Plan, the Operator shall report coded ice and iceberg messages and all relevant ice observation, reconnaissance, monitoring, and deflection reports to the Regulator in the event that ice enters the Installation's ice alert/response zones or in the event that the Operator undertakes an aerial reconnaissance for their area of interest. In these instances, daily reports to the Regulator as a minimum are required. Special reports shall be made to the Regulator when dictated by any significant events.

## **2.5 Ice Season Reports**

Essential to ice management is the documentation of the iceberg conditions encountered and operations activities undertaken. Key outcomes include an annual ice season report and associated digital archives of the data. Regular updates for the PERD Iceberg Sighting and Iceberg Management databases follow as well. Figure 2.7 shows an example ice season report table of contents from Provincial Airlines Limited (PAL) illustrating the wealth of information generally provided in these compilations. The reports present a full history of all icebergs tracked and towed.

Figure 2.8 illustrates a daily iceberg plot from an AMEC end of year report, showing a tabular summary of each icebergs position and track together with a plot of all iceberg positions, including any towing activity.

## **2.6 Iceberg Detection**

As outlined above in Section 2.3 strategic and tactical iceberg information comes from many different platforms and sensors, each with different characteristics and potential sources of error. Aerial and satellite based systems provide maps or snapshots of iceberg positions, while rig or platform observations generally provide continuous tracking. The data from all of the systems need to be combined in a rational and seamless fashion. Iceberg detection therefore involves not only the sensors themselves, but the systems and procedures used to integrate them. Further discussion is provided in Section 3.7.

The consequences associated with unaccounted icebergs "slipping through the cracks" in the management system and approaching a platform are potentially very serious. Considerable effort has gone into systems for forecasting iceberg positions, the management of iceberg position and track data. Great strides have been made in this area for the Grand Banks over the last 10 years since Hibernia went on stream, and now Terra Nova and White Rose.

As a practical recognition of the key challenges when developing an effective ice management system, McKenna et al. (2003) modelled the main issues for iceberg management: detection, towing, and disconnection in a risk reduction framework. Their

strategy model shows that risks for offshore installations can be reduced by nearly an order of magnitude through effective detection and towing operations, and a further order of magnitude improvement through introduction of a disconnection capability for the installation. As noted, a significant challenge is integration of iceberg detection for a range of sensors/systems to provide the desired seamless detection for the expected size of icebergs and environmental conditions to be encountered.

## **2.7 Iceberg Towing and Deflection**

### **2.7.1 Single Vessel Iceberg Towing Procedure**

The standard method for deflecting an iceberg posing a threat to offshore facilities has been to encircle the berg with a heavy floating rope which can act as a bridle from which the berg may be towed by an offshore supply vessel. For larger icebergs, the objective is to deflect the ice mass by a few degrees from its naturally preferred route.

Towing requires a supply vessel with minimum 70-140 tonnes bollard pull, towing winch, 100-400 m steel towing hawser, 1200 m synthetic floating line or rope. The rope commonly used is braided polypropylene, 4-1/2" in diameter, generally used in two to three sections each 400 to 500 m in length. The encircling and hookup procedure shown in Figure 2.9 is as follows:

Icebergs with masses up to 4 million tonnes have been towed successfully: most effective for masses in the 1000 to 100,000 tonnes. The technique has good reliability for medium to large icebergs but is ineffective for small ice. It is safe, with small incremental cost, and usually practical in seas to significant wave height of about 4 m



*Ice Season 2003*

**Table of Contents**

Summary.....	6
1.0 Grand Banks Ice Regime .....	8
1.1 Description of Data Sources .....	9
1.1.1 Support Vessels.....	9
1.1.2 Rig-Based Radar Systems.....	10
1.1.3 Dedicated Ice Reconnaissance.....	10
1.1.4 Helicopters .....	11
1.1.5 Synergistic Surveillance.....	11
1.1.6 Northern Radar.....	11
1.1.7 International Ice Patrol (IIP) .....	11
1.1.8 RADARSAT .....	11
1.2 Ice Management Strategy .....	12
1.2.1 Ice Management Zones.....	12
1.2.2 Strategic Ice Management Functions.....	14
1.2.3 Tactical Ice Management Functions .....	15
1.2.4 Field Coordinator .....	15
1.3 Facilities and locations.....	16
1.3.1 Henry Goodrich .....	16
1.3.2 Terra Nova FPSO.....	16
1.3.3 Hibernia.....	16
1.3.4 Eirik Raude .....	17
1.3.5 Sea Horse .....	17
1.4 Ice Management Resources .....	19
1.4.1 Vessels .....	19
1.4.2 Reconnaissance Aircraft .....	21
1.4.3 Information Systems .....	22
1.4.4 Ice Drift Forecasts.....	23
1.5 Description of Ice Management Techniques .....	24
1.5.1 Rope Towing.....	24
1.5.2 Water Cannon .....	25
1.5.3 Prop-Washing .....	25
1.5.4 Net.....	26
2.0 Icebergs .....	27
2.1 Iceberg Measurement.....	40
2.2 Iceberg Size.....	43
2.3 Iceberg Shape.....	51
2.4 Iceberg Drift.....	54
2.5 Iceberg Groundings.....	56
2.6 Iceberg Management Operations .....	59
2.6.1 Tow Statistics.....	68
2.6.2 Comparison to Long-Term Mean .....	75
2.6.3 Evaluation of Tow/Management Success.....	76
2.7 Ice within Tactical Range of Facilities .....	77
3.0 Pack Ice.....	81

*Ice Season 2003*

3.1 Pack Ice Maximums.....	86
4.0 Ice Reconnaissance .....	87
4.1 P.A.L. Dedicated Ice Reconnaissance Reports.....	89
5.0 Recommendations.....	90
6.0 Operational Analysis of the CIO Iceberg Drift Model .....	94
6.1 General.....	94
6.2 Delivery System.....	94
6.3 Overall Reliability.....	95
6.4 The Utility of the Forecasts as an Operational Tool.....	95
6.5 Conclusions.....	98
7.0 Data Description .....	99
7.1.1 Associated Data .....	102

APPENDIX I - INDIVIDUAL ICEBERG PLOTS

- I-a - Terra Nova and Hibernia
- I-b - Flemish Pass
- I-c - White Rose

APPENDIX II - ICEBERG MEASUREMENT LOGS

APPENDIX III - INDIVIDUAL ICEBERG TRACK LISTING

- III-a - Terra Nova and Hibernia
- III-b - Flemish Pass
- III-c - White Rose

APPENDIX IV - TOW LOGS

- IV-a - Terra Nova and Hibernia
- IV-b - Flemish Pass

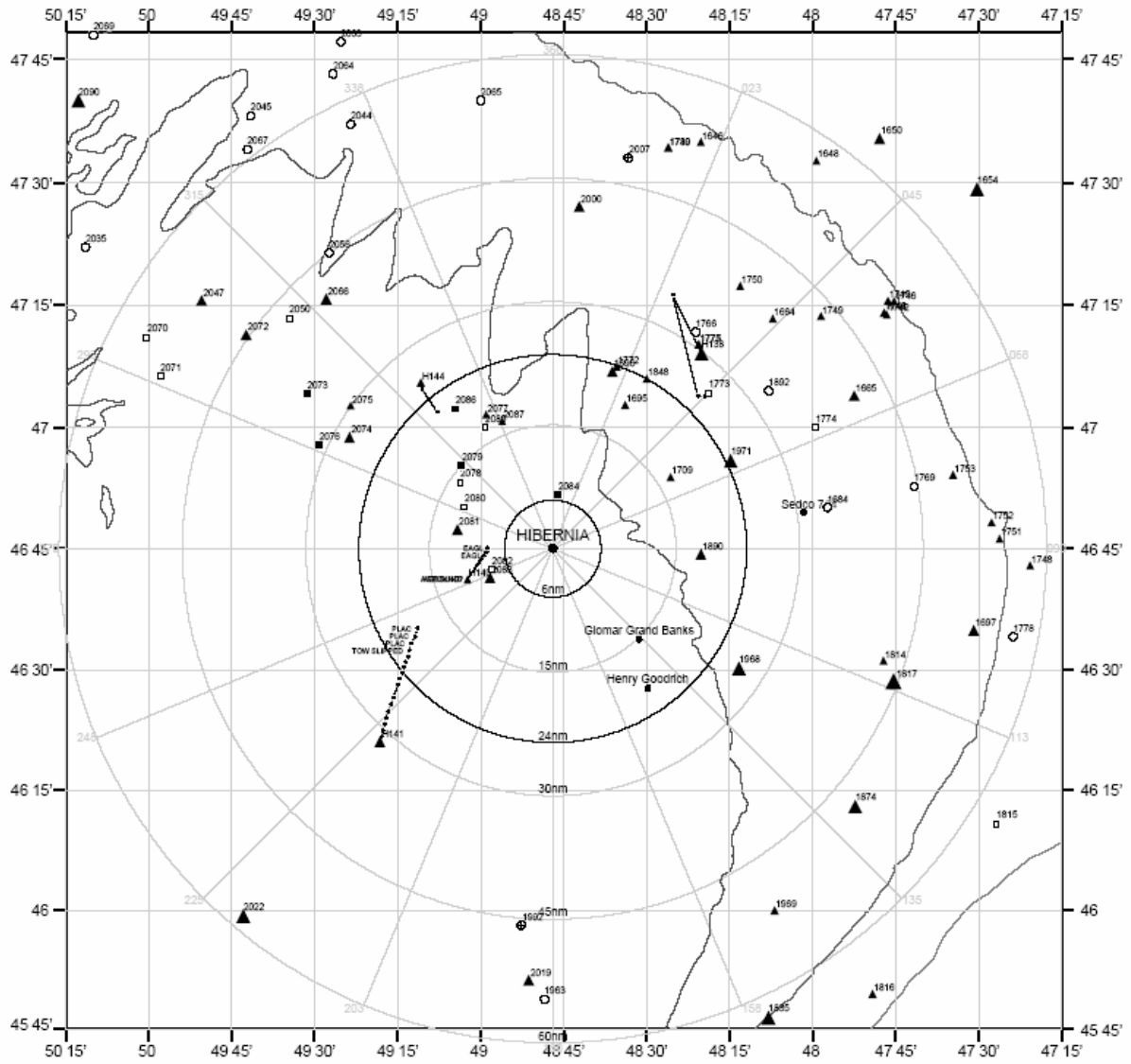
APPENDIX V - DEDICATED ICE RECONNAISSANCE REPORTS

APPENDIX VI - ICE STATUS REPORTS

Figure 2.7 Sample Ice Season Report Table of Contents (PAL, 2003).

Berg ID	DD/HHMM	Def	Siz	Shp	Latitude	Longitude	Rng(nm)	Brg(T)	Spd(kt)	Hdg(T)	CPA(nm)	BCPA(T)	TCPA(D/HHMM)
H138	30/1300	LG	PNC	47-09.1N	48-20.1W	30.3	037	6.42A	154	27.1	064	0/0205	
H140	30/2330	AGR	SM	WDG	46-41.3N	49-02.4W	11.2	250	0.83R	212			
H141	30/1800	MED	DOM	46-21.1N	49-18.2W	32.2	222	0.62R	198				
H144	30/1700	SM	DDK	47-05.5N	49-10.8W	26.2	322	0.66R	350				
1646	30/1200	SM	BLK	47-35.0N	48-20.2W	53.2	020						
1648	30/1200	SM	TAB	47-32.7N	47-59.3W	57.7	034						
1650	30/1200	MED	BLK	47-35.4N	47-47.9W	64.4	039						
1654	30/1200	LG	GEN	47-29.2N	47-30.3W	68.4	050						
1664	30/1200	SM	NTB	47-13.4N	48-07.2W	39.3	044						
1665	30/1200	MED	TAB	47-03.9N	47-52.5W	41.7	063						
1684	30/1200	GEN	GEN	46-50.1N	47-57.4W	34.3	082						
1695	30/1200	SM	DD	47-02.8N	48-33.9W	19.9	027						

\*\*\* Additional plotted bergs are not listed \*\*\*



Hibernia Iceberg Drift Tracks 30 March 2000, History/Observed/Forecast Plot, prepared 11/10/2000 15:17 UTC

Figure 2.8 Sample Daily Tactical Iceberg Plot (AMEC, 2000c)

### Iceberg Towing Procedure

1. Secure a towing shackle to the eye of the steel towing hawser while the eye is secured at the stern of the tow vessel work deck.
2. Secure one end of the (polypropylene) tow rope to the towing shackle now attached to the tow hawser using a second shackle.
3. Secure a "light" buoy or plastic Norwegian fishing float as a tail buoy to the free end of the tow rope using 10 m of 3/4" tag line. A sea anchor may also be attached to the free end of the tow rope to increase drag.
4. The tow rope (with "light" buoy and/or sea anchor) is paid out over the stern roller as the vessel approaches the iceberg on a heading opposite to the desired final tow heading. The length to tow rope selected (number of 400 m sections) is based on berg size and the conditions in which the tail buoy will have to be recovered
5. Secure tow rope to stern quarter to minimize risk of the tow rope fouling the propeller.
6. With tow rope streaming astern and the inboard end attached to the towing hawser, the vessel circles the berg.
7. A lookout should be posted to watch the tail end of the tow rope at all times to ensure that it does not become fouled with the ship's propellers.
8. Approach the tail end of the rope from the down wind side and retrieve the tag line using grappling hook. Retrieve the tow rope with a tugger line and secure the tow rope tail end eye to the 85 tonne shackle already attached to the towing hawser.
9. With the polypropylene tow rope forming a bridle around the berg, a minimum of 100 m of steel towing hawser can then be paid out over the stern roller. This will serve several purposes:
  - The line of the tow force will be brought closer to the iceberg's centre of buoyancy, thereby reducing the overturning moment.
  - With the steel hawser in the water, the recoil action will be damped in the event the rope should suddenly slip or break free from the berg.
  - The towing hawser serves as a shock absorber to compensate for surges in tension in the line due to sea state and vessel motion during towing.

When the towing hawser is deployed and the towing winch brake set, tension is applied and the tow commences.

If the iceberg does not have a good waterline groove to seat the tow rope, or the iceberg is unstable, 200 to 300 m of tow hawser can be used with low power so that the catenary caused by the weight of the steel hawser gives the rope a more downward pull on the iceberg. The technique involves paying out steel towing hawser in sufficient quantity to create a pronounced catenary in the line to bring the line of action of the tow force closer to the centres of hydrodynamic drag and gravity of the iceberg. This reduces the rolling moment of the iceberg from a given tow force as illustrated in Figure 2.14.

Should the berg roll towards the ship or should the rope slip over the top of the berg, the ship's power should be reduced to reduce towing tension and, therefore, potential backlash from the towing hawser. This action should also reduce the chances of the tow rope tangling as tension is taken off the line.

Another option established to deal with slippery, unstable, or otherwise problematic icebergs, following development, sea trials, and operational use and success is the C-CORE iceberg net described in Section 4.3.

If the rope is secured in a waterline groove, power should be increased gradually. During this stage, the berg should be observed carefully for any indication of rolling. The overturning moment applied by the towing hawser may cause the berg to roll towards the ship until the icebergs own inherent stability overcomes the applied overturning turning moment. If rolling of the iceberg is observed, it is important to reduce power and leave enough slack in the hawser to allow for the gyration of the berg. Once the berg is safely under tow, the vessel can be turned slowly onto the appropriate course.

When the towing operation is completed, the tow rope is retrieved as follows:

#### Rope Retrieval Procedure

1. Reduce power to minimum steerage way and heave in the towing hawser until the shackled connections to the polypropylene tow rope are on deck.
2. Release one end of the tow rope and continue steaming ahead until the rope slips around the berg and is streamed out in a straight line astern and the vessel is on a comfortable course.
3. Transfer the end of the tow rope to a storage drum or cathead and commence retrieval.
4. Maintain steerage and ship's heading during recovery to keep the tow line clear of the ship's propellers.

Smaller ice pieces are often rounded or domed with no waterline groove in which to attach a tow rope. The rope sometimes slips over the ice prior to completion of hook-up. High sea states tend to worsen this situation and contribute to increased safety risk to vessel crew members working on deck.

Iceberg Towing is illustrated in Figure 2.10 and Figure 2.11 and also in the pair of pictures Figure 2.12<sup>3</sup> and Figure 2.13 all from the West Greenland ice management (AMEC, 2002a).

---

<sup>3</sup> "Week 6, 14 Aug Icebergs F157,174,176,179,184 towed H. Charisma has difficulty with problem berg F170. It takes three attempts and straightening out of fouled towed gear to bring F170 under control, but F170 comes within 1/3 nm of the West Navion, safely under tow."

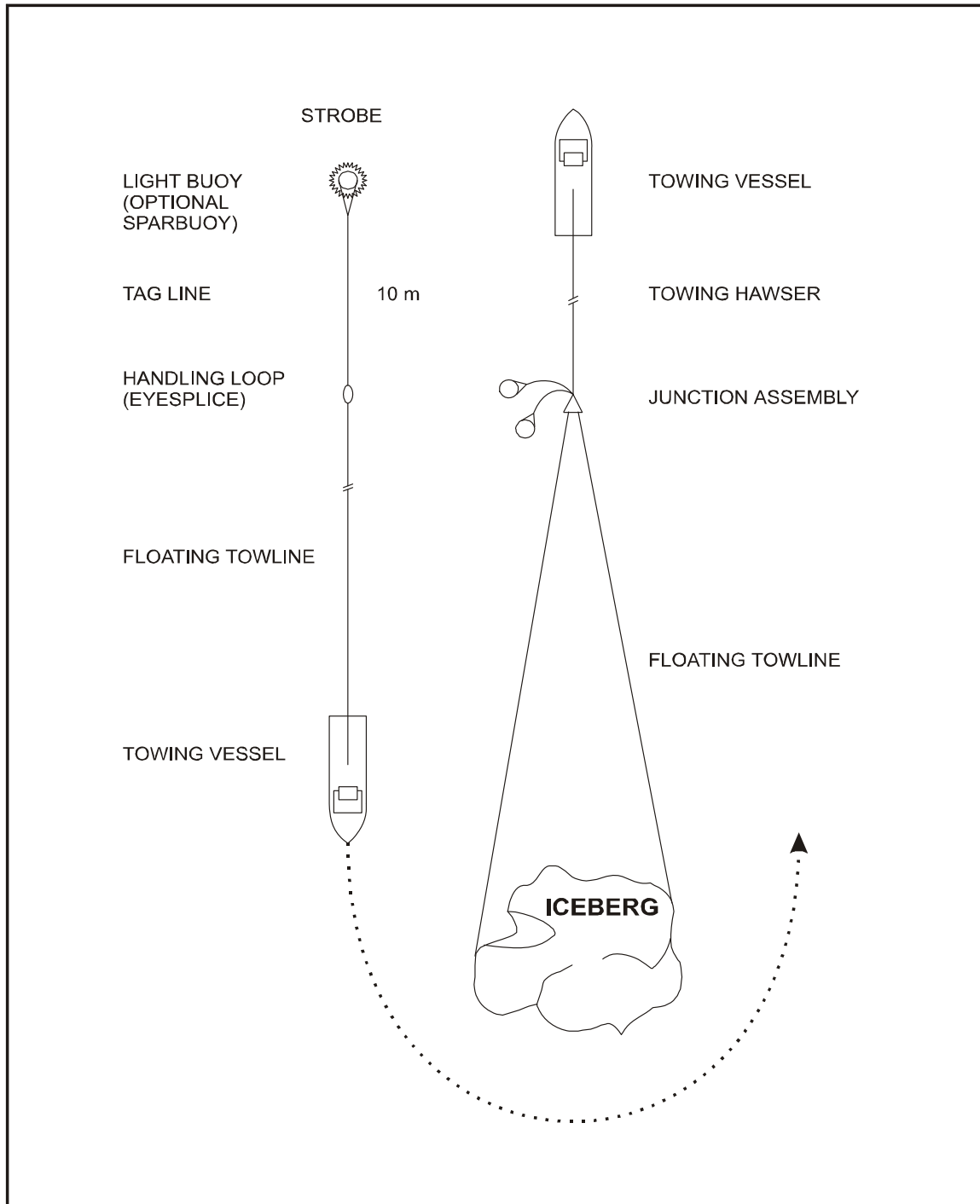


Figure 2.9 Single Vessel Iceberg Towing



Figure 2.10 Retrieving the Tow Line, *West Navion* in Distance



Figure 2.11 Iceberg Towing by *Normand Jarl*



Figure 2.12 *Havila Charisma Towing Iceberg F170 as Seen From the West Navion*



Figure 2.13 *Iceberg F170 Under Tow by Havila Charisma, West Navion in Background*

### High Sea State Deployment of Iceberg Towing Equipment

An additional technique can be used with single vessel towing operations for deploying tow ropes in higher sea conditions. The process is illustrated in Figure 2.15. During periods of high wind and sea state, the vessel always heads into the wind when approaching the iceberg to be towed regardless of the desired eventual tow heading. This minimizes the time that the vessel must be broadside to the sea during deployment. In addition, it ensures that the trailing end of the tow rope is drifting with the wind, away from the ice mass and not toward it. In poor visibility conditions it is easier to predict where the trailing end of the tow rope will be during recovery. The desired tow heading is eventually assumed after successive, gradual course changes.

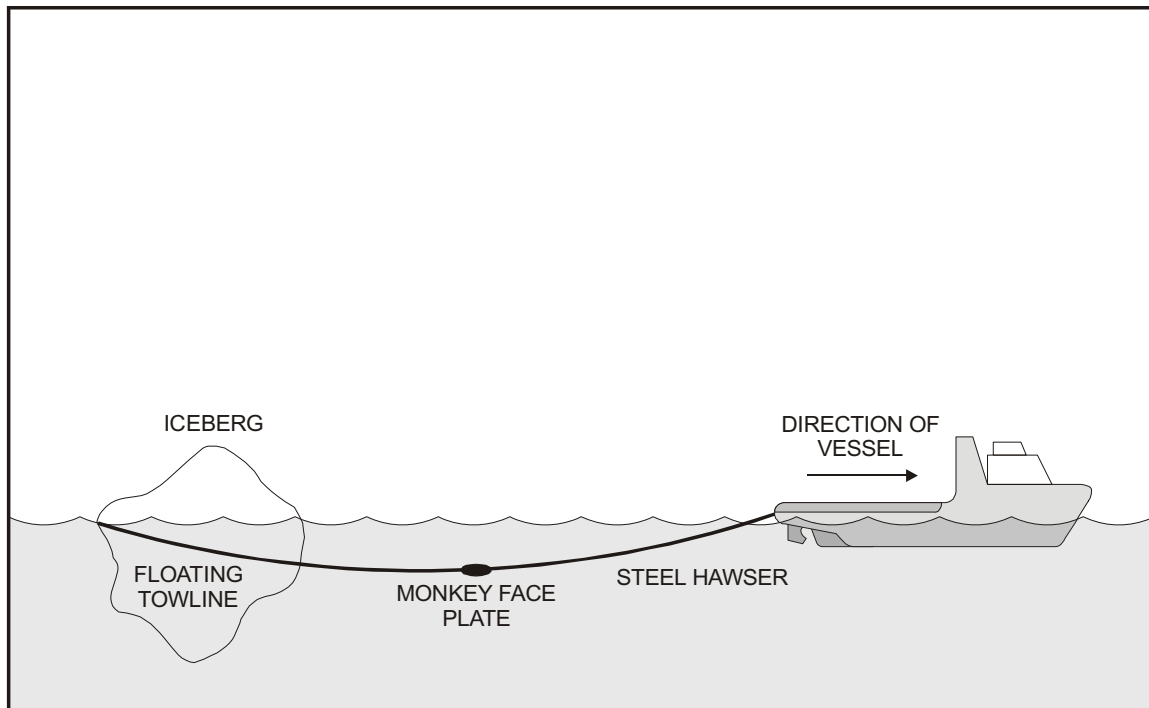


Figure 2.14 Use of Towing Catenary to Reduce Overturning Moment of Unstable Icebergs

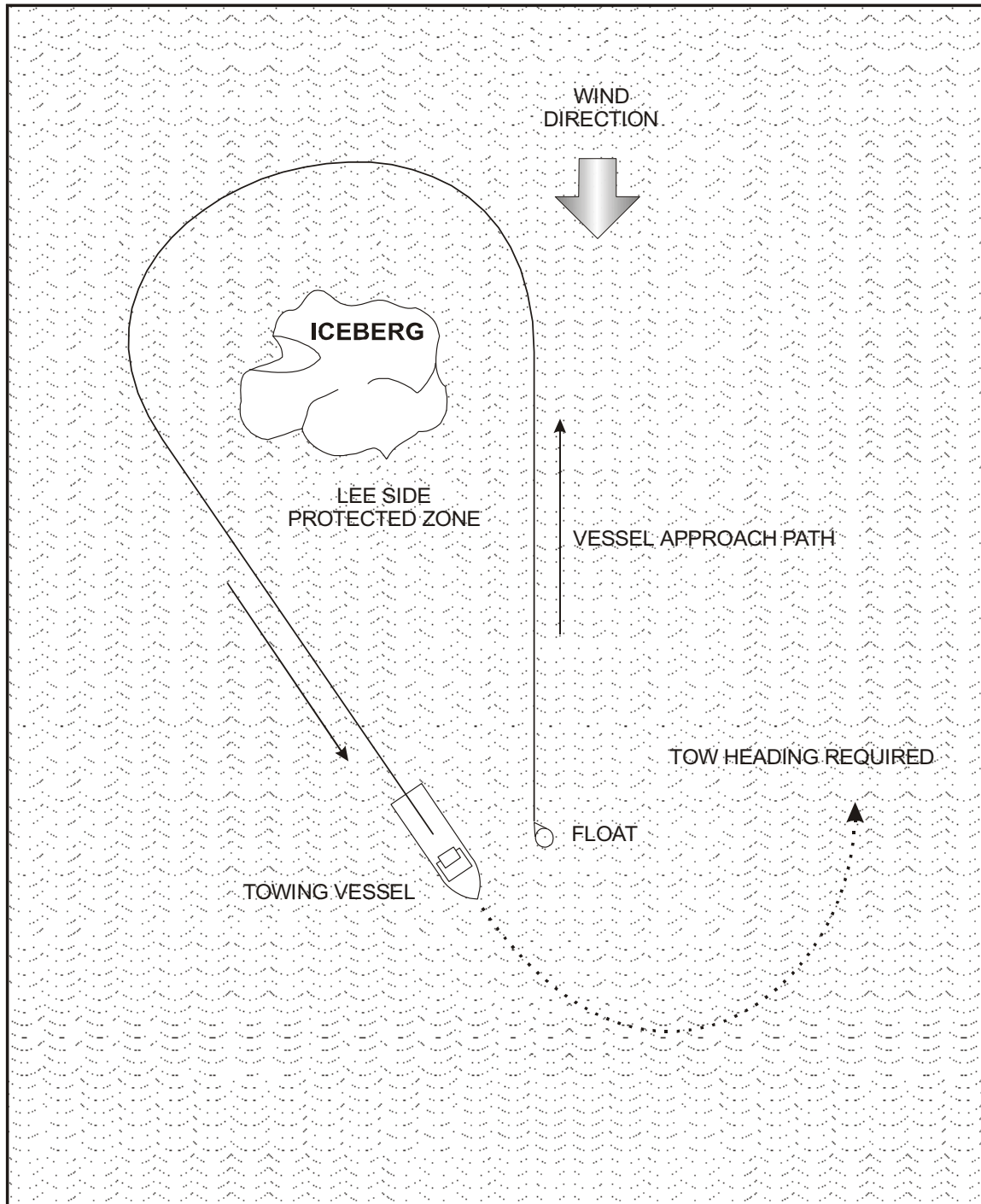


Figure 2.15 High Sea State Deployment of Towing Equipment

### 2.7.2 Dual Vessel Towing

Towing is conducted with two vessels to deflect larger or unstable ice masses. The approach requires two vessels, a single wire rope, and one steel hawser for each vessel. The approach is practical and can produce a significantly greater tow force; however, there can be difficulties in having a balanced vessel thrust, a tendency to see-saw around the iceberg while towing, and difficulty in maintaining depth control over the tow wire.

The PERD IMDB (Section 4.2) reports the technique has been tried 25 times on 13 icebergs over about 10 ice programs. About half the time the lines slipped with two suitable outcomes although in the other cases the evaluation was poor, but operations were unaffected. The method is not suitable for smaller icebergs with lengths less than 60 m and is generally safe. There is significant added cost with the requirement to engage two vessels. As with a single-line tow, there is a limiting sea state of about 4 m and visibility must be good.

### 2.7.3 Water Cannon

For completeness, the standard deflection techniques for small icebergs, bergy bits, and growlers too small to be towed with the conventional floating towline, water cannon and prop-washing, are described

Water cannon are actually fire monitors or nozzles mounted on the superstructure of the support vessels which can direct a high pressure stream of sea water to deflect small ice masses. While their primary function is fire fighting, tests and experience have proven them highly effective in managing small ice masses up to 40,000 tonnes, which might not be towable. The approach requires a supply vessel with high capacity water cannon (e.g., volumes as large as 3600 m<sup>3</sup>/h, ejected through the cannon nozzle at speed of 54 m/s, yields pushing force of five tonnes) and a high-powered hydraulic control system with vessel motion compensation. Cannons are best mounted on the bow, close to target and thereby reducing vessel icing potential during operations.

Water cannon can be useful in iceberg management in three ways:

- The impact of the mass of water on the iceberg can directly move the iceberg.
- The steam of water hitting the sea surface can also induce a current which will help to move the ice mass.
- The impact of the stream on the berg will help to break up and melt the ice. This may have the benefit of "roughening" a smooth iceberg to facilitate a tow.

Small icebergs can be moved by water cannon in any direction at a speed of up to 2 knots while larger bergs can be induced to change direction by as much as 40° from their natural course without increasing their speed.

For ice management purposes, the stream of water from one or more water cannon are directed directly at the visible ice mass above the water line on the opposite side from the direction in which one wishes it to be moved. The thrust generated by the water cannon can create a reactive force in the vessel in the opposite direction which can move the vessel away from the target at up to three knots. This reactive force must be compensated by the vessel's drive and stabilization system and for this reason, the target is generally positioned

directly in front of the bow. Different nozzles can be used on the water cannon to improve the power of the stream or to increase the cutting effect on the ice.

The use of water cannon for ice management is depicted in Figure 2.16.

The use of this technique is limited in freezing spray conditions as blow back from the water streams may result in severe icing on the vessel's metal surfaces. Its use may also be ineffectual in rough seas because of the inability to keep the water stream focussed on the target. Safe and effective operations have been achieved in 7 m combined seas and 30 knot winds. The incremental cost for can be small if part of firefighting water cannon hardware although fuel consumption can be high, on the order of 500 L/h.

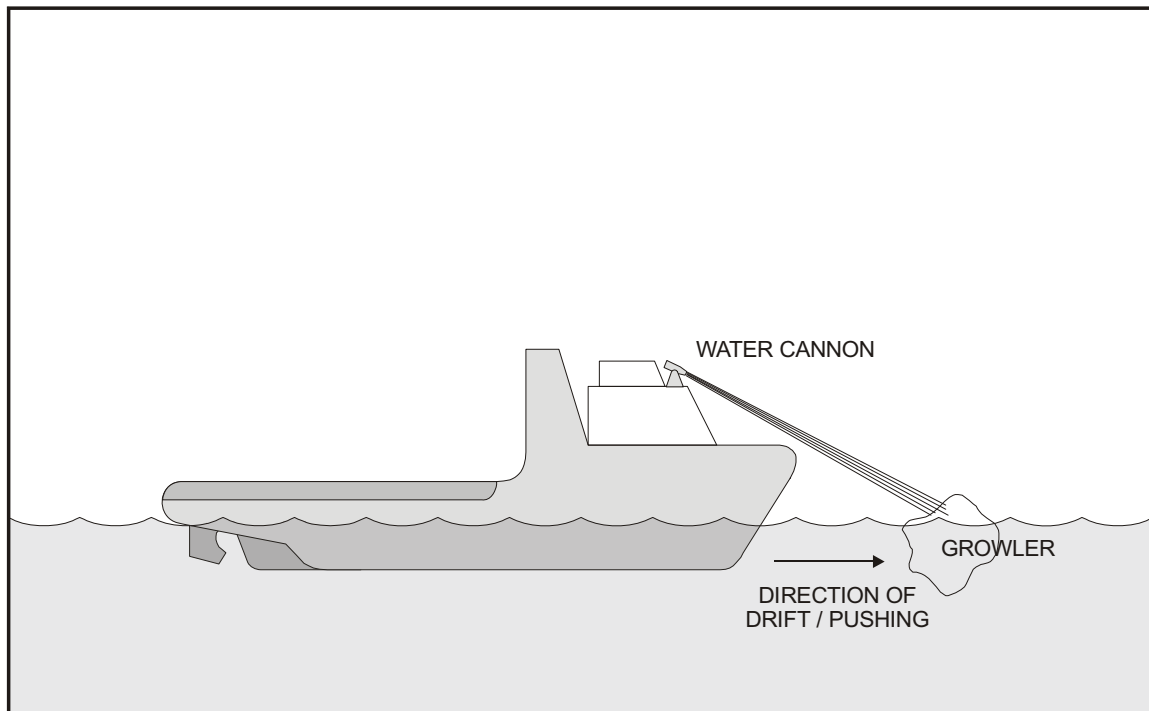


Figure 2.16 Water Cannon

#### 2.7.4 Propeller (“Prop”) Washing

Propeller washing can be a generally successful technique for small ice mass deflection, typically used when a bergy bit or growler is close to facilities and its drift path can be accurately predicted. The tow vessel repeatedly backs up to the piece of ice and accelerates away, thus moving the ice in the desired direction with the backwards thrust of the water from the propellers. This technique is illustrated in Figure 2.17.

This method is really only effective when problem bergy bits and growlers are very close to the facilities since long range deflection (greater than 1 n.mi.) may require many hours of prop-washing. Extended prop-washing tends to be a very arduous task for the vessel master, as well as resulting in high fuel consumption and excessive wear on vessel machinery.

This technique requires skilled vessel handling and vessel contact with the ice must be avoided, which can be difficult in high seas. As well, high sea states tend to reduce the effect of the vessels wake quickly, thereby reducing the effectiveness of this method.

The presence of any sea ice could also be a limiting factor. Cost considerations include fuel consumption and machine wear.

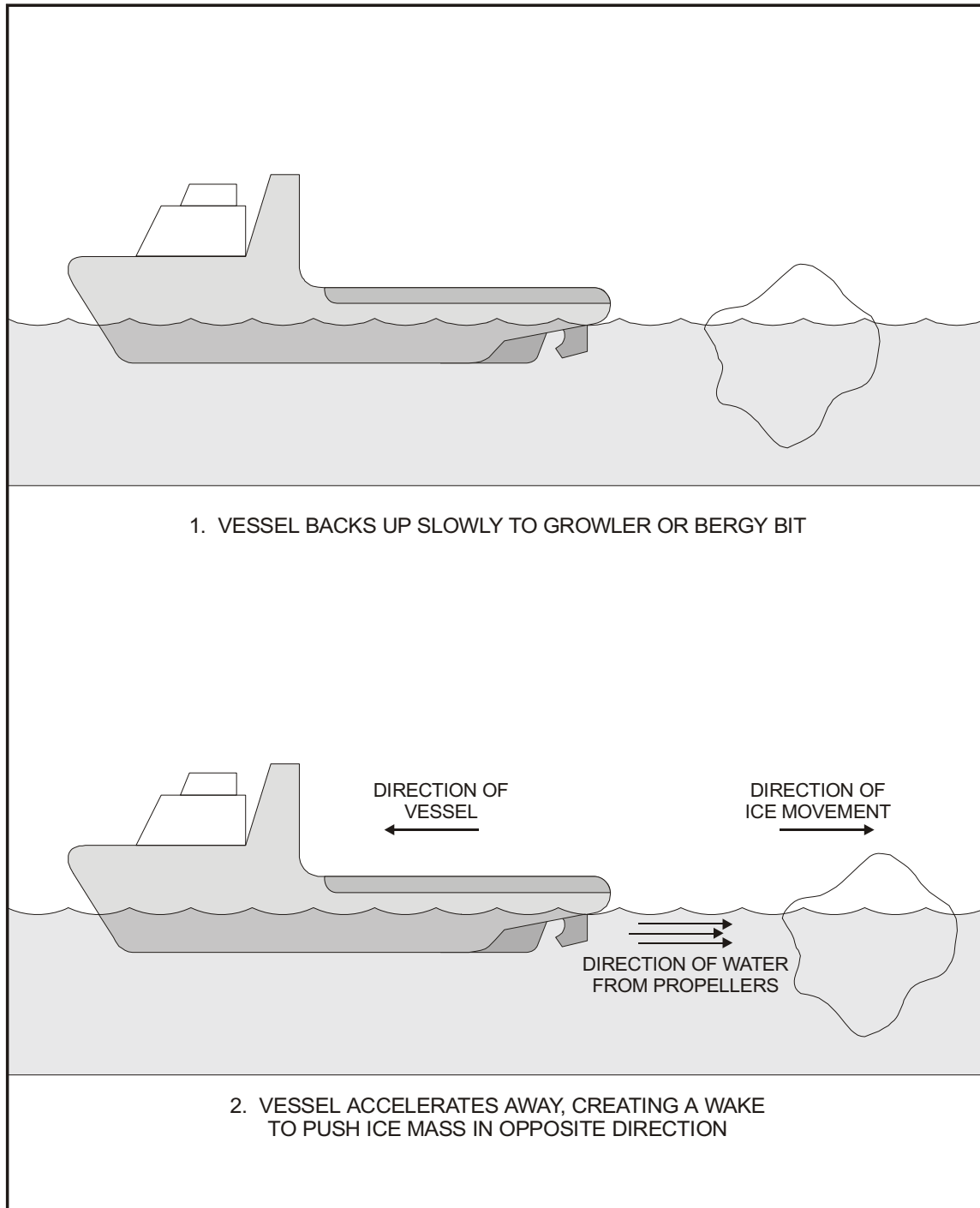


Figure 2.17 Propeller Washing

### 3.0 ICEBERG DETECTION RESEARCH

#### 3.1 Overview

##### 3.1.1 Range of Potential Platforms and Sensors

A number of actual and potential iceberg detection systems are shown in Table 3.1. Those labeled “Possible” are not necessarily feasible. What this table illustrates is a great potential for innovative systems should the need arise.

Visual iceberg detection, whether from offshore facilities, supply vessels or aircraft, is always best but is severely limited by fog. Consequently, there is a heavy reliance on radar systems for iceberg detection regardless of the platform. Locally at Grand Banks facilities, detection is either visual or by marine radar. Regionally, it is done by aircraft, supply vessels and satellites, and further afield using aircraft or satellite.

Table 3.1 Detection Systems and Supporting Platforms

PLATFORM SENSOR	Ice Management or Supply Vessel	Production or Drilling Facility	AUV	Moored u/w platform	Fixed Wing Aircraft	UAV	Helicopter	Satellite
visual	X	X			X		X	
marine radar	X	X						
SAR					X	O		X
search radar					X		O	
infra red	O	O			O	O	O	
optical sensor	O	O			O	O	O	X
sonar			O	O				

NOTES: X Existing System  
O Possible System  
UAV Unmanned Aerial Vehicle  
AUV Autonomous Underwater Vehicle  
SAR Synthetic Aperture Radar

##### 3.1.2 Strategic Issues

For Grand Banks offshore operations, strategic detection is imperative for establishing a state of readiness for the initial arrival of icebergs each spring and routinely for the timely deployment of ice management vessels. Key considerations for Grand Banks operations include:

- the most southerly progression of any icebergs
- average numbers and locations of icebergs
- the presence of very large icebergs, tabular and otherwise

Prior to the start of the season, a wide area extending up the Labrador coast is often surveyed. Exact positions and iceberg dimensions may not be necessary unless very large icebergs are sighted. Once icebergs are present on and around the Grand Banks, icebergs that could potentially feed into the tactical zone need to be monitored. While precise locations may not be required, the need for positive identification of icebergs is increased.

Unexpected icebergs slipping into the tactical zone are of considerable concern. So are false identifications, because they involve needless effort and expense, and can potentially lead to decreased preparedness.

### 3.1.3 Tactical Issues

The distinction between tactical and strategic zones is not clear cut. For single installations, ice management vessels are deployed to prevent the entry of icebergs into a critical zone, defined by the time required for the installation to shut down. The size of the tactical zone therefore depends on expected iceberg drift velocities and the time to manage the icebergs. For drilling operations, shutdown times are often about a day. For production, orderly FPSO shutdown can be performed in a couple of hours and emergency shutdown in less than an hour. Iceberg towing operations average less than 10 hours. A rough guide for the radius of the tactical zone would then be about 20 km for an iceberg drift speed of 0.5 m/s. With finite vessel resources, the tactical zone would need to increase with increasing numbers of icebergs present. For multiple installations, tactical zones can overlap or come in close proximity so the tactical zones may need to encompass a larger area.

Tactical components include:

- detection
- tracking
- threat evaluation

For threat evaluation, the size, position and drift speed of an iceberg need to be estimated with some accuracy. The maximum waterline dimension or mass (based on above water volume) can be used as measures of iceberg size.

In the tactical zone, detection requirements are quite stringent. All icebergs need to be detected and tracked on a near continuous basis, whether remotely or from the production facility or supply vessels. Furthermore, icebergs need to be detected at night, in fog and under high wind conditions. With the potential for calving, regular observations need to be made since forecasts and projections will be inadequate in such cases.

Ideally, all icebergs should be detected, although it may be difficult to detect growlers and bergy bits except in the immediate vicinity of the facility. A good guide for the minimum detection limit is the size of iceberg that can make contact with the structure without causing damage. For FPSOs, bergy bits may not cause significant damage unless drift speeds are high or impact speeds are increased through wave action. Bergy bits should not cause damage to a fixed structure.

In recent years, circumstances have arisen where storm conditions have reduced aircraft surveillance capabilities, prevented management operations from being carried out, made satellite iceberg detection difficult and resulted in downtime for drilling operations. Detection issues have contributed to these events. While all efforts have been made to prevent recurrence, there is still room for improvement through research. A couple of these – iceberg detection in high winds and sea states, and iceberg detection in pack ice – are dealt with in this chapter.

### 3.1.4 Radar Bands

Because of its weather penetration, radar is an element of most iceberg detection systems. The various radar bands are shown in Table 3.2. The lower frequency bands, L and S, have lower resolution but better all weather capabilities. X band, because of the shorter wavelength, provides more detail but has less snow, rain and fog penetration. Most marine radars are X and S band. C band is used for RADARSAT-1, RADARSAT-2 and Envisat, and provides a good compromise.

Table 3.2 Radar Bands

Band	Wavelength (cm)	Frequency (GHz)
L	15-30	1-2
S	8-15	2-4
C	4-8	4-8
X	2.5-4	8-12

## 3.2 Airborne Systems

Presently, most of the strategic and tactical iceberg detection for Grand Banks operations is performed by PAL Environmental Services from fixed wing aircraft. The same system has been used extensively for regional iceberg surveys for the CIS, fisheries patrol and a number of other surveillance activities. The primary sensor is an X-band search radar, supported by visual observations and thermal imaging. Complete geographic coverage is provided through overlapping flight patterns, and the redundancy helps to improve detection capability. Radar cross section data have been correlated with iceberg size and detection has been optimized through many years of experience.

Detection capability is less due to the sensors themselves, but on the availability of the aircraft. The flexibility of the aircraft to re-fly certain areas, change altitude and provide visual confirmation can make up for deficiencies in the sensors.

## 3.3 Satellite Systems

### 3.3.1 Background

Because of cloud and fog penetration requirements, the only feasible satellite based sensor is radar. Optical sensors, although offering better resolution are ineffective for a very significant proportion of the time on the Grand Banks. Satellite radar is the sensor of choice for sea ice observations worldwide and is slowly gaining acceptance for iceberg detection.

Since 1998, considerable research has been conducted on satellite detection of icebergs, the bulk of which has been led by C-CORE. This has been done under the ADRO-1 and ADRO-2 programs for the ESA and CIS (Randell et al. 1999, 2000), under the integrated ice management initiative (IIMI) joint industry program (C-CORE 2001a, 2002, 2003a, 2004a, 2005a), and under several other projects. A summary is provided in Table 3.3.

Table 3.3 Research Projects on Satellite Radar Detection of Icebergs

Program	Reference	Detail
ADRO 1997/1998	Randell et al. (1999, 2000)	RADARSAT 1 fine mode iceberg detection – ground truthing off Newfoundland & antarctic
ADRO 1999	Flett et al. (2000)	RADARSAT 1 range of scansar and wide resolution modes – ground truthing off Newfoundland – some data on ship discrimination
ADRO-2, CIS 2000 IIMI	Power et al. (2001)	RADARSAT 1 range of scansar and wide resolution modes – ground truthing off Newfoundland – some assessment of POD based on wind speed & look angle
ADRO & CIS, ENVISAT 2003	Lane et al. (2003)	RADARSAT 1 & ENVISAT assessment of POD based on wind speed & look angle
CIS/IIMI 2003/2004	Howell et al (2004, 2006)	RADARSAT 1 & ENVISAT – effect of polarization in ship/ice discrimination
CIS GMES 2005	C-CORE (2005b)	ENVISAT ship – iceberg discrimination
Barents Sea 2003	C-CORE (2006a)	ENVISAT – ground truth ship & icebergs – inexact ground truthing, hence correlations uncertain

### 3.3.2 Operational Experience with Satellite Radar in Canada

Radar satellites have been used operationally for iceberg detection on the Grand Banks since 2003. Most of the effort has been conducted by C-CORE on behalf of the IIP and the CIS, with sponsorship from the Canadian and European space agencies. Approximately 100-150 scenes have been collected per year in a quasi operational mode.

The fall iceberg population surveys conducted by the CIS are now all performed using satellite radar. Most of the sea ice monitoring activities of the CIS are conducted using satellite radar.

The ISTOP oil spill monitoring project involves the collection of 4000 images per year by CIS.

The DND sponsored Polar Epsilon project, aimed at ensuring Canada's marine sovereignty, involves satellite based surveillance.

AMEC provided ice management planning and operational ice management services for Norwegian oil and gas company Statoil in summer 2000 as part of the Fylla Bank Exploration Drilling Program in the Davis Strait 130 kilometres southwest of Nuuk, Greenland (AMEC 2000b, AMEC 2002a). During the ten-week drilling program, 228 iceberg targets were tracked near the dynamically-positioned drillship *West Navion*. Of a total of 168 confirmed icebergs, 64 icebergs were deflected.

The Danish Meteorological Institute (DMI) provided twice daily weather forecasts and a series of 16 RADARSAT overflights, every few days over the drilling program, with associated iceberg target information provided operationally. These aided in determining large-scale patterns of bergs over the area. This is believed to have been the first fully operational use of this technology. RADARSAT imagery provided iceberg positions which

correlated highly with vessel radar positions, and provided useful strategic information about upstream icebergs.

Only one fixed-wing aerial reconnaissance was performed at the beginning of the program. Poor visibility conditions over the area for much of the program meant that flying was generally not a viable reconnaissance option. Furthermore, in practice, the on-board Ice Watch relied primarily on vessel radars and used support vessel reconnaissance to locate and track icebergs. The success with this approach and the prevalence of icebergs within 20 or 30 miles or less which kept ice operations in a tactical response mode most of the time, together with the more strategic view afforded by RADARSAT, meant that aerial reconnaissance was not required.

### 3.3.3 Iceberg – Vessel Discrimination

In the studies listed in Table 3.3, it was found that icebergs could be detected with confidence when their maximum waterline dimension was greater than or equal to the resolution of the radar image. Under strong wind conditions, the probability of detection ranges between 50% and 75%.

Improvements can be made in ship/iceberg discrimination with the dual polarization capability of Envisat, and will be eventually with RADARSAT 2. The 25 m-30 m resolution modes of RADARSAT 2 also have quadpolarization, but only for narrow swath. There has been some recent DND research on quad polarization for marine applications, in which equivalent detection capability was achieved but higher sea states.

### 3.3.4 Iceberg Detection in Sea Ice

Lane et al. (2004) have addressed the performance of satellite radar for the detection of icebergs in sea ice. Using backscatter characteristics of RADARSAT images for sea ice only and icebergs only, they were able to estimate iceberg detection probability in surrounding sea ice. Comprehensive tests with ground truthing have not yet been conducted, although it is possible to identify larger icebergs, particularly where there is differential drift and where present in leads in the sea ice.

### 3.3.5 Trade-off Between Resolution and Swath Width

Potential limitations of satellite systems for Grand Banks operations are mostly related to coverage and resolution. With existing radar systems and those anticipated in the near future, only low resolution modes can be used to achieve adequate coverage. Referring to the above research, a resolution of about 10 m is required to distinguish smaller icebergs from fishing vessels with confidence and maintain false alarm rates to acceptable levels. For larger icebergs and ships, a 30 m resolution is probably sufficient.

Presently, RADARSAT-1 and ENVISAT are the only commercial satellites providing radar data. The nominal resolutions and swath widths for these systems are provided in Table 3.4 and Table 3.5. Corresponding data for the RADARSAT-2 satellite, to be launched this year, are given in Table 3.6. Repeat coverage over the same area for one satellite is about 2 days on the Grand Banks. Using multiple satellites, near daily coverage might be possible.

Basically for these systems, 10 m resolution is associated with a 50 km swath, 30 m resolution with a 100 km swath, and 100 m resolution with a 500 km swath. Since realistically a resolution of 10 m-30 m is required to distinguish icebergs, only a 100 km swath is possible. Consequently, satellite radar cannot presently provide the necessary coverage to support ice management operations on the Grand Banks on its own.

The next generation of satellites, involving two Canadian and three European platforms, is expected to begin operation by 2012. For this initiative driven by Canadian military, the technology would be simpler and cheaper, and more satellites would be available. Access would be real time with a 15 minute turnaround expected.

Table 3.4 ENVISAT Modes, Resolutions and Swath Widths

Mode	Resolution [m]	Swath Width [km]
IM Image	30	56 – 100
AP Alternating Polarization	≥30	100
WS Wide Swath	150	400
GM Global Monitoring	1000	400
WV Wave	30	5-10 x 5

Table 3.5 RADARSAT-1 Modes, Resolutions and Swath Widths

Mode	Resolution [m]	Swath Width [km]
Standard	25 x 28	100
Fine	8-9 x 9	50
Wide	35/27/23 x 28	150
ScanSAR Narrow	50 x 50	300
ScanSAR Wide	100 x 100	440-500

Table 3.6 RADARSAT-2 Modes, Resolutions and Swath Widths

Mode	Polarization	Resolution [m]	Swath Width [km]
Fine		10 x 9 m	50 km
Standard		25 x 28 m	100 km
Low Incidence		40 x 28 m	170 km
High Incidence		20 x 28 m	70 km
Wide		25 x 28 m	150 km
ScanSAR Narrow	send H or V	50 x 50 m	300 km
ScanSAR Wide	receive H and V	100 x 100 m	500 km
Fine Quad-Pol	send H and V	11 x 9 m	25 – 50 km
Standard Quad-Pol	receive H and V	25 x 28 m	25 – 50 km
Ultra-Fine Narrow	send H or V receive H or V	3 x 3 m	10 km
Ultra-Fine Wide		3 x 3 m	20 km
Triple Fine		11 x 9 m	50 km

As data from multiple satellite radars become available in future, combining high resolution and wider swaths, this method could potentially cover off most strategic iceberg detection requirements and tactical requirements beyond marine radar range. While satellite radar is very promising as a reliable all-weather detection system, it may not always be the most efficient and cost effective to support Grand Banks operations.

### **3.4 HF Radar**

HF radar transmits electromagnetic waves of about 3 MHz to 50 MHz, (about 100 m to 5 m wavelength) that travel along the sea surface by ground wave propagation. HF signals can follow the earth's curvature for very long distances and are used routinely for remote ocean wave and current measurement. HF radar systems typically require very long antennas and are best suited to shore based sites

HF radar data on iceberg tracks were collected for brief periods from sites at Cape Race and Bonavista. Some success was achieved for tracking larger icebergs in lower sea states (e.g., C-CORE 2001a, 2003a). Better detection was achieved in daylight than in darkness because of atmospheric conditions. Presently, HF radars are not used for iceberg detection and tracking on the Grand Banks, and general interest in such systems has decreased of late. A program to install new systems and Cape Bonavista and Cape Race has been cancelled. One reason for this is that HF radar signals travel very long distances and there are concerns that they may interfere with other radar signals in coastal areas of Europe. The licensing of such sites for commercial applications can be a concern.

### **3.5 Marine Radar**

#### **3.5.1 Background**

Marine radar is used routinely for iceberg detection from production facilities, drilling rigs and ice management vessels. Standard marine radar is quite susceptible to sea clutter in higher winds and sea states.

A scan averaging system developed by Sigma Engineering (now Rutter Technologies) allows the averaging of up to 64 radar scans, thereby reducing clutter and allowing for the detection of bergy bits in higher sea states. The scan averaging process is analogous to the human interpretation of marine radar, in which repeat targets are identified and the changing sea clutter is filtered out. Its effectiveness for iceberg detection has been demonstrated (e.g., C-CORE 2003a) and systems have been tested on the Terra Nova FPSO and on shuttle tankers.

Performance curves based on a model of scan averaged systems have been developed (Johnson and Ryan, 1991) and used for estimating marine radar performance (e.g., McKenna et al. 2003). Generally, detection is quite good out to the horizon and falls off quickly beyond. Bergy bit detection is also impaired in higher sea states.

### 3.5.2 Coherent Radar

While the use of coherent radar has been limited to military applications, the IMO is presently developing specifications for coherent S-band 3GHz marine radar. The institution of these specifications will result in a breakthrough for coherent systems and widespread use is expected within a few years. Offshore production facilities and supply vessels are expected to have coherent radars within this time frame.

C-CORE (2003b) developed a prototype coherent UHF radar with L-band and S-band capabilities. In preliminary testing, bergy bits were detected successfully over a limited range of sea states.

Coherent radars will have better iceberg discrimination capabilities, especially in higher sea states. Coherent radars also have good tracking capability, unlike regular and scan averaged systems, and this will be an added benefit. Actual performance of coherent systems will need to be assessed if detection probabilities for icebergs of various sizes and shapes in a range of sea states.

## 3.6 Other Systems

### 3.6.1 UAV

The RAVEN research project was initiated in 2003 to investigate the use of UAV platforms for environmental monitoring, including spills off Canada's east coast. While there is some potential for the eventual use of small unmanned aircraft for iceberg detection, the smaller cost effective craft have payload limitations that preclude them from acquiring and storing or transmitting radar imagery in a practical sense at present.

Because of data transfer limitations, UAV systems are not presently appropriate for iceberg detection. Even with the micro SAR systems, radar coverage using a UAV system is severely limited. There may be a future for such systems and research efforts should be encouraged, but clearly technological advances need to be made before they can be part of an operational iceberg detection system.

The Instrumentation Control and Automation Centre (INCA) at Memorial University in 2003 initially planned to develop a project called RAVEN which was a fixed wing remotely operated aerial vehicle which was to be used for offshore environmental monitoring. One of the initial tasks was to locate and identify icebergs. A recent search of the INCA web page<sup>4</sup> indicated that the RAVEN project now entails the use of RC helicopters with goals to monitor pollution levels in remote environments that are unsafe for human travel, and there is no mention of the RAVEN project as described above and at the time of writing there had been no reply from INCA regarding the initial incarnation of the project.

---

<sup>4</sup> <http://inca.engr.mun.ca/aras.htm#overview>

### **3.7 Integration of Detection and Tracking Systems**

#### **3.7.1 Trajectory Forecasts**

With marine radar, icebergs can be detected continuously and tracking is straightforward. For airborne, satellite or ship based detection, there may be significant time intervals between observations and tracking accuracy deteriorates with increasing lag time. Some of this deficiency can be made up through accurate trajectory forecasts.

Considerable research has been completed by the CIS over the last 10 years to improve iceberg trajectory modelling. The verification work, undertaken with the assistance of ice management service providers, research contractors and government research organizations, has been documented in Sayed and Carrieres (1999), Carrieres et al. (2001), PAL (2003, 2004), Kubat et al. (2005) and Kubat and Sayed (2006). The efforts of the CIS have focused on:

- (i) improving ocean current modelling, since currents represent the primary driving force for iceberg drift (Yao et al., 2000)
- (ii) improving the characterization of iceberg shape in the drift model (Barker et al., 2004; McKenna, 2004b)
- (iii) acquisition of well defined trajectory and supporting data (McKenna, 2003, 2004a)

While progress has been made on (i) and (ii), more effort is required to provide reliable forecasts for the oil and gas industry. The CIS and others have identified potential improvements to ocean current forecast models. Further accurate underwater iceberg shape measurements would improve the relationship between above water dimensions, and underwater size and shape. Aside from a single study (Smith and Donaldson, 1987), there is a distinct lack of data documenting drift tracks, iceberg and metocean parameters. To make any progress on (iii), a commitment from industry to field programs with a dedicated vessel is required.

#### **3.7.2 Fusion of Data from Multiple Sensors**

Iceberg management systems for the Grand Banks rely on data from aircraft, offshore facilities, supply vessels, satellites and other sightings of opportunity. The data are acquired at different times and with different precisions in terms of position and iceberg attributes. Present management systems used for the Grand Banks have evolved gradually over the years and are now able to identify unique icebergs in most cases. The experience gained over the years has been adapted by Churchill et al. (2004, 2006), who have developed an automated technique for the fusion of iceberg data from different sources. The approach is based on multiple hypothesis tracking and the CIS drift model outlined in Section 3.7.1. The approach has been integrated with the data sources used presently for Grand Banks operations.

There is ample potential for the data fusion approach to evolve over time as more sensors are introduced and as the performance of the CIS drift model and data sources are better understood.

### 3.7.3 Calving Forecasts

One aspect of ice management that is sometimes overlooked is the calving process, by which icebergs break up into smaller pieces. Sometimes only small pieces calve and other times two or more icebergs of considerable size can result. The significance to ice management operations is anticipating and dealing with events in which one iceberg problem is multiplied into several ones. Undetected smaller calved pieces can pose a threat to supply vessels and shuttle tankers.

The CIS has taken a number of initiatives in this respect, with the acquisition of calving and deterioration data (Crocker 2000, 2001, 2002, 2003) and with the modelling of the deterioration process (Savage et al. 2000, 2001). An interesting aspect of the calving data is the documentation of differential drift between the parent iceberg and smaller calved pieces.

## 4.0 ICEBERG TOWING RESEARCH

### 4.1 West Greenland Towing Experience and Analysis

In 2002, AMEC documented the successful Fylla iceberg management program in 2000 off the West Coast of Greenland where a total of 168 confirmed icebergs were tracked and 64 icebergs were deflected, and related the experience gained to operations on the Grand Banks on the East Coast of Canada (AMEC, 2002a). The report included details of each of 64 icebergs towed over the ten week program and identified key practical issues in iceberg management. An edition of the PERD Iceberg Management Database (Section 4.2) was compiled for the Fylla (Qulleq-1 wellsite) iceberg deflection dataset (AMEC, 2002b).

For this program, towing operations were successful 91% of the time. 57 icebergs were towed with a single line, while 7 were prop-washed. Figure 4.1 shows the size distribution of icebergs deflected (15 of them small, 33 medium). There were 77 tows on the 64 icebergs, and a total of 96 attempts. Of the 96 attempts there were a total of 32 complications. Line slippage occurred 21 times (four times for small icebergs and 17 times for medium ones) during 16 tow attempts (Figure 4.2) being the greatest practical limitation to the towing.

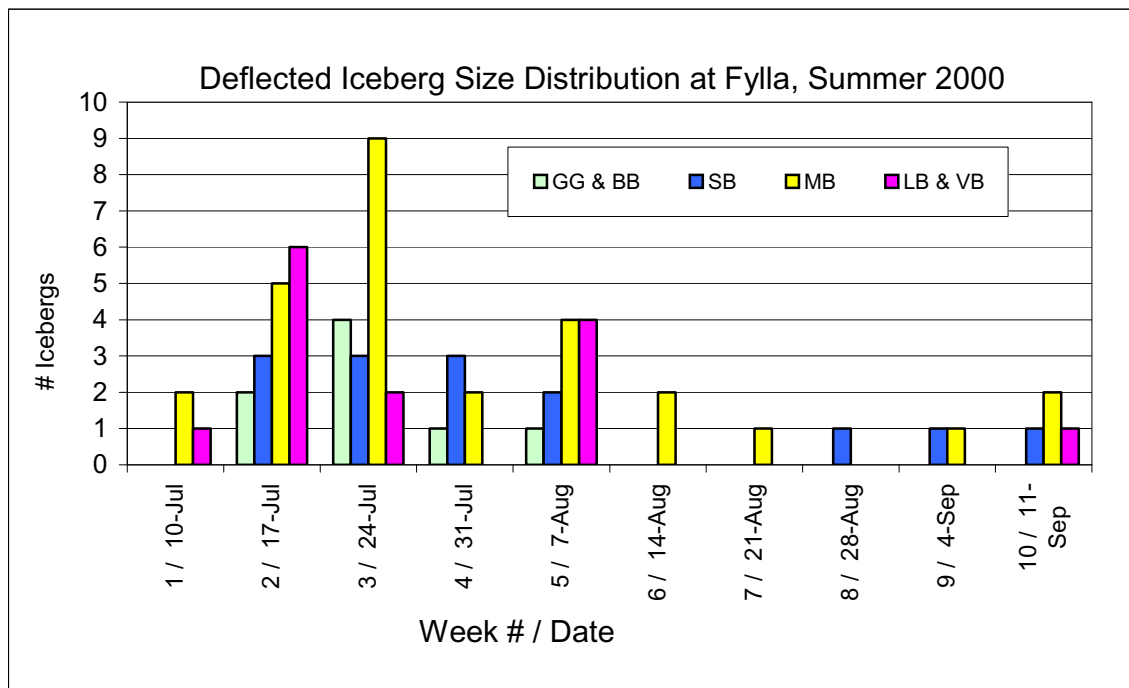


Figure 4.1 West Greenland, Deflected Iceberg Size Distribution (Source: AMEC, 2002a).

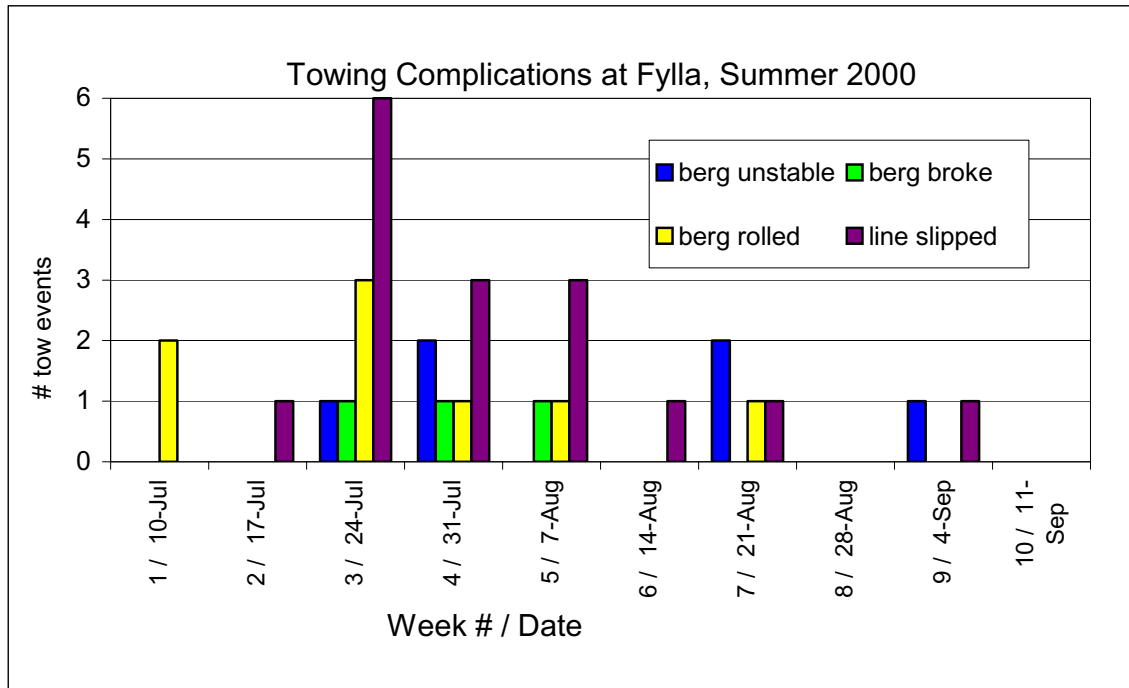


Figure 4.2 West Greenland Towing Complications (Source: AMEC, 2002a).

The availability of two dedicated support vessels to deflect the icebergs was a key resource factor that led to the high level of success. This was an intense program. 18% of all iceberg towing operations were stopped early to enable the vessels to take up towing on a new, higher priority, iceberg approaching the site. While several large icebergs with masses greater than one million tonnes were successfully deflected, 22% of all tow attempts ended due to tow line slippage, a factor attributable mostly to problematic, smooth-surfaced, small and medium sized icebergs.

#### 4.2 The PERD Iceberg Management Database

The PERD Comprehensive Iceberg Management Database presently contains detailed information on 1505 iceberg management operations (PAL Environmental Services, 2005, Rudkin et al., 2005, p.5-8 in Ice-Structure\_Interaction\_06.pdf in CHC-Organized Workshops, Presentations at the PERD'06 Grand Banks Workshop on the web site (National Research Council Canada, Canadian Hydraulics Centre, 2007)). The database documents in detail past iceberg deflection activities so that analysis of different techniques employed, conditions, factors, and outcomes can be performed. Figure 4.3 lists some of the key parameters relevant for reviewing tow performance. In addition to detailing the creation and contents of the database, the cited references provide extensive analysis, findings, and discussions from the towing events. For illustration several results are presented here. In practice, the database can be exported to a spreadsheet and statistics, graphs, pivot tables or other readily assembled.

size_seq	berg_size
2	Very Large
3	Large
4	Medium
5	Small
6	Bergy Bit
7	Growler
8	Unknown

shape_seq	berg_shape
2	W edge
3	Tabular
4	Non-Tabular
5	Dome
6	Pinacle
7	Drydock
8	Blocky
9	Unknown

tow_seq	method
2	Single Vessel Rope Tow
3	Two Vessel Rope Tow
4	Cantary Tow
5	Chock Tow
6	Net
7	Prop-Wash
8	Water Cannon
9	Skran Tow
10	Other
11	Ramming
12	Triple Strand
13	Fire Monitor

End reason Sequential from 1 - 11

Reason Management Ended

- Rope Slipped
- Berg Split
- Berg Grounded
- Berg Rolled
- Rope Parted
- Tow Ended
- Change of Method
- Change in Vessel Priorities
- Change in Ice Priorities
- Vessel Change
- Other

Outcome Sequential 1- 8

Outcome of Management Operation

- Planned Objective Achieved
- Past CPA
- Suitable Outcome
- Poor, but Operations Unaffected
- Operations Affected
- Operations Disrupted
- Un-Manageable
- No Affect

Figure 4.3 PERD Iceberg Management Database Key Parameters.

Figure 4.4, Figure 4.5, and Figure 4.6 present annual totals of the different tow methods employed, the reasons for tow ending, and the tow evaluation. Note there are no records for 1991 to 1999, or 2005 and 2006. In Figure 4.4, the predominance of the single vessel tow rope is evident: 72% of tows are with this method. Increased recent use of the net (Section 4.3) is seen (7%) while the other staples, prop-wash and water cannon account for about 9% and 6% of all tows respectively. Two vessel rope tows were required in 2003 and 2004 for large ice islands (PAL, 2003). As has been noted, line slippage is the leading cause of tow complication. Figure 4.5 reports the reasons each tow ended, with the line slippage the cause 22% of the time (the same value as for the summer 2000 West Greenland program). Finally, Figure 4.6 shows the outcomes of each tow operation. The planned objective was achieved 44% of the time: the three other largest outcomes, all around 17-18%, were a suitable outcome, past CPA (closest point of approach) so that the iceberg was at least guided past the installation, or poor but operations unaffected. Only in about 2% of cases were the icebergs unmanageable or operations were affected or disrupted.

Year	Tow Method									Grand Total
	Chock Tow	Fire Monitor	Net	Prop-Wash	Single Vessel Rope Tow	Three Part Rope (test)	Triple Strand	Two Vessel Rope Tow	Water Cannon	
1987					4					4
1988			3	2	20			2		27
1989					18			1	1	20
1990			1	9	47					57
2000	1	8		13	115				7	144
2001							3			3
2002	1		1	7	20	1		4	3	37
2003			21	5	65			2	12	105
2004			2	2	6					10
	2	8	28	38	295	1	3	9	23	407

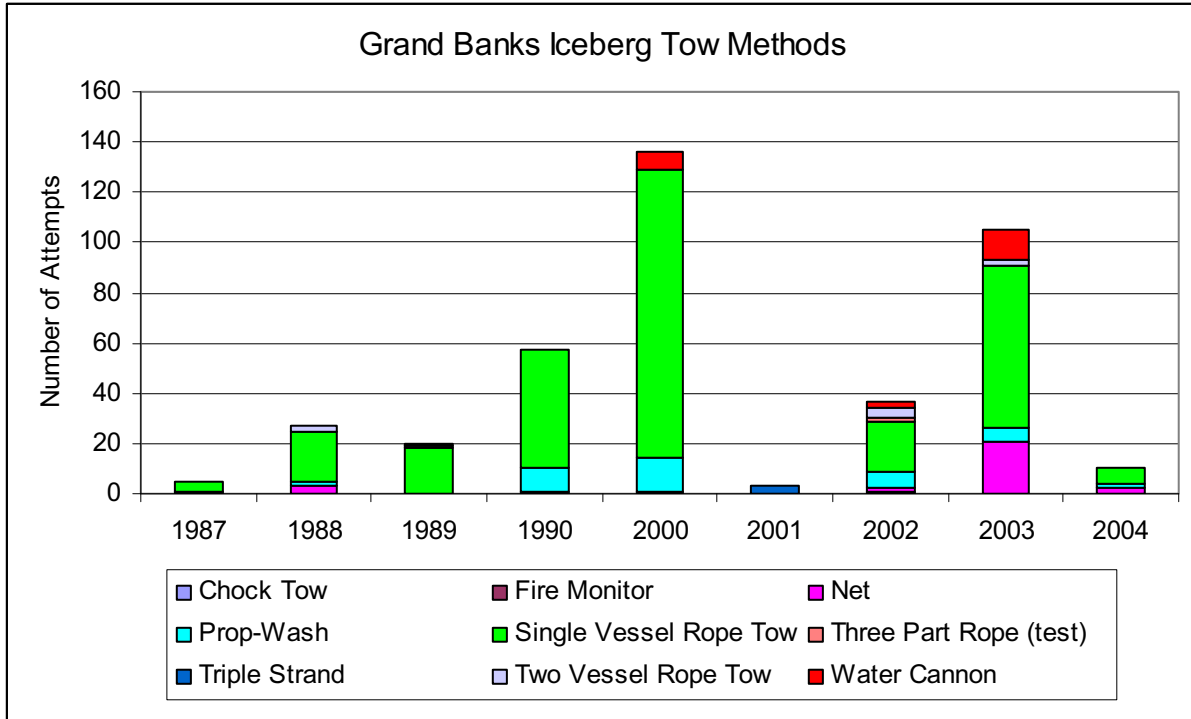


Figure 4.4 Grand Banks Iceberg Tow Methods (Data From: PERD IMDB)



Year	Reason Tow Ended											Grand Total
	Berg Grounded	Berg Rolled	Berg Split	Change in Ice Priorities	Change in Vessel Priorities	Change of Method	Other	Rope Parted	Rope Slipped	Tow Ended	Vessel Change	
1987										4		4
1988	4	1						1	2	19		27
1989	2								2	16		20
1990	2	2	1	1		4			20	27		57
2000	4	8	1	16	4	5	1		20	85		144
2001		1							1	1		3
2002		2	1	1		2	1		11	18	1	37
2003	2	4		4	3	4			31	57		105
2004		1					2		2	5		10
	14	19	3	22	7	15	4	1	89	232	1	407

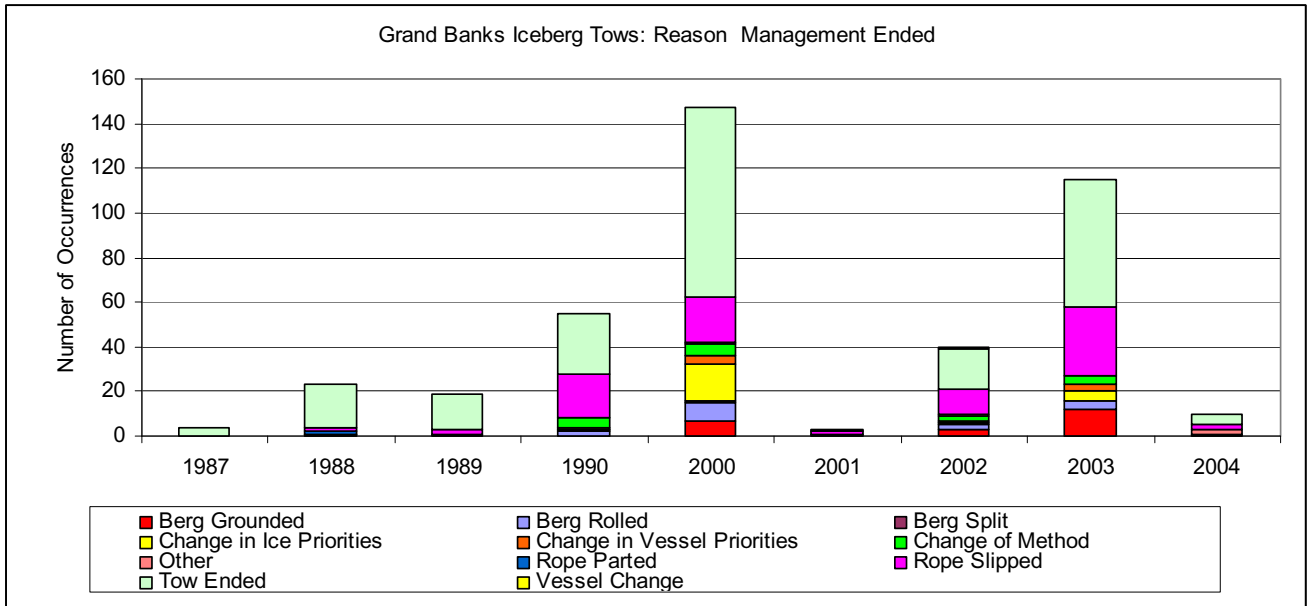


Figure 4.5 Grand Banks Iceberg Tows: Reason Management Ended (Data From: PERD IMDB)



Outcome of Management Operation									
Year	No Affect	Operations Affected	Operations Disrupted	Past CPA	Planned Objective Achieved	Poor, but Operations Unaffected	Suitable Outcome	Unmanageable	Grand Total
1987					4				4
1988					19	6	2		27
1989					16	4			20
1990	4	1		25	7	6	13		56
2000		1	1	26	67	12	31	6	144
2001					2	1			3
2002					18	12	7		37
2003				24	42	27	12		105
2004					4	2	4		10
	4	2	1	75	179	70	69	6	406

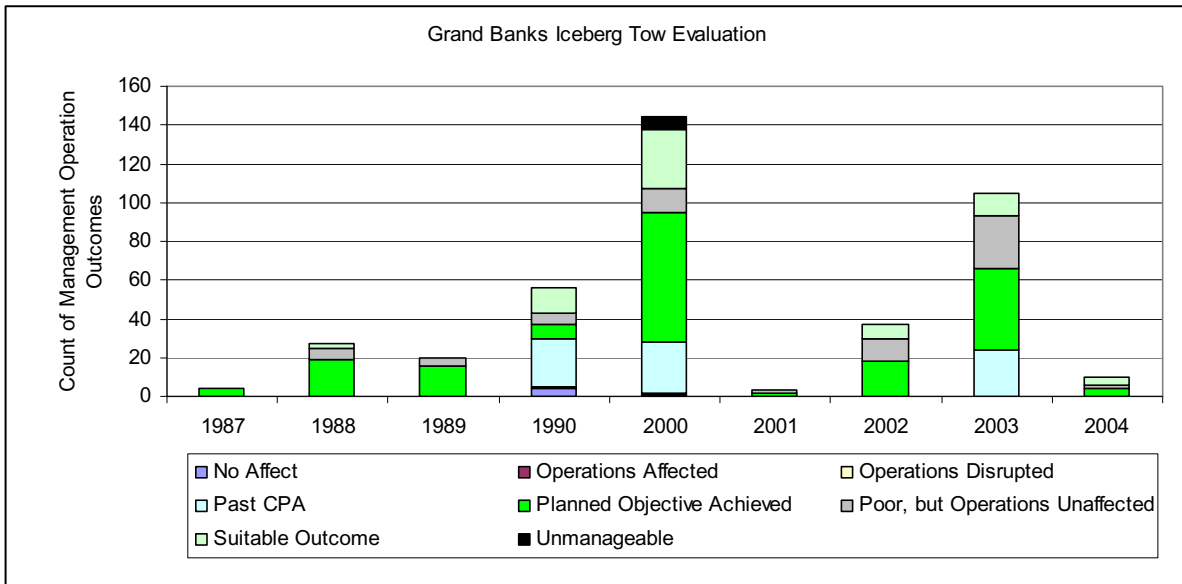


Figure 4.6 Grand Banks Iceberg Tow Evaluations (Data From: PERD IMDB)

### 4.3 C-CORE Iceberg Net

During the Integrated Ice Management Initiative (IIMI) R&D program in 2002 in which C-CORE conducted sinking tow line tests, a net arrangement was developed following sinking tow line tests to consider producing a greater force at depth and to counteract the overturning moment from the force of a tow line at the sea surface. This net concept (Figure 4.7) was directly intended to improve towing effectiveness of small and medium sized icebergs that were slippery, prone to rolling or otherwise problematic. Sea trials suggested this was a feasible option, acknowledging that net handling issues – a long-standing concern with nets – would need to be addressed. Several key features were designed to produce a practical system:

- increased length of the net compared with early net designs of the 1970s and 1980s
- improved bridle design to prevent collapsing of the net
- simple configuration and assembly to facilitate repairs at sea if necessary
- enhanced handling through use of a purpose-built storage reel

In 2003, C-CORE completed the design (Figure 4.8), and Petro-Canada fabricated the net and a storage reel for testing. This was implemented at sea during the 2003 ice season (C-CORE, 2004a) during which 17 tows were conducted on 11 icebergs ranging in size from 15 m to 130 m. Of the 17 tows, 15 were successful, allowing for multiple attempts, yielding a success rate of 88%. Two of the 17 bergs remained “untowable” after multiple attempts with the net: the net slipped underneath one iceberg after several hours of towing (not an uncommon occurrence with single line tows), and for the other iceberg the net slipped repeatedly confounding the tow hookup. Nevertheless, since tows of these icebergs using a conventional single synthetic tow rope may have otherwise been unsuccessful, the net produced an increase in overall tow performance. Importantly, a practical, effective tool had been developed and demonstrated (Figure 4.9).

Some net entanglement was experienced: in one instance high seas at the end of the tow made recovery of the net difficult, and in one other the net stayed attached for some time after the iceberg rolled, coming unattached some time later. In the first case the net was set to shore to be untangled, in the second case the tangled section of net was disconnected and net disassembled to remove the tangles.

There are presently several iceberg tow nets complete with storage reels (Figure 4.10) available for deployment and use aboard the Grand Banks support vessel fleet.

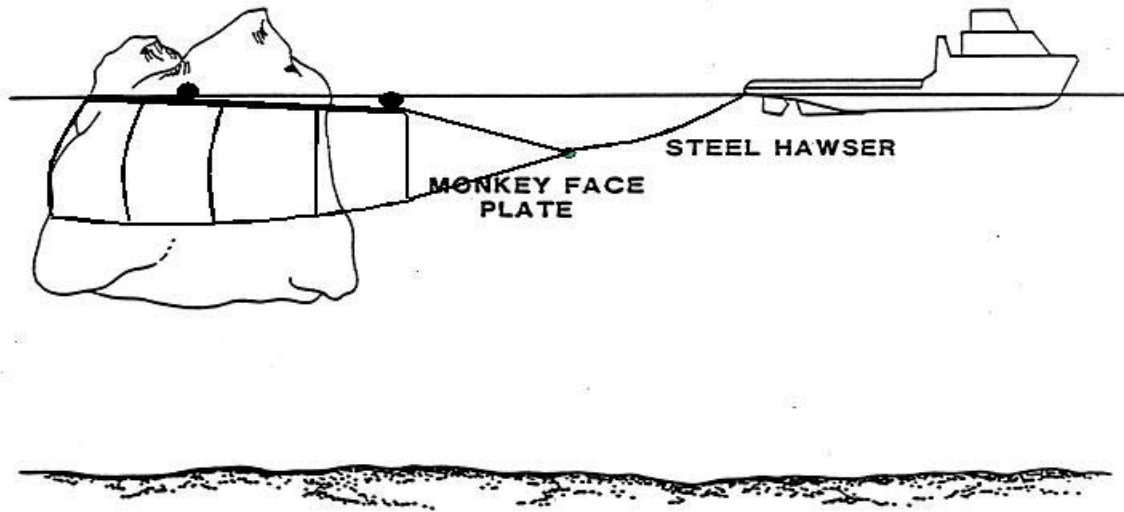


Figure 4.7 Concept of Iceberg Net Towing (Source: C-CORE, 2004a)

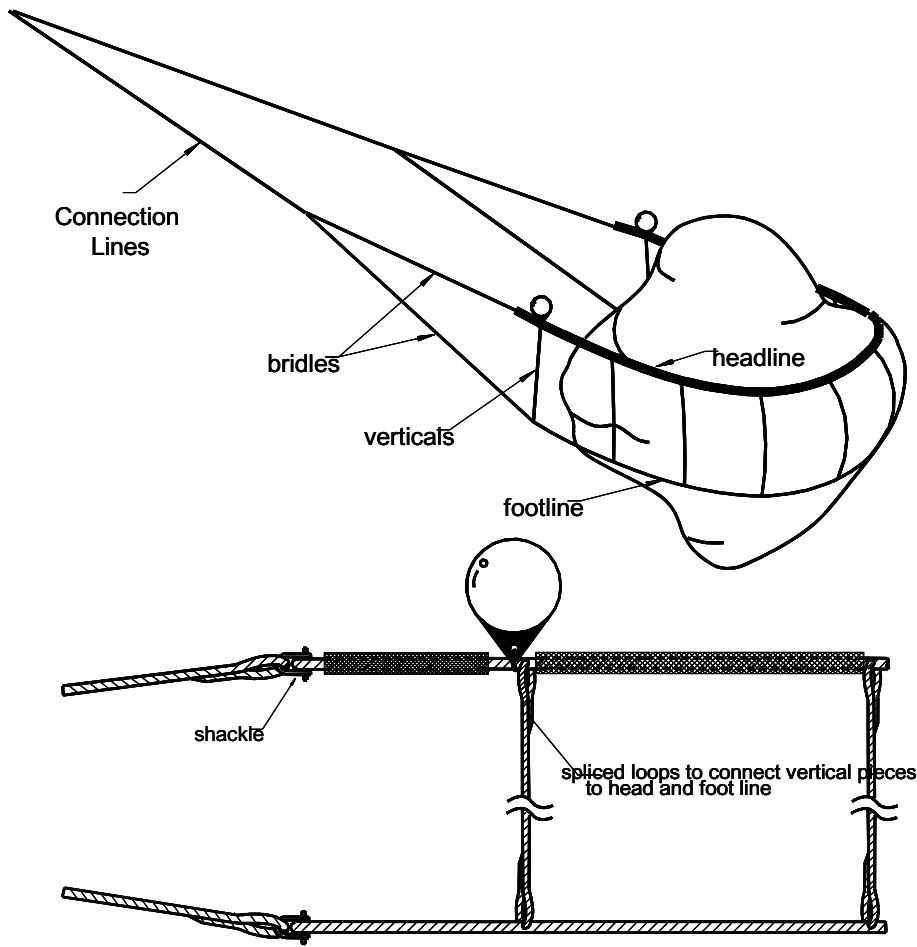


Figure 4.8 Iceberg Net Schematic (Source: C-CORE, 2004a).

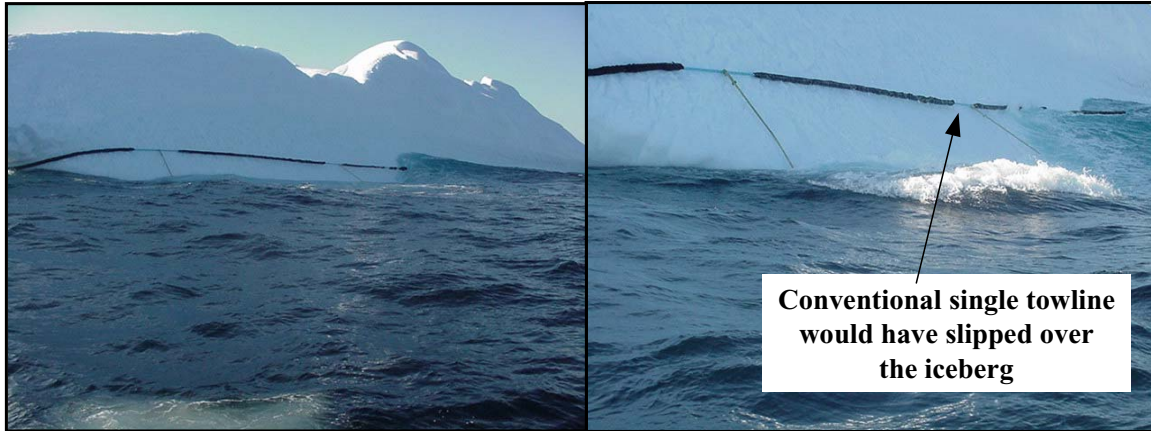


Figure 4.9 Iceberg Net In Use (Source: C-CORE, 2004a)



Figure 4.10 Iceberg Net Storage (Source: C-CORE, 2004a)

#### **4.4 C-CORE Iceberg Decision Making Toolbox**

When making ice management recommendations on complex scenarios that influence production or drilling operations, it is important that the operator has the best resources available on which to base his decisions. To facilitate this, C-CORE (2005a) has been developing an ice management threat analysis tool called the “decision making toolbox” (DMT) to effectively and methodically process data on the ice situation and return concise information for use in risk and management strategies. Thus, the operator is better equipped to make informed decisions on the suspension of operations and possible disconnection, and also to evaluate alternative management scenarios.

The algorithm developed makes use of the factors influencing the threat of an iceberg to a facility. This, along with the precise calculation of risk metrics coupled with the examination of tow solutions and their influence on threat, provide a comprehensive means of comparing alternative ice management strategies.

The independent variables which influence the decisions of when, where, and which icebergs to tow are: iceberg location; confidence in iceberg detection; features of the iceberg, such as size, mass and shape; structure locations; structure operation and corresponding T-time; ice load capacity of the structure; tow resource locations; availability of tow resources; and environmental conditions.

Where the number of combinations of tow vessels and icebergs is reasonable, a search can be performed to determine the best management scenario. The iceberg to facility relationship defines the threat; and the tow resource to iceberg relationship determines the viable tow alternatives. The tow solution, or management scenario, refers to the assignment of tow resources to iceberg threats, and their subsequent tow destinations. The input data is collected and preprocessed prior to iteratively evaluating all possible tow solutions.

Through iterative examination of multiple tow solutions, increased risks from selected tow scenarios can be quantified. Through evaluation of tow solutions, the risk to facilities can be minimized.

#### **4.5 Dunderdale Iceberg Management Planning Aid (IMPA)**

An impressive tool developed originally by the late Peter Dunderdale is the Iceberg Management Planning Aid (Brown et al., 2003). The software is designed to improve iceberg towing effectiveness through prediction of expected drift outcomes for a given input of iceberg size, shape, drift velocity and direction. The model predicts iceberg deflection under a proposed tow force and direction. The software GUI provides the user with important visual feedback of the current and predicted conditions and ease of interaction with the model to view and edit values. In addition to obvious benefits of minimizing potential downtime due to ice, there is potential to optimize vessel utilization as well. The potential exists to incorporate met-ocean conditions, underwater iceberg shape, and real-time iceberg drift prediction models. The software has been tested with historical data sets and received some operational use offshore.

## 5.0 WHERE HAVE ALL THE ICEBERGS GONE?

### 5.1 Background

This section discusses the rapid changes in the melt and calving rate of the Greenland ice sheet in response to equally rapid air and ocean temperature warming in the last decade, and the effects of these changes on sea ice and icebergs. These environmental changes directly affect both the Labrador Sea and the Grand Banks of Newfoundland and are front and centre in the debate over global climate change. They also have implications for renewed interest in exploitation of offshore gas fields on Makkovik Bank in the central Labrador Sea.

The most recent summary of climate change by the Intergovernmental Panel on Climate Change (IPCC, 2007; Lemke *et al.* 2007) reports the following:

- 11 of the last 12 years (1995-2006) were among the 12 warmest since records began in 1850
- Global average sea level rose at an average rate of ~1.8 mm per year from 1961 to 2003 (of which thermal expansion accounted for ~0.4 mm per year)
- The rate of sea level rise increased to ~3.1 mm per year between 1993 and 2003 (whether a decadal cycle or long-term is unknown)
  - Thermal expansion accounts for ~1.6 mm per year and melting of glaciers, ice sheets and ice caps accounts for ~2.8 mm per year
- The total 20th century rise in sea level is estimated to be ~0.17 m
- The Arctic has been warming at twice the global average rate in the past 100 years (but high decadal variability)
- Arctic sea ice extent has shrunk by 2.7% per decade, with larger decreases in summer of 7.4% per decade (Figures 5.1 & 5.2).

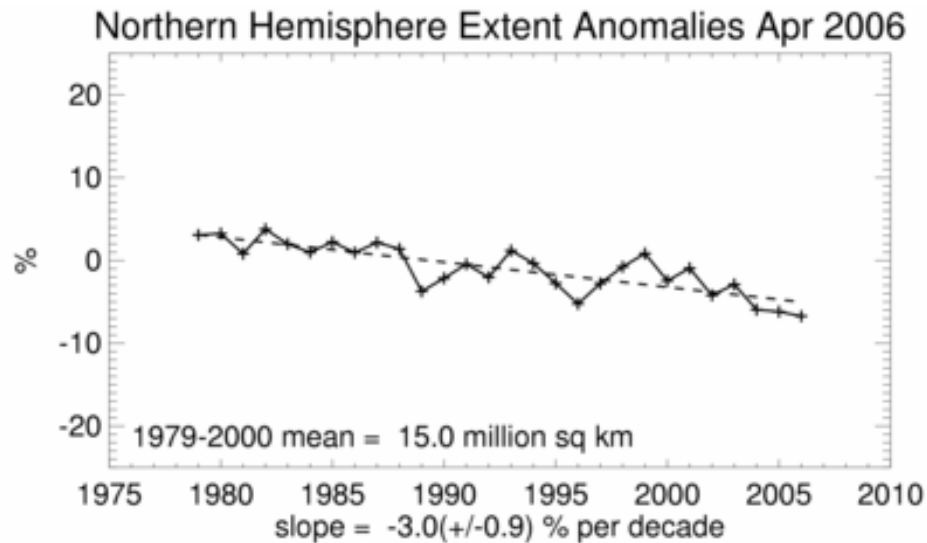


Figure 5.1 Ice extent anomaly for winter showing decrease in Arctic ice in the month of April (the month of greatest ice extent) since 1979 (National Snow & Ice Data Centre).

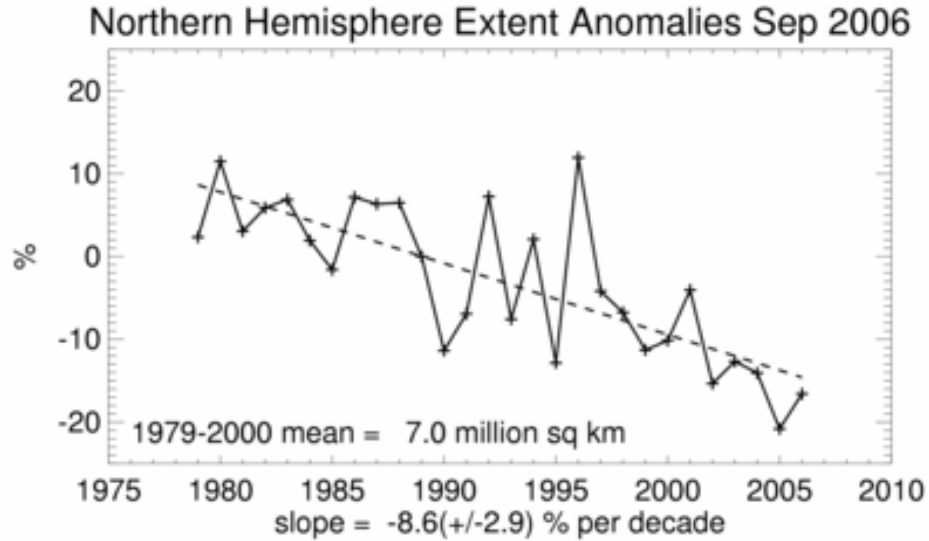


Figure 5.2 Ice extent anomaly for summer showing decrease in Arctic ice in the month of September (typically the month with the least ice) since 1979 (National Snow & Ice Data Centre).

Newly available data show that Arctic sea ice extent is actually decreasing at a rate faster than any of the eighteen prediction models used by IPCC (Figure 5.3).

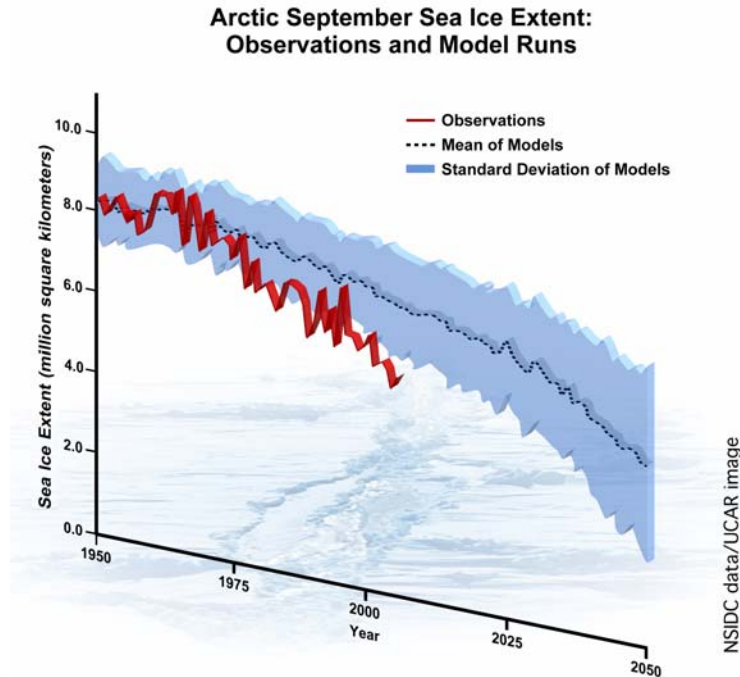


Figure 5.3 Actual ice extent is decreasing at a rate faster than all of the combined 18 prediction models used by the Intergovernmental Panel on Climate Change (IPCC) in preparing its 2007 assessments (National Snow & Ice Data Centre).

## 5.2 Iceberg Climate

The flux rate, size distribution (particularly mass and draft), geographic distribution and circulation together comprise the iceberg climate. The iceberg climate is strongly influenced by local oceanic and atmospheric circulation patterns, water temperature, the prevalence and duration of open water conditions (influenced by sea ice extent) and by a variety of factors affecting the principal iceberg source region of Greenland, and to a lesser extent ice caps on Ellesmere, Devon and Baffin Island.

Provincial Aerospace Ltd. (PAL) provides seasonal forecasts of iceberg severity on the Grand Banks. PAL (2001) notes that there appears to be a number of linked, key environmental factors in the upstream areas through which icebergs pass that directly influence the numbers of icebergs arriving on the Grand Banks each spring including:

- the number of bergs located in Baffin Bay in the late fall
- the extent and duration of sea ice cover in the Labrador Sea during the winter. Sea ice protects bergs from deteriorating by
  - maintaining cool water temperatures
  - suppressing the effects of wave action.

In the last decade the Labrador Sea iceberg climate has been influenced by four significant environmental changes:

1. Increases in intermediate water and sea surface temperatures
2. Corresponding increase in air temperature on the Greenland ice sheet
3. Corresponding decreases in sea ice extent and duration
4. A dramatic, and largely unpredicted, volumetric increase in ice discharge from the Greenland ice sheet.

### 5.2.1 Ocean Temperatures: Intermediate Water

Temperature profiles in the West Greenland current at 60.5° N show steady increase of maximum temperature from 3.5° to 4.8°C (1994 – 1999) and at 60° N 3.7° to 4.1°C (1990 – 2000). The warmest water in polar oceans is at intermediate depths, and regional subsurface ocean warming predates the expression of increased regional sea surface temperatures (Bindschadler, 2006).

### 5.2.2 Ocean Temperatures: Sea Surface

Spring sea surface temperature in the Labrador Sea, southern Baffin Bay and southeast Greenland show consistently warming and expanding trends since 1995 (Figure 5.4). Since 1997 warming anomalies have been increasing in the Disko Bay area of western Greenland, where icebergs from Jakobshavn Isbrae enter the ocean.

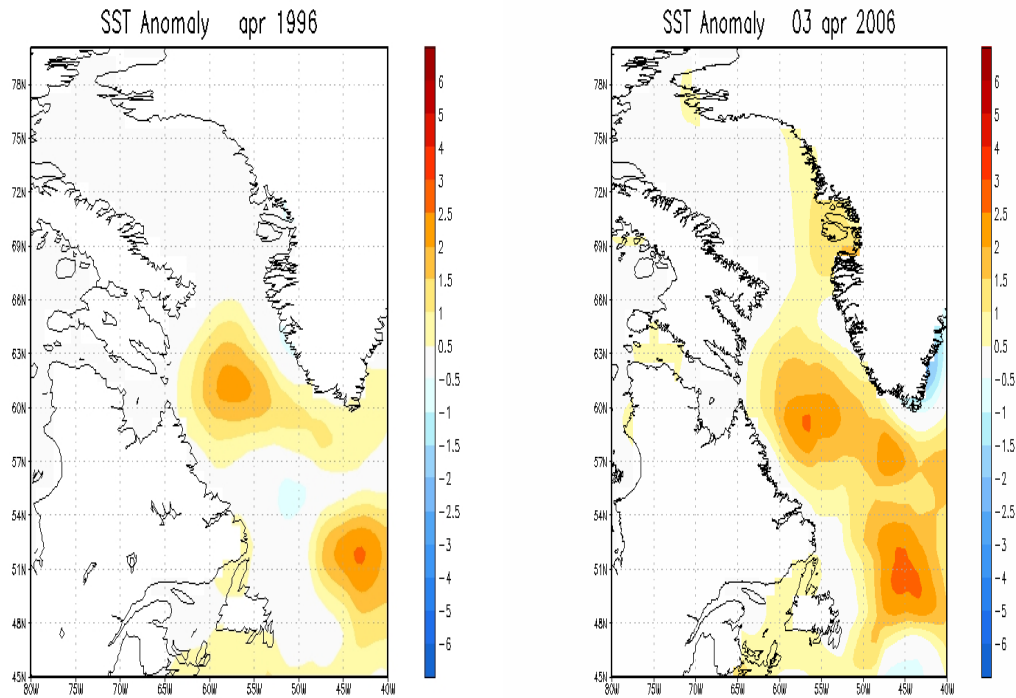


Figure 5.4 Since 1995 spring sea surface temperature (SST) anomalies in the Labrador Sea have increased in size and since 1997 extend into Disko Bay, western Greenland (data from NASA N.O.M.A.D.S.<sup>5</sup>)

### 5.2.3 Air Temperature

1997 marked a change to warmer summer air temperatures over the Greenland ice sheet. For example, sustained increase in summer temperatures appear to be linked to increased surface melting on Jakobshavn Isbrae (Figure 5.5: Figure 5.9 for location). Temperature records at Angmassalik near Helheim glacier (Figure 5.9 for location) also show a 3°C increase in yearly air temperature from 1981–1983 to 2003–2005 (Rignot & Karagatnam, 2006).

<sup>5</sup> [http://nomad2.ncep.noaa.gov/cgi-bin/pdisp\\_sst.sh?ctlfile=oiv2.ctl&povlp=noovlp&ptype=map](http://nomad2.ncep.noaa.gov/cgi-bin/pdisp_sst.sh?ctlfile=oiv2.ctl&povlp=noovlp&ptype=map)

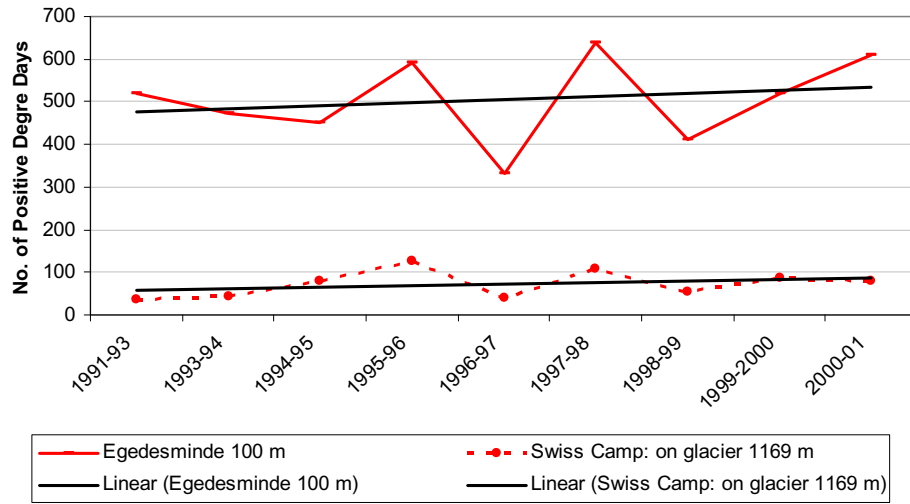


Figure 5.5 Number of positive degree days at 100 m and 1169 m, Jakobshavn Isbrae (from data of Thomas *et al.* 2003)

Sea surface temperature and positive degree day curves show similar trends (Figure 5.6) suggesting summer air temperatures for western Greenland are driven by local ocean temperatures (Thomas *et al.* (2003).

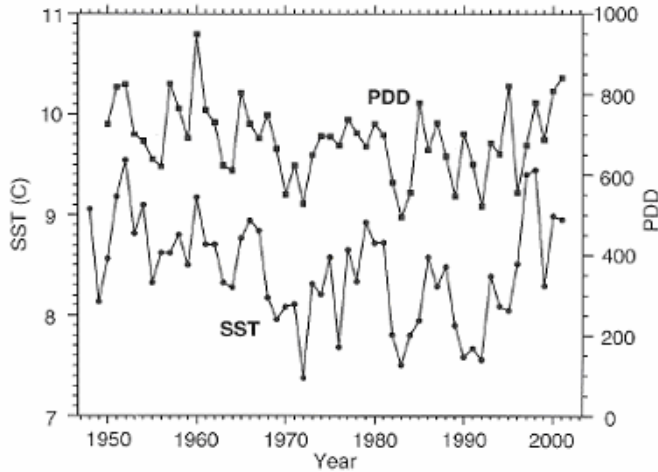


Figure 5.6 Positive Degree Days (PDD) from Egedesminde, near Jacobshavn Isbrae, and Sea Surface Temperatures (SST) for the four warmest months (July – October) for the N. Atlantic and Davis Strait 50 – 65° N, 45 – 65° W (from Thomas *et al.* 2003).

#### 5.2.4 Sea Ice Extent

As with sea surface temperature, since 1997 sea ice concentration in the Labrador Sea and Baffin Bay to Disko Bay region has shown consistent negative anomalies meaning less ice and more open water. Similar, though less consistent, anomalies are seen off the southeast coast of Greenland. The decline in Arctic sea ice extent is shown graphically in Figure 5.7 and anomaly examples for the Labrador Sea for April are shown in Figure 5.8.

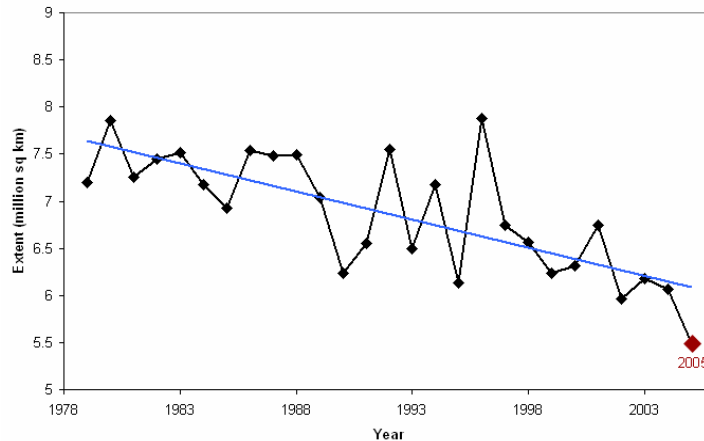


Figure 5.7 Decline in Arctic sea ice extent from 1978-2005. The September trend from 1979 to 2005, now showing a decline of more than 8 percent per decade, is shown with a straight blue line (National Snow & Ice Data Center<sup>6</sup>).

<sup>6</sup> [http://nsidc.org/data/seaice\\_index](http://nsidc.org/data/seaice_index)

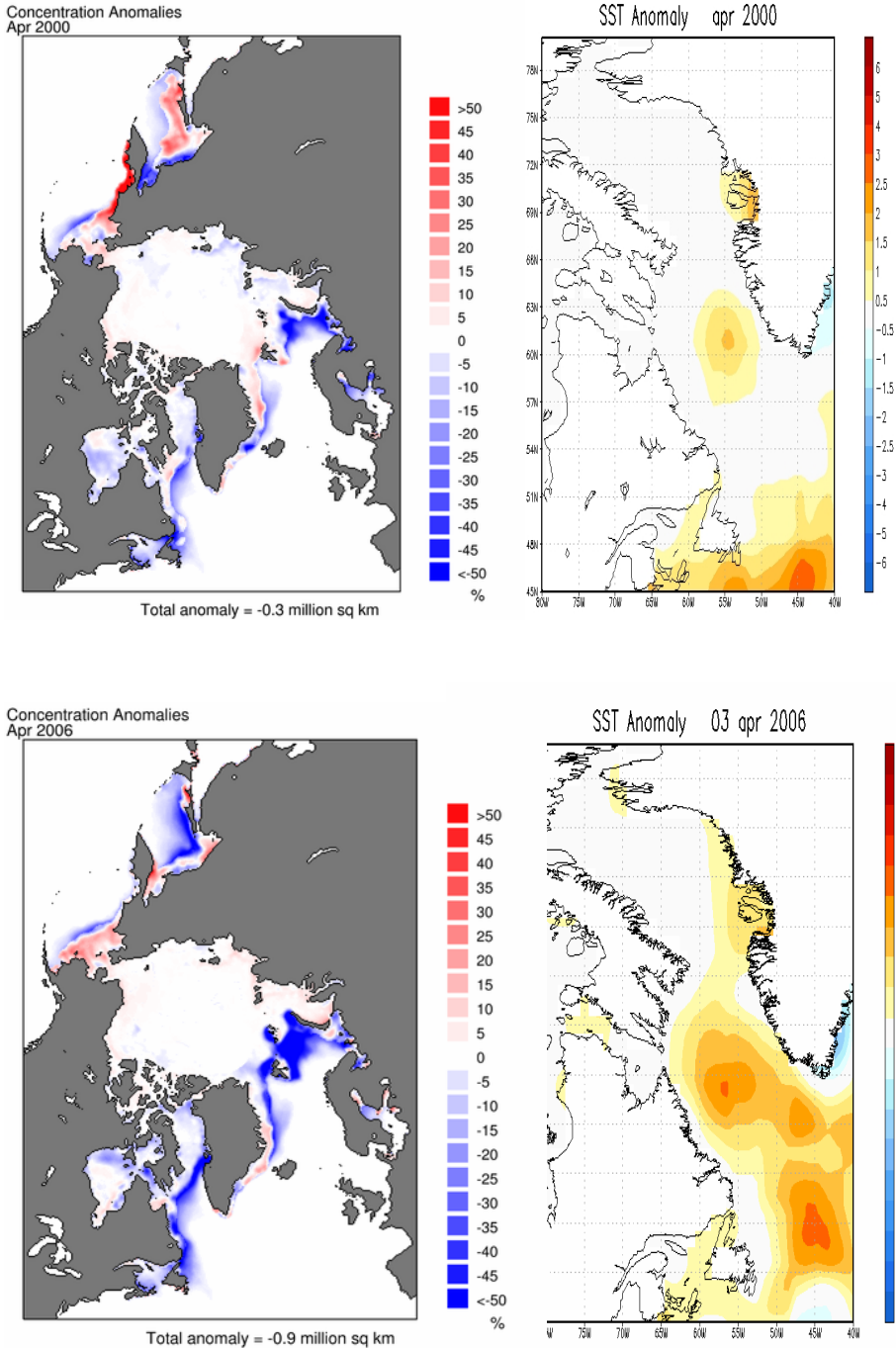


Figure 5.8 Example of sea ice concentration (left) and sea surface temperature anomalies (right) for April 2000 (top) & 2006 (bottom). Increasing sea surface temperatures correlate with below normal sea ice concentration anomalies. (National Snow & Ice Data Center<sup>7</sup>).

<sup>7</sup> [http://nsidc.org/data/seaice\\_index/archives/index.html](http://nsidc.org/data/seaice_index/archives/index.html)

### 5.3 Greenland Ice Sheet and Icebergs

Greenland tidewater glaciers produce a prolific volume of ice in the form of icebergs but information on the rates of production is not easily derived. Even less information is available on the distribution of iceberg dimensions (especially keel drafts) from each glacier. For instance, the thickness of the ice at the grounding-line (where the bottom of the ice meets the ocean) of glaciers extending into floating ice tongues in northern Greenland are well known, but ice thickness is difficult to measure at the fronts of calving glaciers in other parts of Greenland where no floating ice tongues develop, and is only known several kilometres upstream of the ice fronts (Rignot & Kanagaratnam, 2006). Estimates of the volume of icebergs calved annually vary considerably. Danish estimates are between 200 – 300 km<sup>3</sup> per year<sup>8</sup>. The Intergovernmental Panel on Climate Change (2001) report an annual averaged production rate of 261 (+/- 37) km<sup>3</sup> per year<sup>9</sup>.

However, measurements of mass balance made from satellite radar interferometry and airborne radio echo-soundings (e.g. Rignot & Kanagaratnam, 2006) now allows some rough estimates of iceberg production to be made. Two-thirds of the mass lost from the Greenland ice sheet is caused by ice dynamics (in the form of ice flow); the rest is due to enhanced runoff minus accumulation (Rignot & Kanagaratnam, 2006). With melting taken into account then a reasonable educated guess of mass loss in the form of iceberg production is about 33% by volume (E. Rignot. Pers. comm.). Using this estimate the volume of iceberg discharge for 1996 was ~118 km<sup>3</sup> (Figure 5.9). By 2005 the volume of iceberg production had increased by approximately 46% (~54 km<sup>3</sup>) linked to unprecedented calving rates influenced by climate change (Figure 5.9 and Table 5.1).

---

<sup>8</sup> Havis og isbjerge omkring Grønland.  
[http://www.dmi.dk/dmi/index/viden/temaer/havis\\_og\\_isbjerge\\_omkring\\_groenland/havis\\_og\\_isbjerge\\_omkring\\_groenland\\_-\\_havis.htm](http://www.dmi.dk/dmi/index/viden/temaer/havis_og_isbjerge_omkring_groenland/havis_og_isbjerge_omkring_groenland_-_havis.htm)

<sup>9</sup> 235 +/- 33 x 10<sup>12</sup> kg/yr

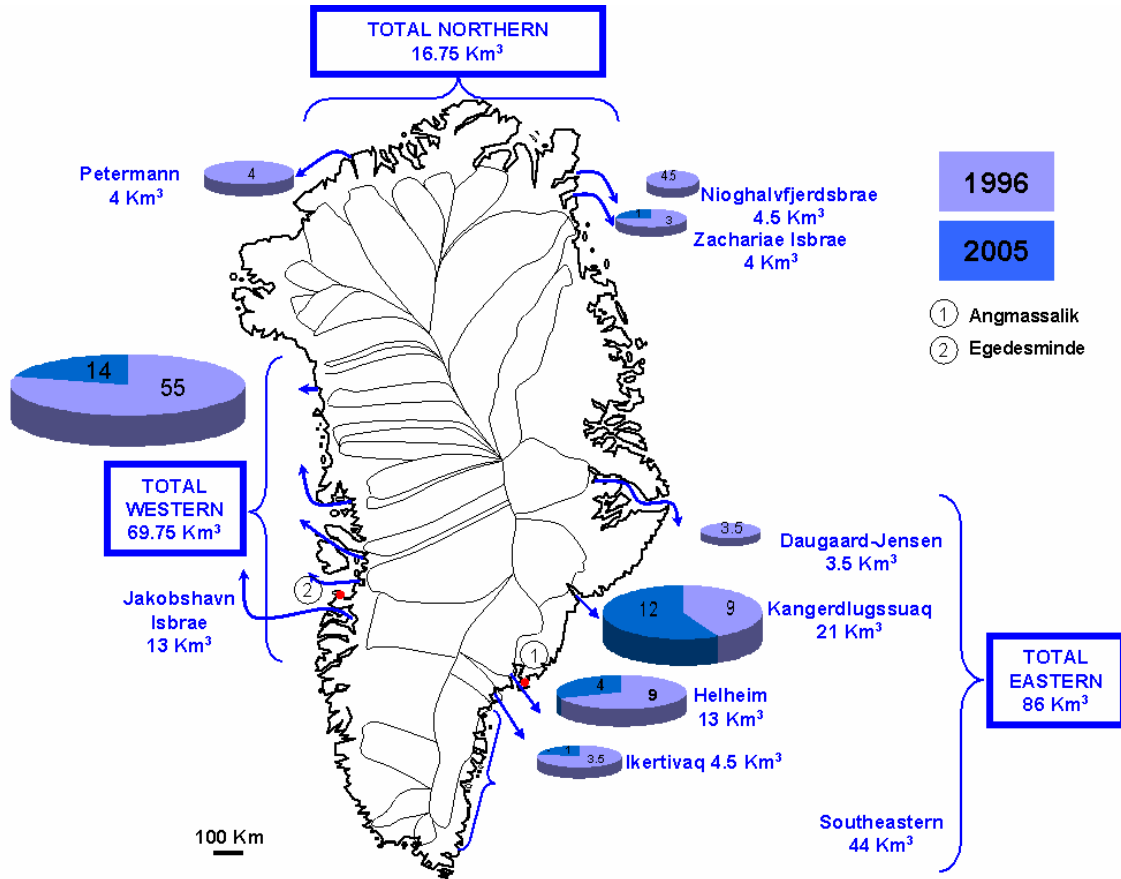


Figure 5.9 Map of Greenland showing the estimated volumetric increase in iceberg discharge in the decade between 1996 and 2005 (based on mass balance measurements for the entire ice sheet by Rignot and Kanagaratnam, 2006).

Table 5.1 Estimated increase in iceberg production (km³) of the Greenland ice sheet between 1996 and 2005 (derived from data of Rignot and Kanagaratnam, 2006).

Glacier	1996 Iceberg Discharge (km³)	2005 Discharge Increase (km³)	2005 Total Discharge (km³)
<b>Eastern Outlet Glaciers</b>			
Southeastern	22	22	44
Kangerdlugssuaq	9	12	21
Helheim	9	4	13
Daugaard-Jensen	3.5	0	3.5
Ikertivaq	3.5	1	4.5
<b>TOTAL EASTERN</b>	<b>47</b>	<b>39</b>	<b>86</b>
<b>Northern Outlet Glaciers</b>			
Nioghalvfjærdsbrae	4.5	0	4.5
Petermann	4	0	4
Tracy/Heilprin	0.5	0.5	1
Humboldt	1.25	0	1.25
Ryder	1	0	1

Ostenfeld	0.5	0	0.5
Academy/Hagen	1.25	0.25	1.5
Storstrømmen	0	-1	-1
Zachariae Isbrae	3	1	4
TOTAL NORTHERN	16	0.75	16.75
<b>Western Outlet Glaciers</b>			
Jakobshavn Isbrae	8	5	13
Rinks	4	0	4
Nordenskiold	3.5	0	3.5
Sermeq	3	1	4
Hayes	3	0	3
Kangerdlugssup	0.8	0.2	1
Upernavik	2.5	0.5	3
Nunatakavsauq	1.25	0.5	1.75
Igdlugdlip	3	0.25	3.25
Steenstrup	0.25	0	0.25
Kong Oscar	2.75	0.5	3.25
Peary/Docke	2.5	1	3.5
Gades	1	0.5	1.5
Nonsurveyed	19.75	5	24.75
TOTAL WESTERN	55.3	14.45	69.75
<b>GRAND TOTAL</b>	<b>118.3</b>	<b>54.2</b>	<b>172.5</b>

Rignot & Kanagaratnam (2006) detected widespread glacier acceleration below 66° N, just north of Jakobshavn Isbrae, between 1996 and 2000, which rapidly expanded to 70° N in 2005. Accelerated ice discharge in the west and particularly in the east doubled the ice sheet mass deficit in the last decade (1996 to 2005) from 90 to 220 km<sup>3</sup> per year. Ironically, the ice sheet is nearly in balance in the interior but its periphery is thinning, with deterioration concentrated along outlet glaciers. Its contribution to sea-level rise increased from 0.23 +/- 0.08 mm/year in 1996 to 0.57 +/- 0.1 mm/year in 2005.

Confirmation of rapidly increasing mass loss is provided by several other analyses (e.g. Luthke *et al.* 2006 using GRACE satellite gravity data; Thomas *et al.* 2003; Zwally *et al.* 2002) which also report that the increase in mass loss is seasonal, coinciding with summer surface melting.

### 5.3.1 Glacialquakes

Observations of Greenland's glacial seismicity between 1993 and 2005 confirm a seasonal signal, with summer seismicity nearly five times greater than in winter (Ekström *et al.* 2006; Joughin, 2006). One hundred and thirty six earthquakes, with magnitudes ranging from 4.6 to 5.1, were analyzed by Ekström *et al.* (2006) and all were spatially associated with major outlet glaciers of the Greenland Ice Sheet (Figure 5.10). The observed duration of the quakes is typically 30 to 60 s. Apart from the strong seasonality there has been an increasing number of glacialquakes since at least 2002.

The glacialquakes all originated on fast-moving (>2 km/year) glaciers, with Kangerdlugssuaq, Jakobshavn Isbrae, and Helheim accounting for 72% of the events.

Products of the displaced mass and slip range from  $0.1 \times 10^{14}$  to  $2.0 \times 10^{14}$  kg m. Thus the 26 glacialquakes of Helheim Glacier each resulted from roughly 0.16 to 3.7 m of slip if the displacement occurred along the full 14-km length of its fast-moving trunk.

The glacialquakes can be accounted for by summer surface melt-water flowing to the glacier sole via moulins, the melt-water lowering the effective friction at the base allowing increased basal sliding. However, glacialquakes also occur during the winter months implying that the influx of summer melt-water accelerates the events rather than controls them (Ekström *et al.* 2006).

Another explanation of the quakes may be the seasonal variation in iceberg calving, which for Jakobshavn Isbrae demonstrates an annual variability similar to that of the glacialquakes. There are two possible seismic scenarios (Joughin, 2006):

1. Large calving events could yield mass displacements sufficient to produce glacialquakes
2. Alternatively, a calving event may introduce a force imbalance, leading to a slip-related quake in the outlet glacier as a new force balance is established.

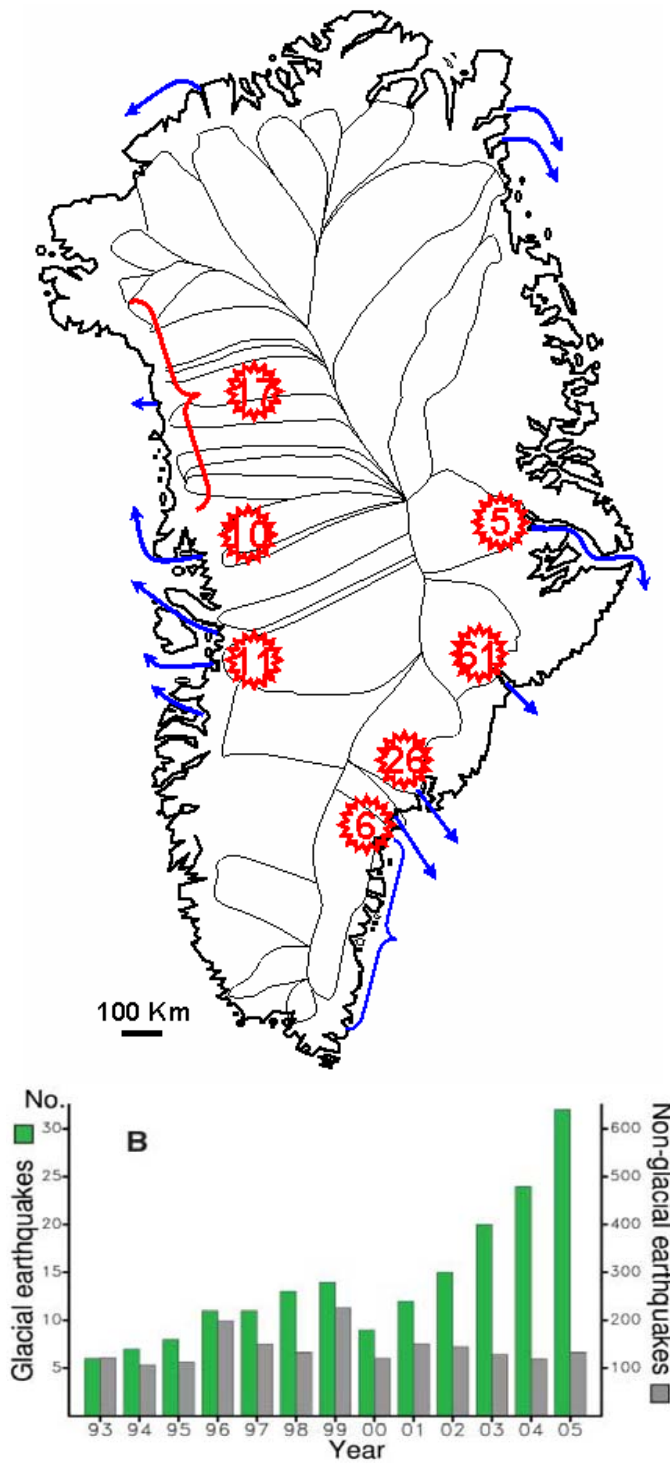


Figure 5.10 Top: Map of Greenland showing locations of summer glacialquakes between 1993 and 2005. Summer seismicity is more than 5 x greater than in winter. Bottom: Graph showing increase in frequency of glacialquakes (green bars) against a constant background of earthquakes (grey bars). Based on Ekström *et al.* 2006; Joughin, 2006.

### 5.3.2 Response of Individual Glaciers

#### **North Coast Glaciers**

Northern glaciers are more or less stable. Mass losses from decelerating Nioghalvfjærdsbrae and accelerating Zachariae Isstrøm include estimated iceberg production rates of 4.5 and 4 km<sup>3</sup>/year compensate for the mass gain of decelerating Storstrømmen (Rignot & Kanagaratnam, 2006). There was a large break out of icebergs from Zachariae Isstrøm in 2003. The break out of tabular bergs with drafts of ~100m coincided with the breakup of a semi-permanent cover of multi-year landfast ice across the terminus (Peter Wadhams, Cambridge University, pers. comm. 2007). Although there was a spectacular flotilla of tabular icebergs released from the Petermann glacier in 2000 and 2001, the glacier has been stable since 1996. Its mass balance remains slightly negative (Rignot & Kanagaratnam, 2006) with an estimated iceberg production rate of 4 km<sup>3</sup>/year (Figure 5.9). The large tabular Petermann icebergs that drifted into the Grand Banks region in 2002 and 2003 had sizes between 3 and 20 million tons and drafts of 65-80 m (Peterson, 2006).

#### **East and Southeast Coast**

On the east coast the major outlets of Kangerdlugssuaq and Helheim glaciers, both occupying deep submarine channels, have been thinning rapidly. Kangerdlugssuaq Glacier has been stable in speed since 1962, but was thinning and losing mass in 1996 (Rignot & Kanagaratnam, 2006). The glacier accelerated 210% between 2000 and 2005, thinning at rates of 40 m/year (Bindschadler, 2006) to flow 13 to 14 km/year at the calving front, which is the largest speed in Greenland (Rignot & Kanagaratnam, 2006). The ice front retreated about 10 km. An 8-km/year additional frontal speed over the last 30 km probably thinned the ice from 1 km to 750 m. The acceleration increased the mass loss and resulted in an estimated increase in iceberg production from 9 km<sup>3</sup> in 1996 to 21 km<sup>3</sup> in 2005 (Figure 5.9). Helheim Glacier began thinning in 2003 at a rate of 25 m/year (Bindschadler, 2006) with an estimated increase in iceberg production from 9 to 13 km<sup>3</sup> ice/year in 2005.

Even more pronounced changes are taking place in the southeast, where most glaciers have no names and are rarely visited. Here snow accumulation is the highest in Greenland, causing high rates of ice discharge per unit area. Rignot & Kanagaratnam (2006) estimate a 29 km<sup>3</sup>/year ice loss over an area of 73,700 km<sup>2</sup> for 1996. The largest 21 glaciers accelerated 57% between 1996 and 2005. Total loss more than doubled between 1996 and 2005 doubling estimated iceberg production from 22 km<sup>3</sup>/year to 44 km<sup>3</sup>/year.

#### **West Coast**

The most important iceberg-producing glacier on the west coast is Jakobshavn Isbrae that had a floating ice tongue at its terminus in front of a grounding line over 1,000 m below sea level. From 1851 to 1953 the calving front of the floating ice tongue retreated by 26 km but stabilized within a 2.5-km-long calving zone from 1962 to the 1990s. In October 2000, this pattern changed when a progressive retreat began that resulted in nearly complete disintegration of the ice shelf by May 2003 (Joughin *et al.* (2004). After 1997 a trend of increasing speed began, linked to thinning at a rate of 15 m/year (Bindschadler, 2006). The glacier slowed down from a velocity of 6.7 km/year in 1985 to 5.7 km/year between 1992 and 1997. By 2000 its speed had increased to 9.4 km/year, speeding up again in spring 2003 to 12.6 km/year. Airborne laser-altimeter profiles show that since 1997 there has been

substantial thinning of several metres/year within 20 km of the ice front (Thomas *et al.* (2003). Increased speed persisted through summer and winter so it seems unlikely that increased surface meltwater input to the bed directly caused the acceleration. Several of the speed increases coincide with losses of sections of the ice tongue as it broke up (Joughin *et al.* 2004).

The floating ice tongue was deeply fractured in 2001 within 6 km of the ice front and was almost completely broken up by May 2003 (NASA, 2004) (Figure 5.11). Total dynamic thinning of the floating ice tongue between 1997 and 2001 was about 35 m with thinning rates exceeding 10 m/year since 1998. After thinning, ice freeboard was about 75 m so that total thickness was about 690 m (ratio of 8.2:1), making the draft of the floating ice tongue, and therefore of large icebergs in 2001, about 615 m (Thomas *et al.* 2003). Freeboard prior to the 35 m of surface thinning would have been 110 m (75 + 35 m), and consequently draft would have been about 902 m. This translates into an astonishing total thinning of about 320 m, or 80 m/year. This is far higher than the thinning rates of ice in the grounded upstream portions of the glacier. Most of this reduction is likely due to increased basal melting caused by intrusion of warmer oceanic water into the fjord.

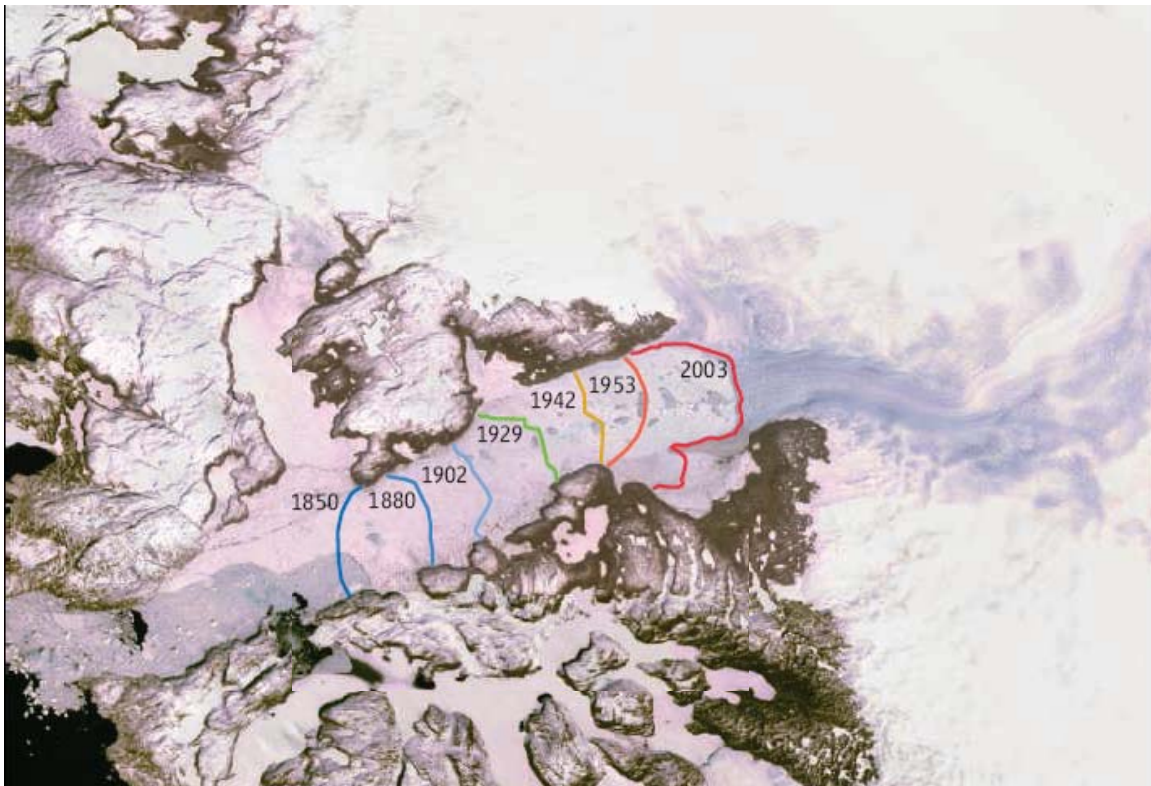


Figure 5.11 Retreat of the floating ice tongue of Jakobshavn Isbrae, west Greenland.

These changes mean that the maximum draft of icebergs calving from Jakobshavn Isbrae has decreased by nearly one third in the four years between 1997 and 2001. Estimated iceberg discharge increased from 8 to 13 km<sup>3</sup> from 1996 to 2005. The total estimated increase in iceberg discharge from all west coast glaciers rose from 55 to nearly 70 km<sup>3</sup> from 1996 to 2005.

## Causes of Increasing Mass Loss

The increase in number of positive degree days in summer is causing significant increase in surface melting on the ice sheet. Surface runoff collects in pools and drains to the glacier base through large moulins (Figure 5.12). Reduced basal friction from lubrication and high hydrostatic pressure may be one reason for associated rapid thinning (Thomas *et al.* 2003). Reduced basal friction certainly seems to explain the increase in glacialquakes in summer, and these quakes are associated with rapid accelerations in glacier velocity, and possibly with large iceberg calving events.

Once warm intermediate water breaches fjord sills it will sink in the cold, fresh water behind the sill and reach ice at the grounding line. Increased pressure at these greater depths lowers the melting point of ice, increasing the melting efficiency of the warmer water. Basal melting of Jakobshavn Isbrae ice tongue is thought to be responsible for the 80 m per year decrease in draft reported by Thomas *et al.* (2003).

## 5.4 Significance to Icebergs

It is estimated that there has been a volume increase of 63% in iceberg production from the tidewater glaciers of Greenland in the last ten years. Intuitively this increase would suggest that iceberg severity may have increased dramatically on the Labrador shelf and Grand Banks of Newfoundland. However, such an increase in iceberg production is not reflected by an increase in icebergs during the iceberg season on the Grand Banks or further north in Labrador waters. In fact, the reverse is true and fewer icebergs are reaching the Grand Banks. The reasons are not clearly understood but are influenced by several factors:

- Increases in the number of atmospheric positive degree days on the Greenland ice sheet
- Increased outlet glacier flow triggered, or accelerated, by summer surface melting
- Warming intermediate water that causes basal melting of floating ice tongues and reduced iceberg draft
- Sea surface temperature increase and corresponding decrease in sea ice concentration in the region of iceberg production and transport;
- Possible reduction in iceberg size caused by:
  - dynamic thinning of accelerating glaciers and
  - increased fracturing/crevassing caused by thinning



Figure 5.12 Left: Surface runoff on the Greenland ice sheet draining into a large Moulin<sup>10</sup>.  
Bottom: view of large meltwater pool<sup>11</sup>.

<sup>10</sup> Photo by Roger J. Braithwaite, University of Manchester  
<http://earthobservatory.nasa.gov/Newsroom/NasaNews/2002/200206069411.html>

<sup>11</sup> Photo by James Balog, National geographic: <http://www7.nationalgeographic.com/ngm/0706/feature2/gallery1.html>

## 5.5 Summary

### 5.5.1 Iceberg Production is Increasing

Measured by volume the Greenland ice sheet is producing more icebergs, and this can be clearly linked to increases in ocean temperatures that increase the number of air temperature positive degree days in summer causing more surface melting on the ice sheet. Surface melt-water in turn flows to the bases of the glaciers lubricating the ice/rock contact surface, and resulting in accelerated glacial flow and iceberg production.

### 5.5.2 Iceberg Flux is Decreasing

The same oceanic factors that are triggering greater iceberg production also are responsible for their more rapid destruction. Glacier acceleration is resulting in dynamic thinning and probably causing mechanical fracturing of the ice. These two effects will result in more numerous icebergs than before but with decreased drafts. Warming intermediate water also appears to be moving into fjords, increasing the melt rate of ice at the grounding line and having the effect of further reducing grounding line depth and consequently iceberg draft.

Larger numbers of smaller icebergs emerging into the open ocean are now exposed to warmer surface and intermediate water temperatures, increasing the melt rate. Warmer sea surface temperatures are directly correlated with the continuing decrease in sea ice concentration in Baffin Bay and the Labrador Sea. Icebergs, formerly protected by sea ice from wave action, are thus exposed to larger regions of open ocean and to wave action which is one of the primary mechanisms that rapidly accelerates melting.

### 5.5.3 The Future

The resulting irony is that although icebergs are presently being produced at a rate unprecedented in recent history, fewer of them are surviving the journey south to the Grand Banks of Newfoundland. If global climate change continues to result in increasing ocean and air temperatures (notwithstanding local and regional temperature variations associated with decadal oscillations in the North Atlantic) what will be the effect on iceberg production? It is likely that Greenland outlet glaciers will continue to speed up and produce large numbers of smaller icebergs, but this can only be sustained for so long before glacier dynamics will result in deceleration of thinning and stagnating glaciers as drawdown from the central ice sheet cannot be sustained. Similarly, the increasing numbers of icebergs likely will continue to be more than offset by increased ocean temperatures and decreased protection from wave action as the margins of the annual sea ice canopy continue to recede.

## **6.0 OUTSTANDING ISSUES AND AREAS FOR RESEARCH**

### **6.1 Observations**

For Grand Banks Ice Management there is presently a high standard of iceberg towing (and deflection) capabilities and iceberg detection frameworks in place, all implemented with generally proven ice management plans and programs.

There appear to be no major issues with iceberg towing. The long standing synthetic line tow rope method has been effective for many years. The new iceberg tow net has been demonstrated over the past three to four years to significantly improve the prospect of managing slippery or otherwise hard to tow small and medium icebergs. Greater experience with the net would improve confidence for vessel captains and industry. The risk of fouling a tow line or tag line on propellers when retrieving lines is still a concern. This problem is compounded if visibility is poor due to fog or nighttime. Use of beacons or other means may offer some benefit. The ability to manage icebergs in gale to storm conditions would be desirable, although already the net appears to be offering promise for maintaining control of a tow in higher sea conditions.

Early detection of icebergs and minimizing possible gaps in the spatial, temporal, and environmental conditions coverage provided by the growing range of satellite and radar technologies together with aerial reconnaissance, remain challenges. Further quantification of these coverage parameters and the potential benefits and limitations (including perhaps cost) would be valuable as input into planning and decision-making tasks. Increased operational use of satellite would improve their confidence for all stakeholders.

Resource management and decision-making including which icebergs to tow, how soon, in which directions, and for how long are perennial challenges especially with multiple fields since different operators have different needs and priorities. This is significant both from a risk mitigation standpoint, to ensure that the "best" decision can be made, and from a cost perspective so that resources are assigned for a sufficient but appropriate length of time. The use of data fusion and decision-making tools would appear to be the obvious route and good progress has been made for each. Better monitoring and assimilation of met-ocean conditions is another factor for the decision-making.

The PERD iceberg sighting and iceberg management databases are good information resources and they should be maintained. The databases offer utility in a number of areas including study of past conditions and performances, for planning future activities, and possibly as input to other initiatives, such as decision-making or data fusion toolbox technologies.

Given that there are potential improvements to be made, one question is determining which merit dedicated research, and which are basic operational or management of resources issues. The next section attempts to facilitate such a plan.

## 6.2 A Suggested Plan for Ice Management Issues (IMI)

This section presents a suggested initial plan with the intended goal of identifying outstanding iceberg management issues (IMI), issues that in order to solve or measurably improve require dedicated research efforts. The actual level of effort will be determined and will be a function of the issue. The type of research could range from synthesis of different remote sensing technologies, to design and fabrication of new iceberg deflection equipment and procedures, to simply establishing a database that gets updated regularly to analyse the particular issue à la the PERD databases for tracking the numbers of icebergs seen and towed. The plan will require involvement and buy-in from stakeholders, and development of the exact details required to answer the question of *What is going to be changed and how?*

1. Prepare an initial list of possible issues or specific objectives with associated priorities, current standards and targeted levels of performance to be sought for each. One possible starting point of issues and brief description is presented below in Table 6.1. Ideally, the present and target levels of performance with each should be noted or estimated to help judge the possible cost-benefit for each.
2. Stakeholder review and discussion is required to revise and complete the initial list to ensure, initially anyway, there is some agreement of the objectives. Stakeholders will include as a minimum: industry, government, and ice management, environmental or other service providers. This should be accomplished through one or more meetings or workshops, perhaps as CHC-Organized workshops (cf., NRCC, CHC, 2007).
3. At this point, as a next pass, it can be confirmed (by all parties) that the issues being considered are indeed outstanding and have yet to be solved or improved upon significantly. These will be recurrent iceberg detection, towing, data fusion, decision-making or related ice management, or perhaps iceberg engineering issues. Any others can be dropped.
4. The next consideration is which of the issues in fact need, or might lend themselves well to, a dedicated research program and course of critical investigation, and which may be addressed in other ways, e.g., through changes in operating practice. Any of the latter could be dropped. Again, some stakeholder consultation would be in order for this step and some assignment of priorities may be in order.
5. Constraints are assessed for each objective. These will consider time and resource limitations, and what factor existing technology and systems may play in pursuing the objective. For example, can a pilot ice management decision-making tool be targeted for use offshore operationally, or should it be run in parallel from shore or perhaps in a hindcast mode. Synergies are inevitably sought to coordinate multi-discipline research efforts, e.g., *in situ* iceberg position, profile, and wind and current monitoring, drift trajectory forecast, and even detection groundtruthing can all conceivably take place at the same time. Nevertheless, there is generally a requirement for icebergs to be present, and vessel time and access to the area for sufficient time to conduct study. Identification and quantification of some of these constraints is in order.
6. A more detailed list of activities or elements of the research program for each objective is developed. Ideally, this should be a necessary and sufficient list of tasks, meet the original objectives, requirements, and priorities set out, and offer greatest chance of success. A gap analysis could be conducted to check for completeness.
7. Resource requirements are realistically assessed. This may include people, supply boats or other boats, systems, software, data flows, etc. These should be adequate to complete the work. The associated costs and how they are allocated should then be assessed. At this time, a review of the cost-benefit of undertaking the work and the

likely overall importance might be in order. A review of alternatives for the proposed detailed tasks and resources could be considered as well.

8. A schedule is planned, with estimated start and end dates, times required, critical paths (e.g., technology or equipment development, data feeds, testing) determined. The detailed activity list, resource (including cost) and time requirements will define each particular dedicated research effort required.
9. The plan must be validated. Possible threats to the plan (e.g., no icebergs, uncooperative weather, unavailability of resources including vessel time), and contingency planning should be determined. It is confirmed once again that the issues remaining are all significant and with viable research programs. The plan is revised and completed

Once complete, project implementation of the plan must follow. This will include determining who leads each major objective/activity, building the associated team for each, detailing the tasks and schedule, and determining a budget. One idea is the preparation of a startup report. This would document goals of the project, the motivation and anticipated benefits, measures of success being sought, milestones and deliverables, and list of all stakeholders. For the benefit of all stakeholders, team decision-making, good review and communication of decisions, progress, and problems will be essential project management components.



Table 6.1 Potential Ice Management Issues List

Issue	Discussion
<b>Iceberg Detection</b>	
Satellite Radar	<p>Satellite radar systems offer the potential for all weather, wide swath iceberg detection in near real time. Presently, there is a trade-off between the areal coverage and the resolution of the data. With RADARSAT, 30 m resolution data have a swath on the order of 20 n.mi. but false alarm rates may be problematic for real time operations. At present, repeat coverage with this swath is not sufficient to obviate the need for airborne reconnaissance. Fine mode data, with a nominal resolution of 10 m, removes the false alarm issue but the swath is reduced substantially.</p> <p>Systems with dual and multiple polarization have been investigated to date and there is considerable scope for more research in this area.</p> <p>Once the coverage issue is resolved through more satellites, there are potentially big gains to be made by continued research on satellite radar detection.</p> <p>Objectives should be to verify detection capabilities, and to apply advanced processing techniques (particularly in the case of multipolarization) to increase detection probability and decrease false detections in wind and higher sea states. An important component of this work should be to provide concurrent ground truthing for above water iceberg shape and dimensions, and measurement of local wind and sea state.</p>
Marine Radar	<p>A new standard is presently being developed for coherent marine radar systems. Once these become available, field testing and new simulation models for iceberg detection will be required. Within the next few years, it is expected that all offshore facilities and vessels will be equipped with coherent systems.</p> <p>There is very good research potential in the assessment of coherent radar systems for small iceberg and bergy bit detection, and the detection of larger icebergs at the limits of marine radar range. Ground truthing of above water size and shape, and concurrent sea state and wind measurements are critical for marine radar evaluations.</p>
Data Fusion	<p>Satellite systems have not been used to a significant extent operationally and their inclusion in data fusion systems needs to be assessed.</p>



Issue	Discussion
Sea State	Typically, iceberg dimensions can only be confirmed when sea states are relatively low. Ground truthing of iceberg sightings for satellite radar verification needs to be expanded to include higher sea states.
Sea Ice	The presence of sea ice presents a detection problem for icebergs detected using any method. The large amounts of clutter produced by sea ice is an issue for all radar sensors. Dedicated programs need to be in place to investigate iceberg identification and false alarm rates for marine radar, airborne and satellite radar systems. Issues include sea state, sea ice conditions and iceberg dimensions.
<b>Iceberg Towing</b>	
Two-Vessel Iceberg Net Tow	<p>In general, the single vessel with conventional tow line method (Section 2.7.1) has proven with demonstrated experience to be the <i>de-facto</i> standard for iceberg management. Combined with the added capability offered by the recent C-CORE iceberg net for smaller and more problematic icebergs supply vessels should, under general conditions, be in a good position to physically manage most icebergs.</p> <p>One area to be pursued is a two-vessel iceberg net tow (F. Ralph, pers. comm.). The principle would be similar to a single line tow with instead one vessel “shooting” one end of the iceberg net connection line to a second vessel which steams around the iceberg and returns to a position alongside the first vessel. Both vessels increase speed in the pre-determined heading direction and gradually pick up the iceberg and commence the tow. The primary motivation for this is improve/confirm line deployment and recovery, particularly in high sea states. The chronic concern of fouled lines in ship propellers is to be eliminated with this approach. The potential benefits include improved safety (including less crew time on back decks of supply vessel) and efficiency (success in higher sea states).</p> <p>One possible scenario to first test the system in favourable sea conditions, and then to attempt under higher sea conditions and document the success and determined any refinements or improvements to be made either procedurally or in the physical makeup of the iceberg net or associated hardware.</p>
<b>Iceberg Populations</b>	
Global Climate Change	Following on some of the information and ideas presented in Section 5.0, additional study of icebergs reaching the Grand Banks and the greater influence from amounts of sea ice in the Labrador Sea and increased temperatures over recent years may be instructive. There is ample sea surface temperature data and iceberg numbers could potentially be



Issue	Discussion
	<p>correlated with them.</p> <p>In addition to the engineering design considerations, e.g., glory holes mentioned below, this issue may be relevant for revisiting predictions of iceberg season severity. Due to the high degree of variability in iceberg seasons, this has sometimes resulted in a mismatch between management resources and the iceberg threat. Long-term iceberg forecasting can potentially assist with seasonal resource allocation and strategic decisions over several weeks or months. Revisiting this technology and the models employed may yield practical benefits for offshore operators.</p> <p>While in some ways distant from iceberg detection and towing systems, a radical change in the Grand Banks iceberg population would have far reaching effects for all areas of iceberg management, so this is a significant issue.</p>
Iceberg Scour and the Glory Hole Need	<p>Risk of iceberg scour is a consideration both for facility design and construction, especially important for smaller fields, and ice management operations. As noted at the recent Petroleum Research Atlantic Canada (PRAC) 1st Annual Atlantic Petroleum R&amp;D Forum (e.g., Zoon, 2007) one of the research opportunities is to eliminate the need for glory holes: an excavation into the sea floor designed to protect wellhead equipment from iceberg scour. If as put forward in Section 5.0, icebergs reduce in numbers or size and hence draft then the risk of iceberg scour and the glory hole problem may be significantly reduced.</p> <p>One obvious initiative, that could be aided by the existing NRC/PERD iceberg databases, would be to annually monitor and analyse the iceberg population to see what changes are occurring. As has been the case to date, the iceberg drafts and undersea shapes could be measured or estimated. There are at least six profiling sonars on the Grand Banks support vessels to readily support the latter. Other than any particular extra efforts to conduct iceberg profile or 3D shape measurements, the cost for this objective would be very small. There may be additional aspects to consider or research as part of this issue. Also, in addition, or alternatively, to the idea of a changing iceberg population, there may be other iceberg research ideas that address the goal of eliminating or mitigating the need for glory holes. Similar interests and benefits would be in order for possible pipeline developments as well.</p>
<b>Environmental Monitoring/Data Fusion</b>	
Ocean Current Data for Improved Iceberg Trajectory Forecasting	The offshore operators presently monitor ocean currents as part of regulatory and operational requirements. The type of instrumentation varies between operators and platforms offshore; however, in perhaps a somewhat analogous fashion to the data fusion application for iceberg detection there is a significant base of current measurements that could be better utilized to directly support iceberg trajectory forecasting activities in a timely manner. These resources include at least:



Issue	Discussion
	<ul style="list-style-type: none"> <li>▪ MIROS surface currents on the Hibernia platform</li> <li>▪ ROMAN real-time currents at White Rose</li> <li>▪ Vessel-Mount ADCPs on Hibernia and Husky supply vessels</li> </ul> <p>The Canada Newfoundland Ocean Forecasting System is a DFO pilot project in regional ocean forecasting. C-NOOFS (<a href="http://www.c-noofs.gc.ca">www.c-noofs.gc.ca</a>) will pursue improvements and activities in the regional ocean forecasting for the North West Atlantic. Currently, C-NOOFS is implementing the operational system with an initial condition from MERCATOR-OCEAN weekly operational ocean forecasting system, and then running daily updates throughout the week with the latest forecast from environment Canada. This is a simple way of having <i>in-situ</i> and altimetric data as part of the ocean forecast system C-NOOFS. Work however is underway to assimilate data directly into the C-NOOFS forecast system.</p> <p>While C-NOOFS development is underway, there is a strong need for the validation through applications. The first example is validating surface drift with the Canadian Coast Guard CANSARP program. Twelve surface drifters are available for experimental deployment this year. The second important validation example is iceberg drift. Iceberg drift is important for validating ocean models since the drift is not just affected by surface currents but also subsurface currents. Thus iceberg track validation with ocean models helps to validate subsurface currents which are primarily based on geostrophy (pressure force balancing the coriolis force) and dependent on ocean stratification.</p> <p>In the improvements of an ocean forecasting system for the Newfoundland Shelves and adjacent deep water, real-time <i>in-situ</i> data would be very useful. In a first step this would help provide near real-time ocean model forecast validation. Secondly, available data itself could be assimilated into the ocean model to produce the best estimate of the present ocean state prior to running a forecast. Development in the next three years will take place to implement and improve assimilation schemes for C-NOOFS as well as global ocean forecast systems. (F. Davidson, pers. comm.)</p> <p>A possible logical precursor to some of this detailed work would be a detailed “framing up” of all potential offshore current datastreams of interest. As an initial step current data fusion efforts in this regard could be applied to provide additional operational support for ice season operations.</p>
Decision-Making	<p>Ice management decisions, in particular which icebergs to tow, when, in which direction, and for how long, are made to support each facilities’ strategy and respect established response zones as per the ice management plan, e.g., Hibernia has employed a 24 mile tactical zone with an inner 6 mile facilities reaction zone, the Terra Nova FPSO using a T-time of 4.5 hours and exclusion zone of 1 mile, and outer tactical zone of approximately 24 hours. T-times are less for semi-submersible drill rigs or dynamically positioned drillships which can disconnect and move offsite in a relatively short time. The shorter the T-times, the greater the amount of time available to manage (or wait on) the approaching ice. Large T-</p>



<b>Issue</b>	<b>Discussion</b>
	<p>Times introduce a new challenge to ice management, e.g., Grand Banks jackup drilling operations in summer 2006 occasionally exhibited T-times equating to a distance as far away as the Orphan Basin, so that in these instances the question of when to initiate tows and for how long remains an issue and is a factor for success, especially with multiple icebergs.</p> <p>Clearly also the C-CORE Iceberg Decision Making Toolbox and the Iceberg Management Planning Aid software are good practical steps in this direction and greater operational use, experience, and refinement is in order.</p>

## **7.0 REFERENCES**

### **7.1 Personal Communications**

Ralph, F., Director, Ice Engineering, C-CORE, St. John's, March 2007.

Power, D, Director, Remote Sensing, C-CORE, St. John's, March 2007.

Dodge, K, Engineer, Remote Sensing, C-CORE, St. John's, March 2007.

Rudkin, P., Director, PAL Environmental Services, St. John's, March 2007.

Carrieres, T. Ice Modelling Manager, Environment Canada, March 2007.

Davidson, F., Research Scientist, Fisheries and Oceans Canada, St. John's, March 2007.

### **7.2 Literature Cited**

AGRA, 1998. "Ice Season 1998 Summary." Prepared for Hibernia Management and Development Company Ltd., Prepared by AGRA Earth & Environmental, July 1998.

AMEC, 2000b. "Ice Management End of Well Report, Fylla Exploration Drilling, Well 6354/4-1 (Qulleq-1), Offshore West Greenland. Revision 2.1" Prepared for Statoil by AMEC Earth & Environmental, September 2000.

AMEC, 2000c. "Ice Management End of Ice Season 2000 Report, Hibernia Platform." Prepared for Hibernia Management and Development Company Ltd. by AMEC Earth & Environmental, October 2000.

AMEC, 2002a. "Greenland Iceberg Management: Implications for Grand Banks Management Systems". PERD/CHC Report 20-65 prepared for NRC by AMEC Earth & Environmental, March 2002.

AMEC, 2002b. "PERD Comprehensive Ice Management Database for the Fylla 2000 Exploration Drilling". Prepared for NRC by AMEC Earth & Environmental, March 2002.

Barker, A., M. Sayed, and T. Carrieres, 2004. Determination of Iceberg Draft, Mass and Cross-Sectional Areas. Proceedings of 14th International Offshore and Polar Engineering Conference (ISOPE), pp 899-904, Toulon, France.

Bindschadler, R. 2006. Hitting the Ice Sheets Where It Hurts. *Science*, 311 (24<sup>th</sup> March): 1720.

Brown, R., Dunderdale, P.E. and Mills, J. (2003) On The Development Of An Iceberg Management Planning Aid, Proceedings of the 17th International Conference on Port and Ocean Engineering under Arctic Conditions POAC '03, Trondheim, Norway

C-CORE, (2001a). "Integrated Ice Management R&D Initiative – Year 2000." C-CORE Report R-00-C36 to Chevron, ExxonMobil, Husky, Norsk Hydro, PERD and Petro-Canada.

C-CORE, 2002. "Integrated Ice Management R&D Initiative – Year 2001." C-CORE Report R-01-24-605 to Chevron, ExxonMobil, Husky, Norsk Hydro, PERD and Petro-Canada.

C-CORE (2003a), "Ice Management JIP Year 2002", C-CORE Report Number R-02-026-110.

C-CORE (2003b) Coherent UHF Radar for Ice Detection, C-CORE Report R-03-022-099 for Regional Citizens Advisory Council of Valdez, Alaska.

C-CORE (2004a), "Ice Management JIP Year 2003", C-CORE Report Number R-03-059-226 v2, May 2004

C-CORE (2004b) "Satellite Radar Iceberg Detection in Sea Ice", C-CORE Report R-03-095-276 – March 2004.

C-CORE (2005a), "Ice Management JIP Year 2004", C-CORE Report Number R-04-088-300 v2, November 2005.

C-CORE (2005b) "Iceberg and Ship Detection and Classification: Demonstration of Improved Marine Surveillance and Management", Earth Observation Application Development Program, C-CORE Report R-05-003-359 – November 2005.

C-CORE (2006a) "Evaluation of Satellite SAR Data for Iceberg Detection in the Barents Sea", C-CORE Report R-05-046-367 – March 2006.

C-NLOPB (2002) "Operator's Safety Plan Guidelines, Draft for Comment", Canada-Newfoundland and Labrador Offshore Petroleum Board.

Churchill, S., Randell, C., Power, D., Gill, E. (2004) "Data Fusion: Remote Sensing for Target Detection and Tracking, in Proceedings of the International Geoscience and Remote Sensing Symposium.

Churchill, S., Randell, C., Power, D., Gill, E. (2006) "Cumulative Effects of Discrete Fusion on Target Detection Probability, in Proceedings of the International Geoscience and Remote Sensing Symposium.

CODIE, 1995. "Canadian Offshore Design For Ice Environments Final Report Volume 1 Environment and Routes." Memorial University Report prepared for the Department of Industry, Trade and Technology (authors M. Fuglem, I. Jordaan, G. Crocker and C. Olsen).

Crocker, G., Wright, B., Thistle, S., and Bruneau, S. 1998. An Assessment of Current Iceberg Management Capabilities. Contract Report for: National Research Council

Canada, Prepared by C-CORE and B. Wright and Associates Ltd., PERD/CHC Report 20-33.

Crocker, G. (2000) Collection of iceberg model verification data, Ballicater Consulting Report 00-03 to Canadian Ice Service.

Crocker, G. (2001) Collection of iceberg model verification data - June 2001, Ballicater Consulting Report 01-03 to Canadian Ice Service.

Crocker, G. (2002) Collection of iceberg model verification data - May 2002, Ballicater Consulting Report 02-01 to Canadian Ice Service.

Crocker, G. (2003) Collection of iceberg model verification data – June 2003, Ballicater Consulting Report 03-02 to Canadian Ice Service.

CSA (1992) General requirements, design criteria, the environment, and loads, CSA Standard S471-92, Canadian Standards Association.

CSA (2004) General requirements, design criteria, the environment, and loads, CSA Standard S471-04, Canadian Standards Association.

Ekström, G., M. Nettles, V. C. Tsai. 2006. Seasonality and Increasing Frequency of Greenland Glacial Earthquakes. *Science*, 311 (March 24<sup>th</sup>): 1756-1758.

Flett, D., J. Youden, S. Davis, C.R. Randell, and M. Arkett (2000) "Detection and Discrimination of Icebergs and Vessels using RADARSAT Synthetic Aperture Radar". Invited paper, Proc. Ship Detection Workshop, AMRS, Halifax, NS, June 2000.

Howell, C., Youden, J., Lane, K., Power, D., Randell, C., Flett, D. (2004) "Iceberg and Ship Discrimination with ENVISAT Multi-Polarization ASAR, in /Proceedings of the International Geoscience and Remote Sensing Symposium.

IPCC, 2007: Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. <http://ipcc-wg1.ucar.edu/wg1/wg1-report.html>

Johnson, M. and Ryan, J.P. (1991). A Radar Performance Prediction Model for Iceberg Detection, POAC'91 Proceedings Vol. 2, the 11th International Conference on Port and Ocean Engineering under Arctic Conditions, St. John's, Canada.

Joughin, I. 2006. Greenland Rumbles Louder as Glaciers Accelerate. *Science*, 311 (24<sup>th</sup> March): 1719-1720.

Joughin, I., W. Abdalati & M. Fahnestock. 2004. Large fluctuations in speed on Greenland's Jakobshavn Isbræ glacier. *Nature*, 432: 608 – 610.

Kubat, I. and M. Sayed, (2006) CHC/NRC Implementation of the Canadian Ice Service Local Iceberg Drift Model, NRC Report CHC-TR-042, Ottawa, Ont., Canada.

Kubat, I., M. Sayed, S.B. Savage, and T. Carrieres, 2005. An Operational Model of Iceberg Drift. International Journal of Offshore and Polar Engineering, Vol.15, No.2, pp125-131.

Lane, K., Power, D., Chakraborty, I., Youden J., Randell, C. (2002) "RADARSAT-1 Synthetic Aperture Radar Iceberg Detection Performance ADRO-2 A223", in Proceedings of the International Geoscience and Remote Sensing Symposium.

Lane, K., Randell, C., Youden, J. and Power, D. (2003) "Validation of Envisat Synthetic Aperture Radar for Iceberg Detection" NECEC 2003 - November 12, 2003 - St. John's, NL.

Lane, K., Power, D., Youden J., Randell, C., Flett D. (2004) "Validation of Synthetic Aperture Radar for Iceberg Detection in Sea Ice", in Proceedings of the International Geoscience and Remote Sensing Symposium.

Lemke, P., J. Ren, R.B. Alley, I. Allison, J. Carrasco, G. Flato, Y. Fujii, G. Kaser, P. Mote, R.H. Thomas and T. Zhang, 2007: Observations: Changes in Snow, Ice and Frozen Ground. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. <http://ipcc-wg1.ucar.edu/wg1/wg1-report.html>

Luthcke, S. B., H. J. Zwally, W. Abdalati, D. D. Rowlands, R. D. Ray, R. S. Nerem, F. G. Lemoine, J. J. McCarthy, D. S. Chinn. 2006. Recent Greenland Ice Mass Loss by Drainage System from Satellite Gravity Observations Science, 314 (November 2006): 1286-1289.

Makrygiannis, C., McKenna, R., Wright, B., Allyn, N., Sildnes, T., Jolles, W., Morland, M, and Grant, R. (2006) The Development of an Arctic Standard for Floating Production Systems, in Proceedings of ICETECH'06, SNAME, Banff, Alberta.

McKenna, R.F. (2003) Canadian ice service workshop on iceberg drift and deterioration, 14 November 2003, Report 03-10-01-1 v3 for Canadian Ice Service.

McKenna, R., Ralph, F., Power, D., Jordaan, I. and Churchill, S. (2003) Modelling Iceberg Management Strategy, Proceedings of the 17th International Conference on Port and Ocean Engineering under Arctic Conditions POAC '03 Trondheim, Norway.

McKenna, R.F. (2004a) Outline of 2004 field experiment, Report 03-10-01-4 v1 for Canadian Ice Service.

McKenna, R.F. (2004b) Analysis of iceberg projected areas, Report 03-10-01-2 v1 for Canadian Ice Service.

National Research Council Canada, Canadian Hydraulics Centre, 2007. Canadian East Coast Ice Engineering Issues. Web Page.

[http://chc.nrc-cnrc.gc.ca/ColdRegions/Reports/ice\\_engineering\\_e.html](http://chc.nrc-cnrc.gc.ca/ColdRegions/Reports/ice_engineering_e.html)

PAL, 2000. "The 2000 Iceberg Season on the Grand Banks, Final Report for The Grand Banks Ice Management Team". PAL Environmental Services, November, 2000.

PAL, 2003. "The 2003 Iceberg Season on the Grand Banks, Final Report for The Grand Banks Ice Management Team". PAL Environmental Services, November, 2003.

PAL (2003) Operational Analysis of the CIO Iceberg Drift Model - 2003, Provincial Aerospace Report to CIS.

PAL (2004) Operational Analysis of the CIO Iceberg Drift Model - 2004, Provincial Aerospace Report to CIS.

PAL Environmental Services, 2005. Comprehensive Iceberg Management Database 2005. PERD/CHC Report 20-72

Peterson, I. Iceberg forecasting, tabular icebergs. Fisheries & Oceans Canada poster: (<http://starfish.mar.dfo-mpo.gc.ca/science/ocean/seaice/Posters/IngridIcebergPoster2006.pdf>).

Power, D., Youden, J., Lane, K., Randell, C., Flett, D. (2001) "Iceberg detection capabilities of RADARSAT synthetic aperture radar", Canadian Journal of Remote Sensing, vol. 27, no. 5 pp. 476-486.

Randell, C., M. Rokonuzzaman, James Youden and Rifaat Khan (1999) "Evaluation of Radarsat for Detection, Classification and Discrimination of Icebergs", Proc, CSA ADRO Symposium, 1999.

Randell, C., J. Youden, S. Davis, and D. Power (2000) "Point Target Detection and Classification in Ocean Sciences Using Satellite SAR", Proc. OCEANOLOGY International 2000, Brighton, UK, March 2000.

Rignot, E. and P. Kanagaratnam. 2006. Changes in the Velocity Structure of the Greenland Ice Sheet. Science, 311 (17th Feb): 986-990.

Rudkin, P., Young, C., Barron, P. and Timco, G. (2005) Analysis And Results of 30 Years of Iceberg Management Proceedings 18th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC'05), Potsdam, NY, Vol. 2, pp 595-604.

Savage, S.B., G.B. Crocker, M. Sayed and T. Carrieres, 2000, Size Distribution of Small Ice Pieces Calved from Icebergs Cold Regions Science and Technology, Vol.31, pp 163-172

Savage, S.B., G.B. Crocker, M. Sayed and T. Carrieres, 2001. Bergy Bit and Growler Melt Deterioration, Journal of Geophysical Research, Vol.106, No.C6, pp11,493-11,504

Sayed, M. and T. Carrieres, 1999. Overview of a New Operational Model. Proceedings of 9th International Offshore and Polar Engineering Conference (ISOPE), Brest, France. pp622-627,

Seaconsult, 1988. "Physical Environmental Data for Production Systems at Terra Nova." Prepared for Petro-Canada by Seaconsult Limited, 1988.

Smith, S.D. and Donaldson, N.R.(1987) Dynamic modeling of iceberg drift using current profiles, Canadian Technical Report of Hydrography and Ocean Sciences No. 91, Bedford Institute of Oceanography.

Thomas, R.H., W. Abdalati, E. Frerick, W.B. Krabill, S. Manizade and K. Steffen. 2003. Investigation of surface melting and dynamic thinning on Jakobshavn Isbrae, Greenland. Journal of Glaciology, 49 (165): 231-239.

U.S. Coast Guard International Ice Patrol (IIP). "Ice Patrol's Iceberg Counts."  
<http://www.uscg.mil/lantarea/iip/General/icebergs.shtml>

(The 2005 and 2006 numbers are subject to year end review)

Verbit, S., Comfort, G. and Timco, G., 2006. Development of a Database for Iceberg Sightings off Canada's East Coast Proceedings IAHR'06, Vol. 2, pp 89-96, Sapporo, Japan, 2006.

Yao, T., Tang, C.L. and Peterson, I.K. (2000) Modeling the Seasonal Variation of Sea Ice in the Labrador Sea with a Coupled Multicategory Ice Model, Journal of Geophysical Research, V.105(C1), pp.1153-1165.

Zoon, Ruud, 8 May 2007. "East Coast R&D, An Operator's Perspective". PRAC's 1st Annual Atlantic Petroleum R&D Forum, St. John's, Newfoundland, 8-9 May 2007.  
<http://www.pr-ac.ca/files/Zoon.pdf>

Zwally, H. J., W. Abdalati, T. Herring, K. Larson, J. Saba, K. Steffen. 2002. Surface Melt-Induced Acceleration of Greenland Ice-Sheet Flow. Science, 297 (12 July 2002): 218-222.

### **7.3 Additional Reading**

AMEC, 2000a. "Statoil, Fylla Exploration Drilling, Qulleq-1 (6354/4-1) Ice Management Plan. Revision 4." Prepared for Statoil by AMEC Earth & Environmental, April 2000.

Bishop, G., 1989. "Assessment of Iceberg Management for the Grand Banks Area: Analysis of Detection and Deflection Techniques," Mobil Oil Canada Properties, Property Development Department, Hibernia Producing Operations.

BMT Fleet Technology, 2005. PERD Iceberg Sighting Database: 2005. Iceberg\_Sighting\_05.pdf, PERD\_Iceberg\_Sighting\_Database\_05.mdb  
BMT Fleet Technology, Kanata, Ontario, Canada.

Bullock, T., and J. McClintock, 2001. "Greenland Ice Management 2000". Proceedings of the 16th International Conference on Port and Ocean Engineering under Arctic Conditions, POAC '01, Ottawa, ON, Canada, Vol. 2, pp 975-985.

Canatec (1999) Compilation of Iceberg Shape and Geometry Data for the Grand Banks Region, Canatec, ICL Isometrics, Coretec & Westmar, PERD/CHC Report 20-43.

Carrieres, T., M. Sayed, S. Savage and G. Crocker, 2001 Preliminary Verification of an Operational Iceberg Drift Model Proceedings 16th POAC Conference, pp 1107-1116, Ottawa, Canada.

C-CORE (2001b) "Validation of Iceberg Detection Capabilities of Radarsat Synthetic Aperture Radar – 2000 – Final Report", Submitted to Canadian Ice Service.

C-CORE (2005c) "Ship/Iceberg Detection Service: Service Summary and Results Phase 1", C-CORE Report R-05-043-359 – December 2005.

C-CORE (2006b) Iceberg and Ship Detection and Classification: Demonstration of Improved Marine Surveillance and Management – Earth Observation Application Development Program Go/No-Go Report", prepared for Canadian Space Agency, C-CORE Report R-06-004-359 - April 2006.

Comfort, G. (1998) Investigation of Techniques for Continuously Profiling Ice Features , Fleet Technology, PERD/CHC Report 5-91.

Comfort, G. and Verbit, S., 2003, Update and Quality Assurance of the PERD Grand Banks Iceberg Database: 2003, Canadian Hydraulics Centre website, [www.chc.nrc.ca](http://www.chc.nrc.ca).

CSR (2000) Techniques for Determining the Maximum Draft of Icebergs, Canadian Seabed Research, PERD/CHC Report 20-46.

Fleet (2003) Update, Quality Assurance and Query Results for the PERD Grand Banks Iceberg Database: 2003, Fleet Technology, PERD/CHC Report 20-71.

Howell, C., Mills, J., Power, D., Youden, J., Dodge, K., Randell, C., Churchill, S., and Flett, D. (2006) "A Multivariate Approach to Iceberg and Ship Classification in HH/HV ASAR Data", in Proceedings of the International Geoscience and Remote Sensing Symposium

Jordaan, I., Press, D., Milford, P. (1999) Iceberg Database and Verification, PERD/CHC Report 20-41.

Lane, K., Power, D., Youden, J., Randell, C. and D. Flett, 2001. "Overview of Iceberg Detection Capabilities of RADARSAT Synthetic Aperture Radar." Proceedings of the 16<sup>th</sup> International Conference on Port and Ocean Engineering under Arctic Conditions, POAC '01, Ottawa, August 2001.

McClintock, J., 2001. Critical Factors in Deep Water Ice Management. Presentation to Newfoundland Ocean Industries Association, Deep Water Seminar , Technologies & Issues for East Coast Canada, 25 September 2001, St. John's, Newfoundland.

McKenna, R. (2004) Development of Iceberg Shape Characterization for Risk to Grand Banks Installations, PERD/CHC Report 20-73.

McKenna, R. (2005) Iceberg Shape Characterization, Proceedings 18th International Conference on Port and Ocean Engineering under Arctic Conditions, POAC'05, Vol. 2, pp 555-564, Potsdam, NY, USA.

McKenna, R. (2005) Refinement of Iceberg Shape Characterization for Risk to Grand Banks Installations PERD/CHC Report 20-77.

PERD, 1999. "Compilation of Iceberg Shape and Geometry Data for the Grand Banks Region." Written by Canatec Consultants Ltd., ICL Isometrics Ltd., CORETEC Inc. and Westmar Consultants Ltd. PERD Report no. 20-43.

PERD, 2000. PERD Grand Banks Iceberg Database Update II. Fleet Technology Ltd. Report to PERD (authors S. Verbit, B. Trott, Y. Gong and G. Comfort).

PERD, 2001. Update and Quality Assurance of the PERD Grand Banks Iceberg Database. Prepared by Fleet Technology Ltd. PERD/CHC Report 20-59.

Rudkin, P. and Dugal, R. (2001) An evaluation of the multi-field ice management strategy used in support of Grand Banks oil operations. Proceedings - International Conference on Port and Ocean Engineering under Arctic Conditions, Vol.16(Vol. 2), p.987-996.

Rudkin, P. and Dugal, R.. (2000) Ice detection and management in support of Canadian east coast offshore oil operations, ICETECH '2000, Sixth International Conference on Ships and Marine Structures in Cold Regions, St Petersburg, Russia, pp.467-474.

Singh, S., Green, S., Ennis, T., Comfort, G., and Davidson. L., 1998, PERD Iceberg Database for the Grand Banks Regions, Canadian Hydraulics Centre website, [www.chc.nrc.ca](http://www.chc.nrc.ca).

Singh, S., Li, X., and Comfort, G., 1999, PERD Grand Banks Iceberg Database Update, Canadian Hydraulics Centre website, [www.chc.nrc.ca](http://www.chc.nrc.ca).

Verbit, S., et al., 2000, 2001, 2002, 2004, 2005, PERD Grand Banks Iceberg Database Update, Canadian Hydraulics Centre website, [www.chc.nrc.ca](http://www.chc.nrc.ca).

Verbit, S., and Comfort, G., 2006, PERD Iceberg Sighting and Flight Information Database, Canadian Hydraulics Centre website, [www.chc.nrc.ca](http://www.chc.nrc.ca).

Wright (1998) Ice Problems Related to Grand Banks Petroleum Fields, B. Wright & Associates, PERD/CHC Report 20-6.