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Decades of Iceberg Management supporting Grand Banks Operations

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ABSTRACT

Iceberg management is an integral part of operations on the Grand Banks, a region known for its harsh environment having high winds and waves and the occasional presence of icebergs and pack ice. Platforms operating in this region must account for the presence of icebergs, with the exception of Hibernia which was designed for any iceberg that could drift within 80 m water-depth. The Terra Nova and SeaRose FPSOs can disconnect from the mooring/riser systems and move off location to avoid icebergs that are threatening but not manageable.

In a probabilistic design basis, ice management mitigates contact risk and also removes from a distribution of impacting icebergs, any that are detectable and towable (given the occurrence of sea states and iceberg size) and for disconnecting floaters, those that would not be visible in sufficient time to disconnect. In the context of operations, iceberg management is essentially the utilization of different sensors to detect ice features (e.g., satellite, aircraft and vessel radar), monitoring, threat assessment, physical management (e.g., towing) and for scenarios where threats cannot be mitigated, decisions to down-man (e.g., the Cenovus West White Rose Platform) or disconnect (e.g. Terra Nova and Sea Rose FPSOs).

This paper will review operations to date, including statistics that quantify annual numbers of icebergs crossing 48°N, discuss three decades of successful operations that have resulted in zero iceberg contacts or disconnections to date, and illustrate how ice management reduces estimated iceberg contact rates and subsequent reductions in facility design forces.

The paper finally highlights the importance that any full offshore development cycle (concept to operations) maintains strong collaboration between the design team and operational team. If operational success is integrated into the design, and risk mitigation reduces design loads, it is imperative that operations are planned and executed accordingly.

KEY WORDS: Iceberg; Detection; Towing; Loads; Probabilistic

BACKGROUND

Offshore oil and gas exploration began on the Grand Banks of Newfoundland in 1966 with the first major discovery, Hibernia, occurring in 1979. The discovery of Hibernia was the result of a joint exploration venture by Chevron and Mobil. Other major oil and gas discoveries on the

Grand Banks followed with Hebron in 1981 and the White Rose and Terra Nova Fields in 1984. Figure 1 illustrates each of the existing Grand Banks platforms; Hibernia GBS installed in 1997, Terra Nova FPSO in 2002 (Lever and Kean, 2001), SeaRose FPSO in 2005, Hebron GBS in 2015 (Widianto et. al., 2013) and the Cenovus West White Rose Platform expected to be installed in 2025. Bay du Nord is still under development and is scheduled to be producing in the early 2030s. Each of these utilize ice management as part of: *i*) operational risk mitigation, and *ii*) the design basis (with the exception of Hibernia). In the Norwegian Sea, the Wisting development considers iceberg impact risk. Brown et. al., (2016) considered ice management and continued innovation as an enabler for further deepwater development offshore Newfoundland.

With the exception of the Hibernia GBS (which is designed for any iceberg that can reach the facility and not ground in ~80 m water depth), ice management is an integral part of the design and operation of the other facilities. Possible scenarios include: 1) detection of features and actively managing those considered threatening; 2) Scenario 1 plus moving disconnectable facilities off location to avoid interactions if threats persist.

While icebergs maybe expected during any season, there is considerable interannual variability as illustrated in Figure 2 (IIP, 2024). Highlighted as the "Modern Reconnaissance Era," there is notable bias associated with increased numbers since 1980s, resulting from the introduction of Side Looking Airborne Radar (SLAR) in 1984 as well as an increase in number of reconnaissance flights and improved detection technology. Despite the bias, icebergs will continue to occur, and so will the need for ice management operations to mitigate the risk.

Ice management can have a significant influence on design loads, assuming risk mitigation is built into the probabilistic design philosophy (see ISO19906, 2019). It reduces the exposure by reducing the probability of hitting a facility where either threatening icebergs are deflected, or, in the case of floating installations, the facility is moved. For ice management effectiveness to be integrated into the design, the designer must ensure the overall reliability of the system is achieved (i.e., 10^{-5} annual exceedance probability for a high consequence event). This is consistent with requirements in ISO 19906, "Offshore Arctic Structures" and ISO 35104, "Arctic Operations – Ice Management."

Figure 1. Grand Banks production platforms Hibernia, Terra Nova, White Rose, and Hebron

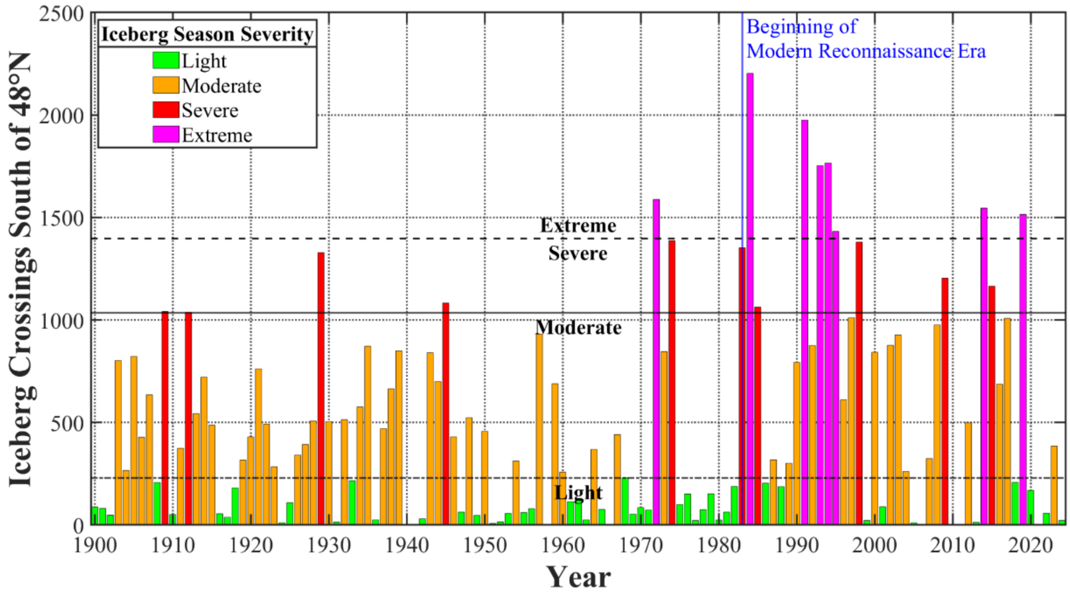


Figure 2. Estimated number of icebergs crossing 48°N each ice year from 1900 to 2024

ICE MANAGEMENT TECHNOLOGY REVIEW

Bishop (1989) and Crocker et.al (1998) reviewed ice management capability and performance success. This led to C-CORE's Integrated Ice Management R&D Initiative (IIMI) from 1999 to 2005 (C-CORE 1999, 2000, 2001, 2002, 2003, 2004, 2005); the goal of which to address technology challenges relating to detection and towing (Randell et al., 2009). Research and development continue with improvements and optimized methods for ice management (detection, forecasting, threat analysis, decision-making and iceberg towing), the modeling of ice management effectiveness for design, and improved methods for iceberg collision and design load analyses.

One achievement was the development of an iceberg net that was designed (C-CORE 2002), built and verified (C-CORE, 2003-2004) and used operationally for the past two decades. While some modifications have occurred, the technology and performance remained consistent. C-CORE (2002) completed a comprehensive review of iceberg towing techniques including the evolution of the iceberg net, including several prototypes through the 1980s that were met with limited success (Anderson et al. 1986). These included the MAREX Growler Net, Husky-Bow Valley Growler Net prototype #1, prototype #2, prototype #3, Acadian Ice Net, Esso Experimental Growler Net, and the Dobrocky Seatech Ice Arrestor Net. The primary reasons for failure were: the net sizes were too small; the bridle arrangement design led to net slipping under or over the iceberg; and there was no appropriate reel for onboard storage. A suitable net was developed (Rogers, 2002) but other than conversation with a veteran captain, no documentation exists. That knowledge led to the development of the C-CORE Iceberg Net Figure 7 b). Towing success (ability to change iceberg drift) before the C-CORE net, was quantified to be on the order of 85% (using a single line technique). Success with the net was evaluated as being 88% for icebergs that were otherwise deemed untowable (0% success) using the single rope. While this sample of tows was limited (i.e. less than 20 at that time), it suggests that towing success could be 90+% but should be regularly verified. This is expected since a pocket provided by a net will perform better for smaller, unstable icebergs in higher seas. Young and Rudkin (2006) showed similar performance measures, including analysis of bollard pull.

Eik and Gudmustad (2010) and Fuglem and Stuckey (2014) studied towing success, including a methodology for systematic evaluation of the need for an iceberg management system and the efficiency of various components based on a combination of a numerical iceberg drift model and a probabilistic analysis. Eik and Marchenko (2010) conducted iceberg towing in sea ice in a basin, measuring towing performance and efficiency with increasing floe size and concentration, noting that feasibly decreases when concentrations exceed 5/10 cover. Kornishin, et al. (2019) conducted icebergs towing experiments in the Barents and Kara seas in 2016-2017, to better understand and develop models for towing force calculations for a wide range of towing speeds, as well as iceberg sizes and shapes, including the derivation of drag force coefficients for model calibrations. Efimov et. al. (2019) conducted trials of iceberg towing in newly formed ice, while measuring the increased tow rope tension associated with the added drag forces. Fuglem et al. (2021) developed a hindcast iceberg drift model called BergCast to evaluate ice management operations and proposed strategies for improving ice management operations and demonstrating the value of reducing forecasting uncertainty. Large numbers of iceberg trajectories are simulated in varied and realistic environmental conditions from hindcast met-ocean data in conjunction with a forecasting uncertainty model derived from forecast validation. It was highlighted that if forecasting were highly accurate, only icebergs passing very close to the platform would require ice management and possible temporary operations suspension.

ICE MANAGEMENT SYSTEM OVERVIEW

The key components of an ice management system are illustrated in Figure 3. Detection forms the basis for threat analysis and subsequent intervention activities. Since fog exists frequently on the Grand Banks, detection tools rely heavily on, marine iceberg radar, airborne radar, satellite-based radar. With advances in data management and storage capability, real-time data collection (and analyses) and digitalization of the marine environment is gaining attraction. With the availably of more frequent higher quality data (e.g., twice daily iceberg detection from RadarSat Constellation Mission (RCM), and the potential for real-time ocean currents), the Machine Learning (ML) capability for iceberg drift forecasting and threat assessment is rapidly advancing. Once a threat has been identified, active physical management is engaged.

For facilities that are designed to disconnect and relocate to avoid interaction with icebergs, management zones are defined (see Figure 3). Zones are sized based on the iceberg drift and T-time (i.e., time required to suspend operations, secure the well, and if necessary move the facility offsite). The monitoring of iceberg movement occurs in the Observation Zone. Iceberg towing is carried out in the Control Zone to prevent icebergs from broaching the Alert Zone. For operations to be safe, the T-Time must be less than the time for the iceberg to reach the facility. The sizing of the Alert Zone is dynamic; operations are suspended to reduce T-Time if the threat persists, and resumed when the threat abates. If the Alert Zone shrinks to the Exclusion Zone, the facility will be shut-in, wells secured and down-manned to mitigate risk. A facility with disconnect capability may move off location to avoid contact.

As noted earlier, from a design perspective, it is reasonable to consider a blend of ice management with structural resistance in the design philosophy, thereby reducing exposure and subsequently the basis to relax the demand for structure resistance. While one might strive for 100% success, this is impractical since safe vessel operations are limited by sea state above a certain level. Sea states can also create radar clutter and reduce detection probability.

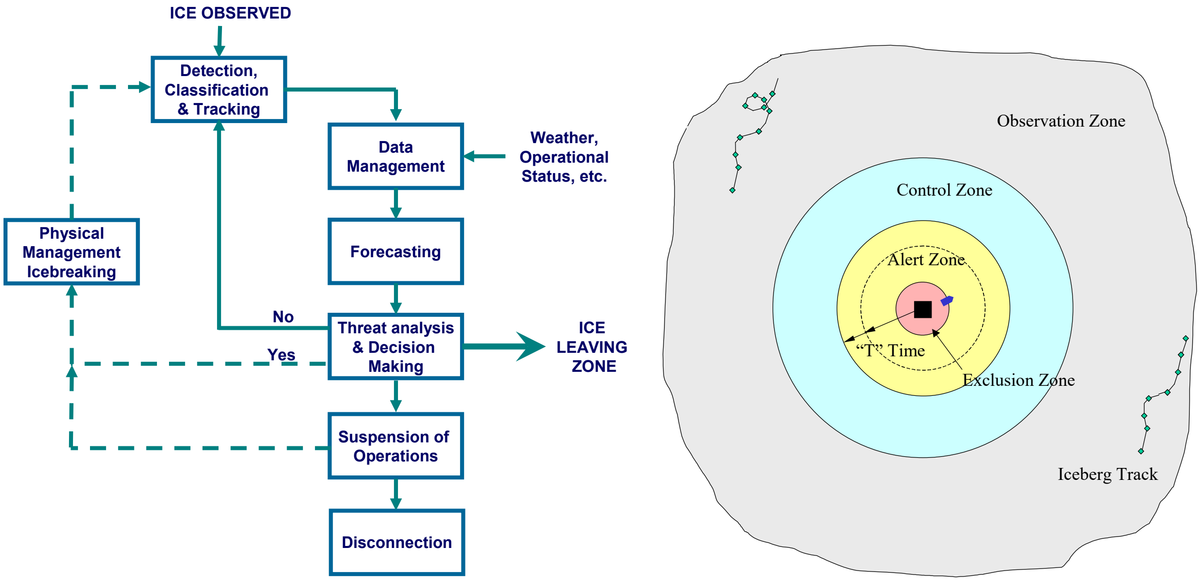


Figure 3. Ice management framework and illustration of alert zones

GROWTH IN SATELLITE DETECTION AND DRIFT FORECASTING

Satellites are an important part of ice management surveillance. Satellites follow pre-defined orbits making it possible for them to image remote regions without any external infrastructure, which is especially important during exploration. Satellite data has been collected for decades, making it possible to understand on a statistical basis the variability and severity of iceberg conditions, which is essential for planning and exploration. Synthetic aperture radar (SAR) sensors on satellites are able to operate day or night and through fog and clouds, which makes them useful even during polar night in the Arctic where high cloud cover is persistent. The synthetic aperture also makes it possible to collect high resolution data even from satellites hundreds of kilometers in orbit.

There has been tremendous growth in satellite technology over the past two decades relating to data availability and access (See Figure 5). In the early 2000s, national space agencies, namely the Canadian Space Agency (CSA) and European Space Agency (ESA), supported high resolution radar imaging satellites capable of observing through cloud cover and darkness. These were single satellite systems primarily focused on government imaging requirements. Within a few years, commercial constellation systems were launched, greatly improving access to data, with the option to specify image acquisition parameters for specific applications. In the early 2010s, data was still costly and image price was a barrier to routine monitoring applications.

The most recent generation of public satellite data, which includes Sentinel-1 (S1) and RADARSAT Constellation Mission (RCM) have a public access satellite data policy, which provides free access for peaceful use for the latest constellations of satellite data. Image coverage and acquisition opportunity is illustrated in Figure 4 and Figure 6 Public access has also been extended to archive data for some previous satellites, making it possible to conduct long-term historical studies. Commercial satellite radar data has been growing even faster than public data, with an emphasis on high resolution imagery and dynamic access to data.

Even greater volumes of satellite imagery, with higher quality, are expected in the future. Both the CSA and ESA are planning for their next constellations to be launched in the 2030s. The New Space companies have plans to continue to grow their constellations and new entrants can be expected, especially to support routine surveillance and defense applications. With the rapid

RCM advancements, including twice daily coverage of all of Canada, automated image acquisition, processing and cloud-based data management and reporting are needed with AI/ML techniques being core to new developments.

With respect to iceberg drift modeling, C-CORE is building Artificial Intelligence (AI) and Machine Learning (ML) based detection/forecast capability using multi-image RCM track data and advanced dynamic drift modeling. The tracks are used to train ML based detection and classification algorithms. For the 2022 and 2023 iceberg seasons, the classification algorithms were trained using approximately 10,000 iceberg and ship targets and demonstrate 92% accuracy. The drift model was trained using 59 iceberg drift tracks consisting of 391 detections. This RCM technology development is unique since the forecasting accuracy improves with more data, and detection accuracy and efficiency improve as new positions are forecasted before the next image is acquired which re-focuses the new search space. The probability of missed detections or false targets is significantly reduced. iceberg detection, forecasting, and threat analysis will be possible from the Greenland glacier sources through the journey to its final melted fate in the Gulf Stream (See companion paper by Yulmetov et al. 2025, “Advanced iceberg surveillance using RCM”).

Currently satellites are used operationally on the Grand Banks to: monitor the potential for major calving events from Greenland glaciers and ice shelves; detect icebergs in the Canadian Arctic to support forecasting for the timing and severity of the ice season on the Grand Banks; track ice islands (icebergs with shallow drafts and waterline lengths above 500 m); monitor icebergs upstream of the operations; and detect icebergs of interest that are close to operations. Satellite data has also been used to support exploration activities through the Arctic, sub-Arctic and southern hemisphere.

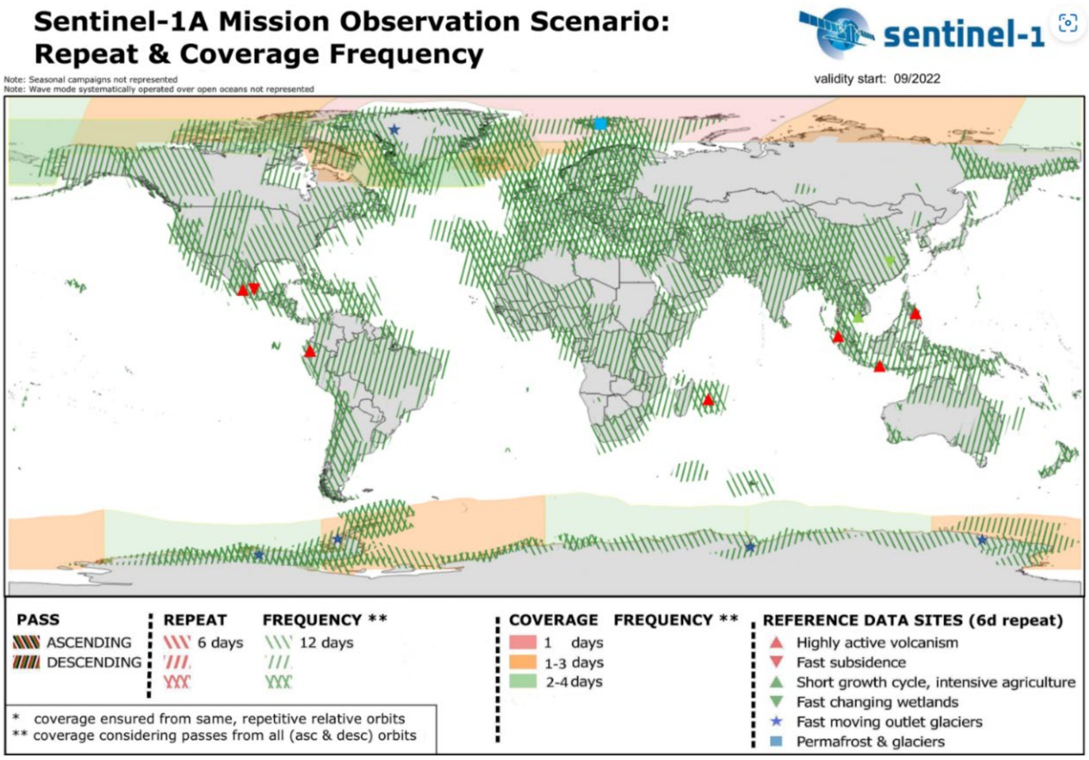


Figure 4. Sentinel-1A mission observation scenarios

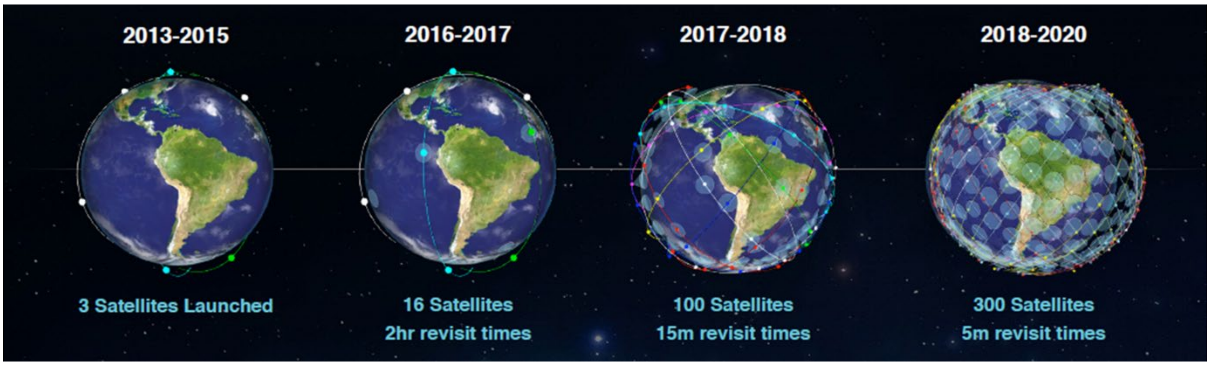


Figure 5: Illustration of growth of satellite launches since 2013.

(a) (b)

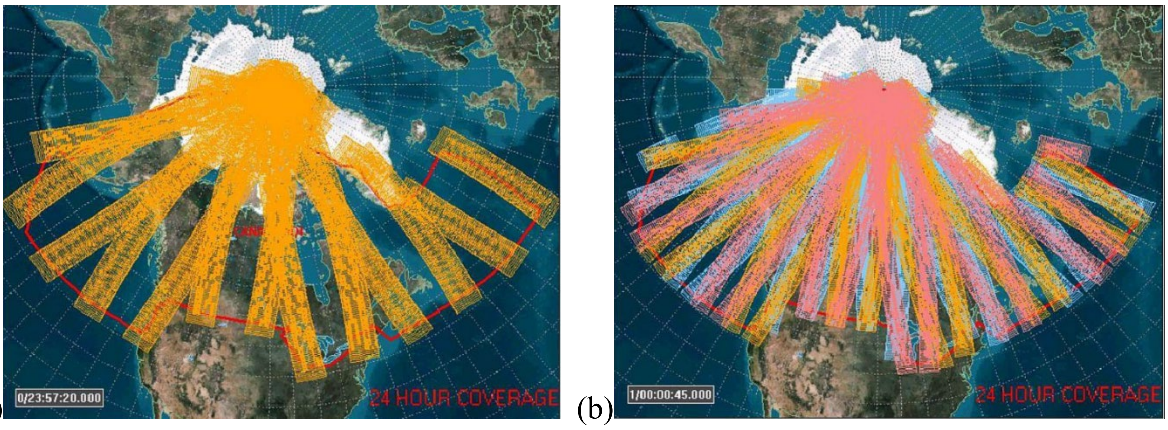
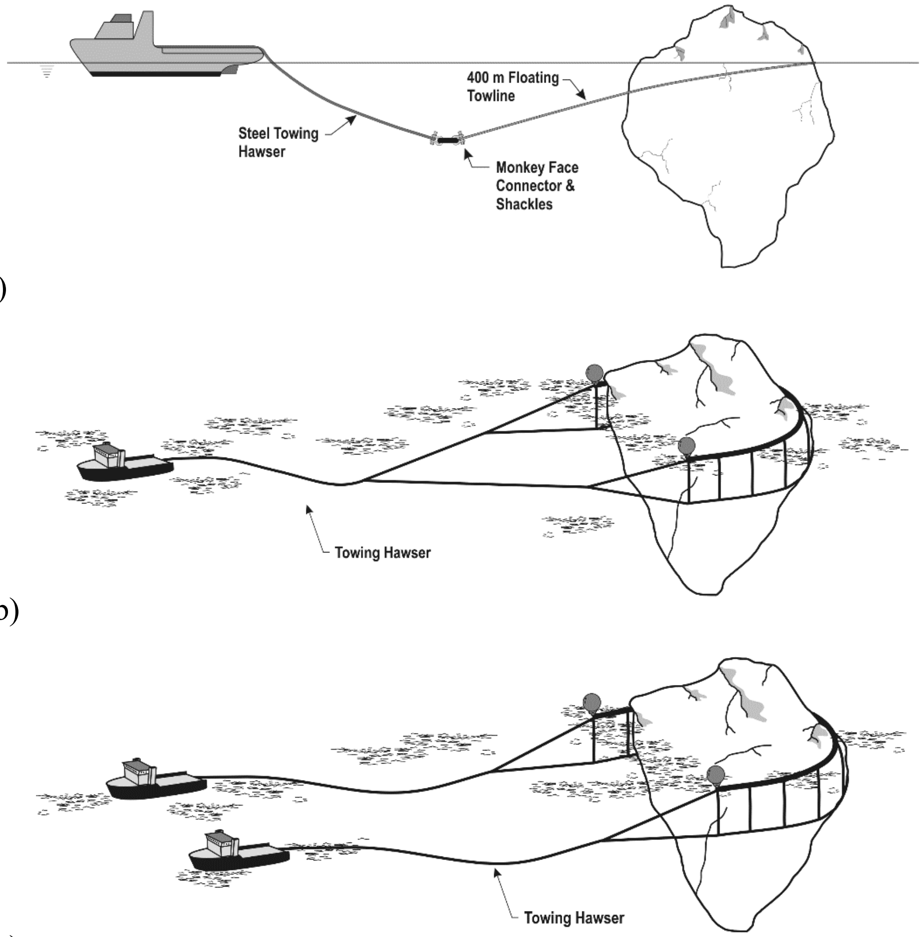


Figure 6. Daily satellite coverage for (a) RadarSat2 and (b) the latest RadarSat Constellation Mission (RCM)

ICEBERG TOWING OR DEFLECTION

Figure 8 illustrates the main towing approaches; although in some cases with low sea states, smaller icebergs (e.g. growlers) may be blasted with a water cannon. The conventional tool is a single floating polypropylene rope. Three 400 m sections are typically available on a towing vessel. One or two vessels may be used depending on sea conditions and iceberg size (See Figure 8). In 2002, C-CORE developed an iceberg net (C-CORE, 2002, 2003, 2004) constructed of four 80 m sections with a floating headline (having a unique ballistic nylon floatation collar) and a sinking footline connected with neutrally buoyant vertical lines. The length could be increased or decreased by adding or removing 80 m sections. Bridals were appropriately sized based on fishing technology. The simple design could easily be disassembled offshore, and reassembled should the iceberg roll and a twist during a tow.

To minimize the tendency for the iceberg to roll or tow rope to slip over the iceberg, the configuration of the towing catenary is important directing the tow force closer through the iceberg's center of gravity. C-CORE Towing Catenary Software (TCS^{TM}) models the configuration of the towing system based on the iceberg size, length of iceberg rope, length of the tow hawser deployed, tow speed and tow force applied (see Figure 9). The system considers the physical properties of the iceberg tow rope and towing hawser including specific gravity, hydrodynamic drag on the cables, drag on the towing vessel, and drag on the iceberg.



a)

b)

c)

Figure 7. Iceberg towing: a) single line; b) C-CORE iceberg net; c) dual vessels

Figure 8. Dual vessel island towing (PAL 2002)

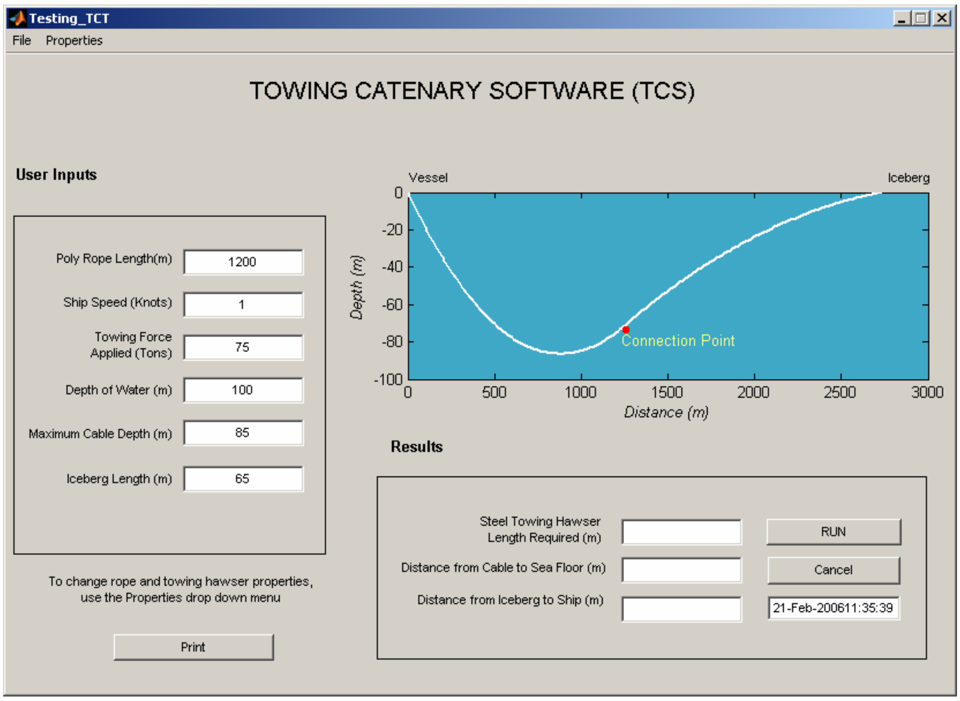


Figure 9. Towing catenary analysis

MODELING ICE MANAGEMENT PERFORMANCE

Ice management can be modeled and used to simulate expected performance based on predicted conditions at a particular site. A decision tree for modeling the probability of iceberg contact with an offshore facility is illustrated in Figure 14. For any facility, with icebergs drifting towards it, the contact probability can be modeled as:

$$P_{IMPACT} = (1 - P_{DET}) + P_{DET}\,(1 - P_{TOW}) \qquad (1)$$

where P_{DET} is the probability of detection success and P_{TOW} is the probability of success for towing operations.

A floating unit (e.g., FPSO) may be disconnected to provide an added level of safety should iceberg towing efforts fail. Analogous to Equation (1), the contact probability with a disconnecting floater can be modeled as:

$$P_{IMPACT} = (1 - P_{DET}) + P_{DET}\,(1 - P_{TOW})\,(1 - P_{DIS}) \qquad (2)$$

where P_{DIS} is the probability of successful floater disconnection. Equation 2 is the mathematical representation of Figure 10. While the success probabilities P_{DET}, P_{TOW} and P_{DIS} depend on a number of parameters, the key ones are range from the installation, sea state and iceberg size. The strategy for assessing the influence of sea state and waterline length on iceberg detection, towing and resultant impact probability was developed by McKenna et al. (2003). Performance curves for detection and towing have been developed based on iceberg size, sea state, and distance from the facility. Figure 11 a) illustrates the performance of X band radar at Hibernia for a 50 m iceberg with a single scan and b) for 16 scans. More recent improvements to the sigma S6 Ice Navigator (Rutter Inc.) radar accommodate over 100 scans and produce even better detection performance, particularly smaller icebergs in higher sea states.

Based on data up to 2024, Figure 12 illustrates the performance of iceberg towing success based on iceberg size and significant wave height including a basis for scaling increasing success with more time available. Tows (over 300) in the database were classed successful if the tow summary was referenced as: planned objective achieved; towed past the closest point of approach (CPA); suitable outcome; and the deflection angle was greater than or equal to five (5) degrees. The performance curves have a 6 m significant wave height cut-off, imposed in the early 2000s, based on safe working conditions on the decks of supply boats (e.g., Atlantic Eagle and Atlantic Hawk). Since then, vessel size and sea keeping performance have advanced considerably, although not yet accounted for in modeling. Figure 13 illustrates the modeling of a 3-dimensional tow success matrix where probability reduces to zero when sufficient time is not available, to increasing probability with increased time; even for additional towing attempts if necessary.

An example of the probability of an impact based on time available for towing operations and disconnection is illustrated in Figure 14; noting emergency disconnection (e.g., 15 min), or planned disconnection considering time available to suspend operations and move the facility (e.g., 4 - 5 hour T-Time). If an iceberg on a course (or heading) in line with the platform is not seen with sufficient time for a towing operation (i.e., detect iceberg, dispatch towing vessel, deploy iceberg net, apply towing force, establish towing force), the iceberg will likely make contact. When time is available, the probability of an impact drops considerably to some minimum. Disconnection may however dominate depending on the type of disconnection and duration relative to towing time. In the case of emergency disconnection, contacts are virtually non-existent. With planned disconnection (shutdown operations, flush lines, depressurize, drop buoy), one can see how impact probability reduces to levels below towing since disconnection has greater reliability.

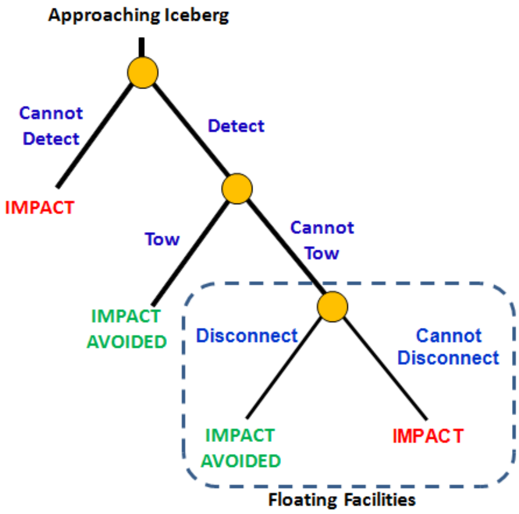


Figure 10. Decision tree for estimating the probability of an iceberg impacting a structure

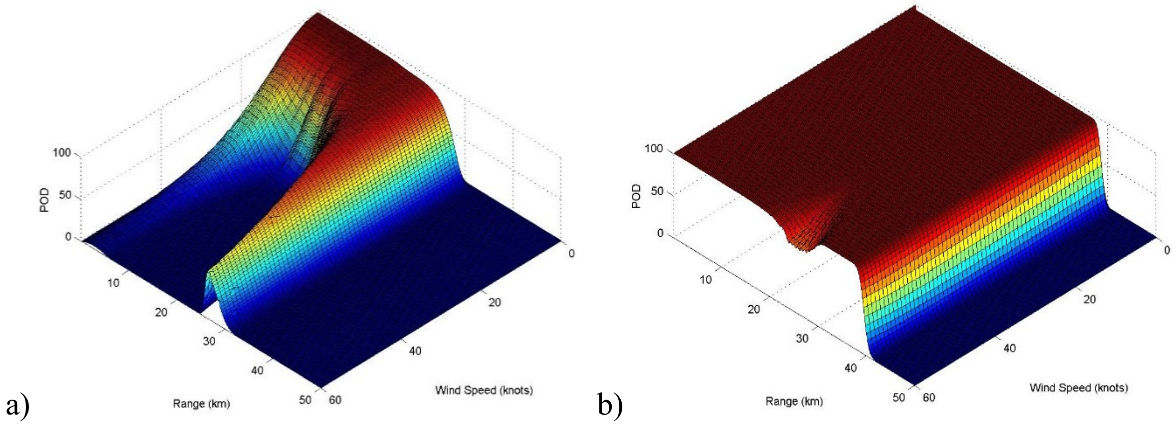


Figure 11. Hibernia, X band radar detection performance for a 50 m iceberg for a) Single Scan and b) 16 scan averaging (Sigma Engineering, 2002, now Rutter)

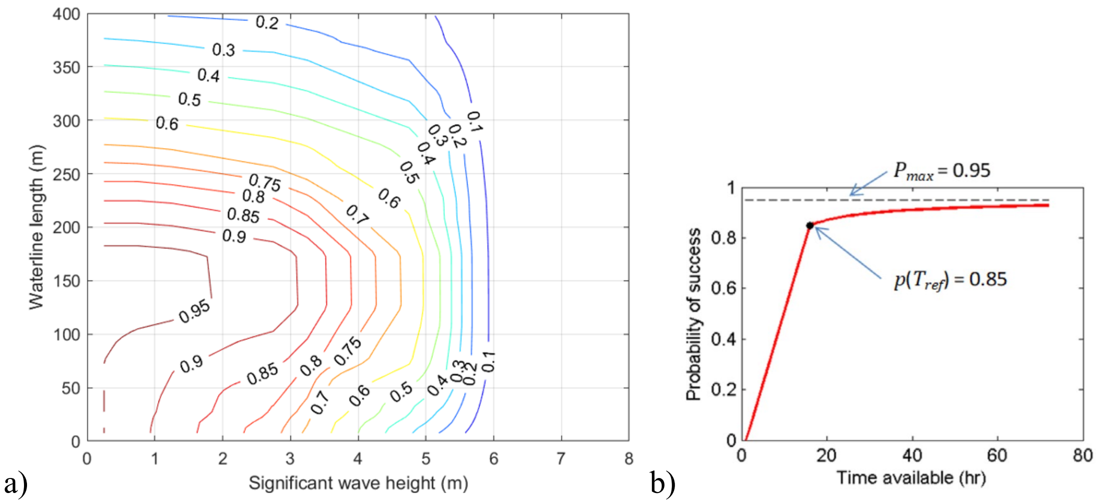


Figure 12. a) Iceberg towing performance matrix for single vessel and b) influence of time recognizing minimum time for deployment and tow force applied

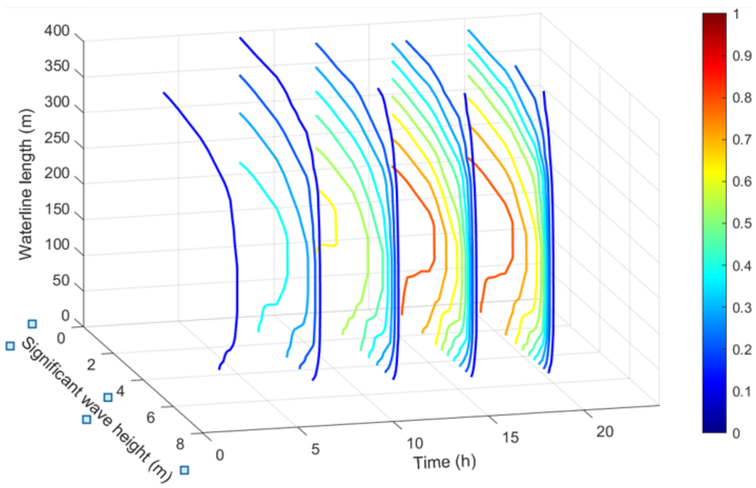


Figure 13. Three-dimensional contour plot illustrating tow success with available time

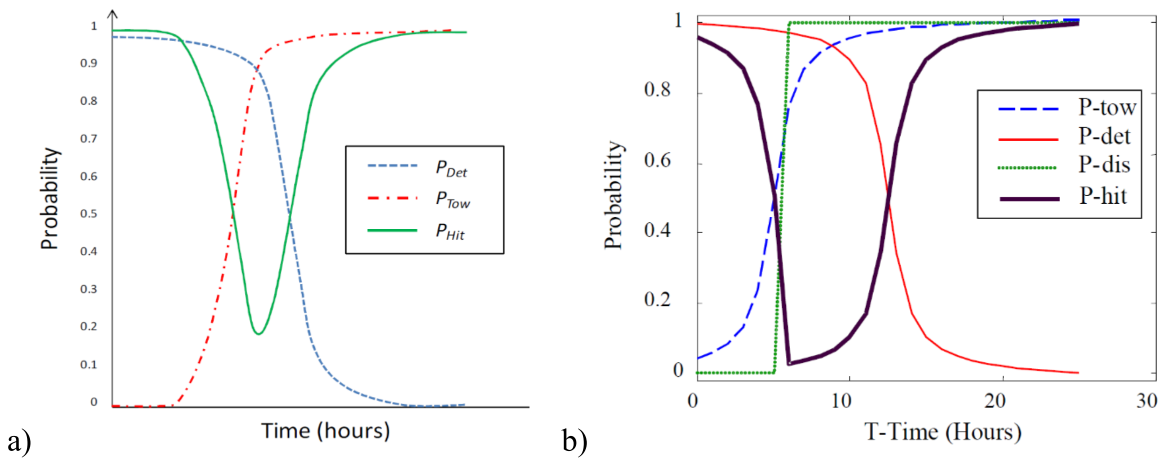
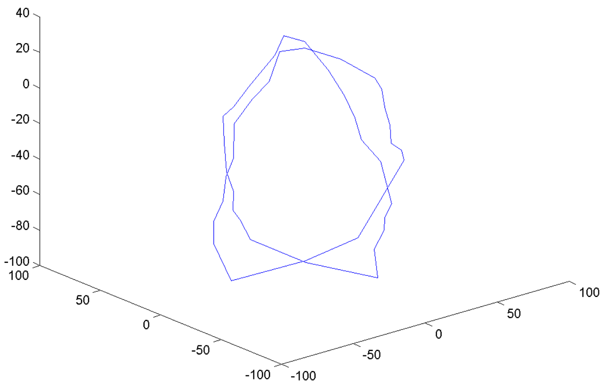


Figure 14. Example probability of an iceberg hitting a platform with a) just detection and towing (Fuglem and Stuckey 2019) and b) detection, towing and disconnection (McKenna et al. 2002)

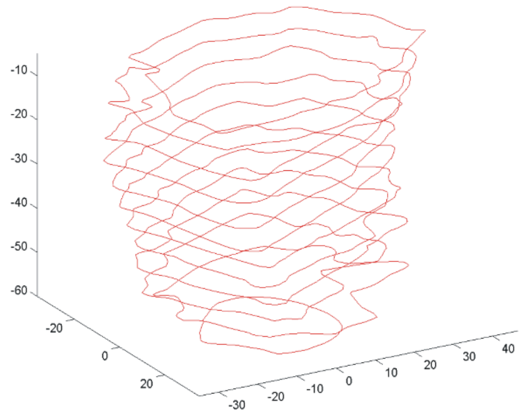
EVOLUTION OF ICEBERG PROFILING AND DRIFT PREDICTION

The evolution of iceberg profiling is illustrated in Figure 15. The latest developments initiated by C-CORE were to: *i*) assist ExxonMobil in assessing Hebron topsides risk and specifying topsides elevation (Stuckey et al., 2016); *ii*) improving underwater shape for dynamic drift forecasting (Turnbull et al., 2016); and *iii*) keel geometry for modeling ice keel/cable/pipe/seabed interaction (Ralph et al., 2022, and Barrett et al., 2022). Initially in 2012, photogrammetry was integrated with a Fugro ROV mounted multibeam system and a maximum of two icebergs were profiled per day; 26 in total over the field campaign (Younan et al., 2016). To be operationally relevant (i.e., profile information available for operational decisions in approximately 1 hour), C-CORE re-engineered the system to deploy an over the side hull mounted multibeam sonar with above-water LiDAR (see Figure 16). C-CORE also developed software to significantly reduce the post processing required (accounting for drift and rotation of the iceberg, and noise removal). With the new Rapid Iceberg Profiling System (RIPS), 175 icebergs were profiled, up to 12 in a single day (Bruce et al., 2021). From a design perspective, greater resolution allows better modeling of iceberg impacts, where kinetic energy is dissipated largely by crushing energy, the rate of which is largely dependent on local geometry (e.g., the blunter the impact area, the higher the forces).

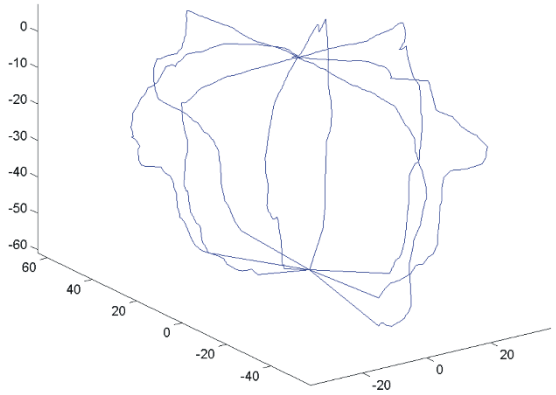
These 3D profiles were further integrated into an advanced iceberg drift prediction software where layered underwater currents (that vary according to depth) are applied to actual measured underwater shapes as opposed to a scaled generic shape based on measured maximum iceberg waterline length (Turnbull et al., 2018 and 2022). Based on drift simulations of fourteen (14) 3D iceberg profiles and corresponding tracks, approximately a 20% reduction in forecasting error was observed. Predictions vs. observations for two of the 14 icebergs (a 243 m blocky and an 83 m dome) during the campaign is illustrated in Figure 17.



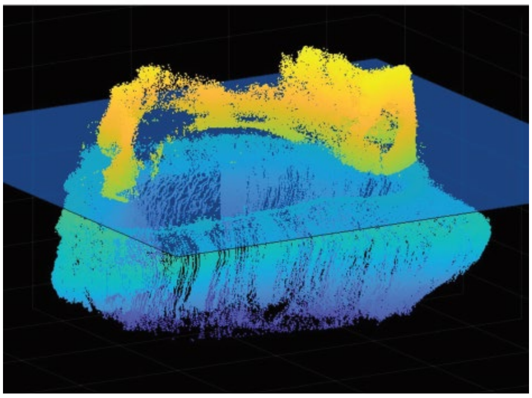
Early 1980's: two orthogonal profiles below and above water



1984: complete underwater profiles; good horizontal resolution, no top



Early 2000's: complete 3D profiles based on 8 vertical profiles



2012; 2015, 2017, 2018, 2019: complete 3D profiles; very high resolution point cloud data

Figure 15. Evolution of iceberg profiling

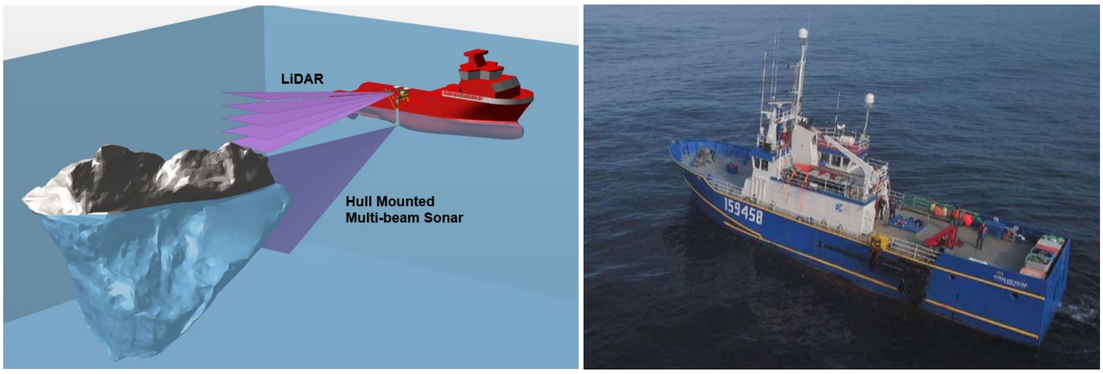


Figure 16. C-CORE's Rapid Iceberg Profiling (RIPS) system

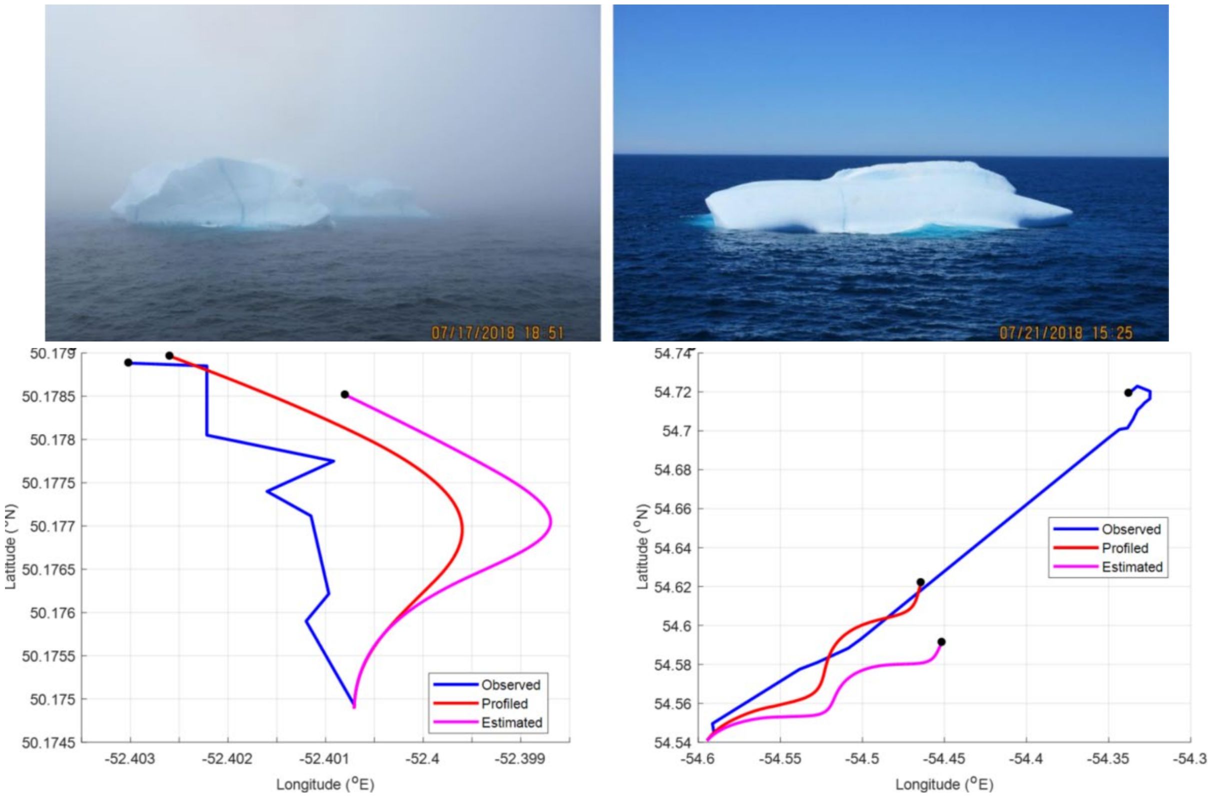


Figure 17. Forecasted vs observed iceberg drift for a 234 m blocky and a 83m dome iceberg (respectively) based on both measured and estimated iceberg profiles vs observed tracks

ICEBERG LOAD MODEL

To illustrate the effect of ice management modeling, C-CORE's Iceberg Load Software (ILS^{TM}) was used. The ILS^{TM}, as illustrated in Figure 18, uses a comprehensive probabilistic kinetic energy dissipation model (Stuckey et al. 2016). Ice management risk mitigation and reduction in exposure can be modeled directly in the design load calculations; example illustrated in the next section.

During an iceberg-structure interaction event, the iceberg will crush against the structure and rotate about its three axes. The initial kinetic energy is dissipated through ice crushing and the transfer of kinetic energy into rotational energy. In order to provide a design ice load for the structure the model requires environmental and iceberg population data. A number of modules are used to simulate the interaction. These modules include an ice-structure interaction model, an iceberg drift speed model, an iceberg collision model, a hydrodynamics model, an encounter model and a detection-management model. Key parameters for estimating both global and local ice loads include: size, shape and drift speed of the approaching iceberg; concurrent sea state and associated hydrodynamic effects on the icebergs motion; and eccentricity of the loading (considered for cases of oblique impacts).

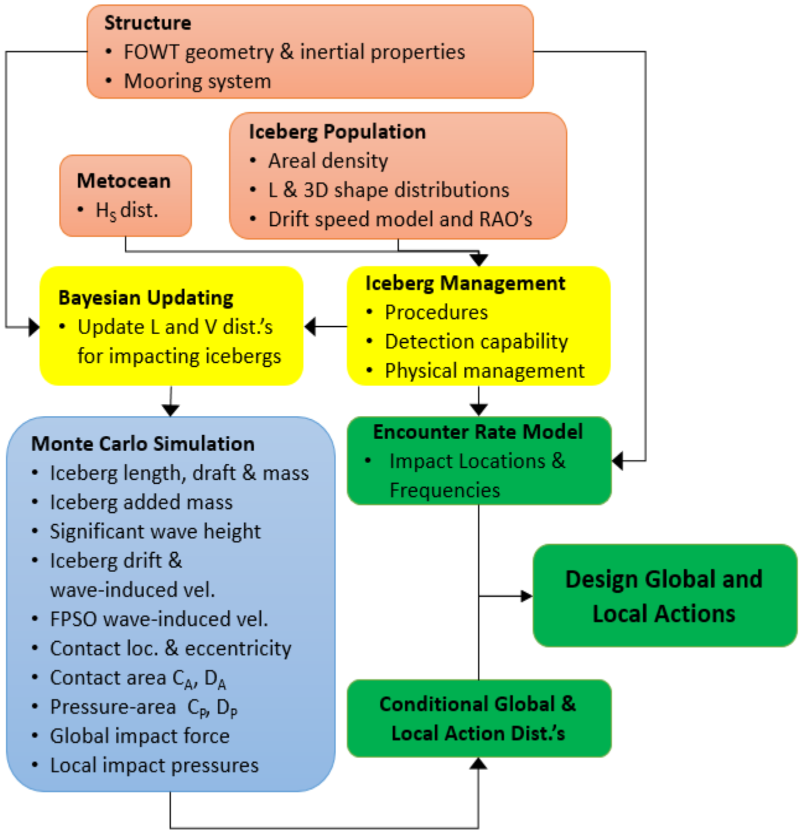


Figure 18. Flow Diagram illustrating C-CORE's Iceberg Load Software (ILS™)

Example Test Case

To illustrate the influence of ice management on design loads, a scenario is modeled in the ILS™ for iceberg interactions with a non-disconnecting 300 x 56 m floater. (See Figure 19). An areal density of 1.55×10^{-4} icebergs/km^2 is assumed (i.e., a snapshot of the expected number of icebergs in a region averaged over the year) and a drift velocity modeled as a gamma distribution with a mean of 0.39 m/s. The area penetration model for iceberg structure interaction accounts for measured iceberg shape and GBS curvature (Stuckey et al. 2008). A random pressure area model is assumed ($P = C_P A^{-D_P}$) where A is the nominal contact area, and C_P and D_P are the pressure and scale effect coefficients to characterize the pressure-area relationship (ISO19906, 2019). Similarly, a random local pressure area model with $\alpha = 0.77\ A^{-0.7}$ is based on CCGS *Terry Fox* iceberg impact data.

As noted earlier, ice management not only reduces the probability of an iceberg collision with a platform, it modifies the size distribution of impacting icebergs. An example of a modified length distribution with and without ice management, compared with the generic distribution is given in Figure 23. The iceberg length distribution is also adjusted using Bayesian updating to account for the fact that larger icebergs are more likely to impact the structure than smaller icebergs (Sanderson, 1998).

Assuming an L1 structure (i.e., highest consequence of failure) with a target reliability of $1\text{-}10^{-5}$, a global design load for an annual probability of exceedance of 10^{-4} is illustrated in Figure 24. Similarly, local design pressures are shown in Figure 25. What is highlighted in each of these plots is the range of design forces and pressures for a ±15% range of ice management effectiveness. Global forces can range from ~190 MN to 230 MN. Local pressures on both

1 m^2 and 2 m^2 are 5.6 - 6.1 MPa and 3.7 - 4.0 MPa respectively. Three important observations are noted: i) if a structure is designed without ice management risk mitigation, but ice management operations are carried out, then considerable added safety exists with the structure; ii) similarly, if a structure is designed for an ice management effectiveness of 70%, and operationally, 85%+ is achievable, then added resistance and safety exists (that may have other commercial value); iii) if the structure, is designed for 85%+ ice management effectiveness, but operationally only 70% is achieved each season, the structure is over exposed. With disconnection, and the ability to avoid icebergs, the corresponding reduction in exposure substantially reduces design loads and pressures.

A critical observation in the latter is the necessity for operational staff to understand the design basis for several reasons: *i*) to ensure the level of ice management integrated in the design is achievable; *ii*) to ensure the level of ice management integrated in the design is carried through in the operations planning; and *iii*) to plan at the end of each season, a critical review of the seasonal performance to review successes and look for improvements in the upcoming season.

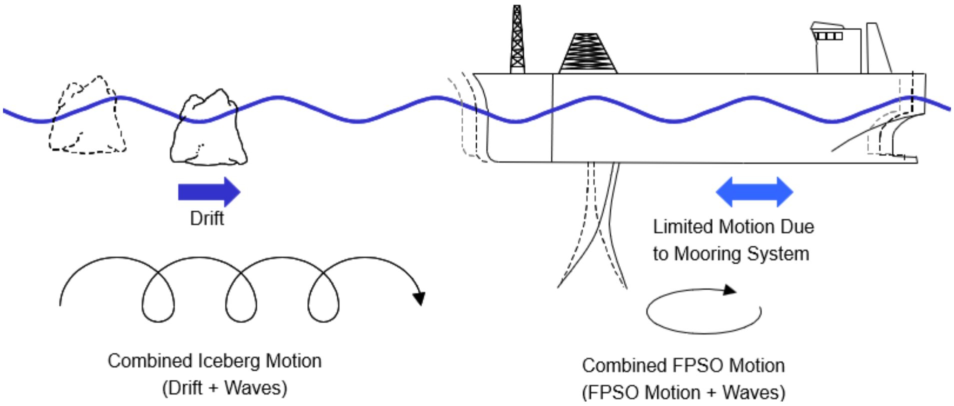


Figure 19. Iceberg impact scenario on a floater considering dynamic motions

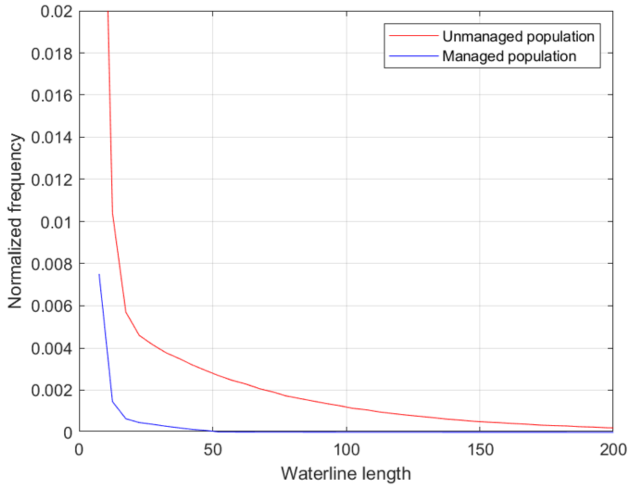


Figure 20. Generic and updated iceberg waterline length distributions

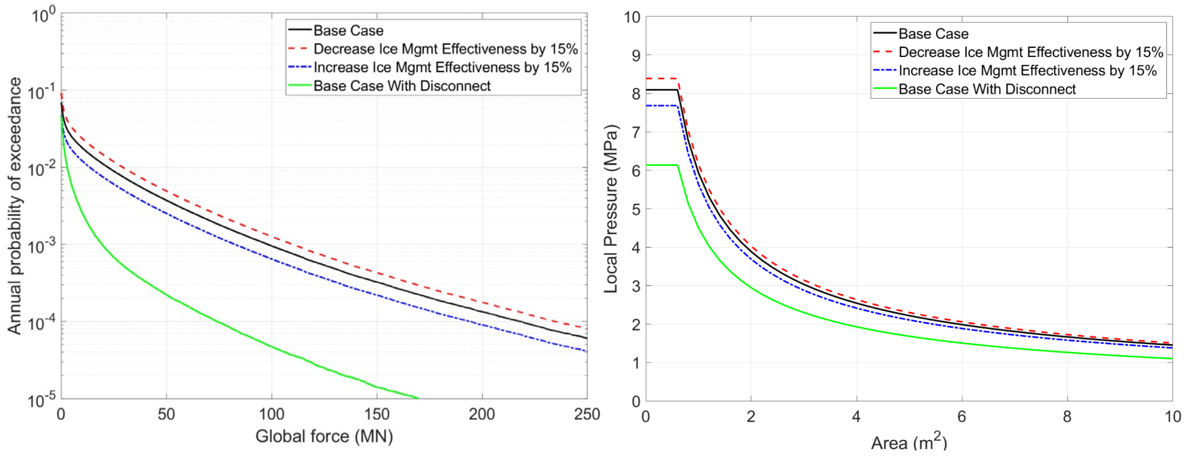


Figure 21. Illustration of 10^{-4} annual exceedance probability design loads and local pressures with and without ice management effectiveness

CONCLUSIONS AND RECOMMENDATIONS

To date there have been no iceberg collisions with an offshore platform, nor a disconnection to avoid the impact. As required by ice management procedures, operations have been suspended to reduce T-Time such that sufficient time was available to disconnect if necessary.

While significant progress has been made in both detection and iceberg towing as well as in models for estimating loads on offshore structures, knowledge and technology gaps still exist providing opportunity for future R&D. The following opportunities are listed.

- With the onset of RCM and twice daily coverage, satellite-based detection will be operationally viable (beyond upstream pre-season outlook).
- The 6 m significant wave height cutoff in the iceberg towing matrix should be revised, particularly with larger and more capable vessels available.
- Measured iceberg profiles should be integrated into operations (not just reporting on dimensions and mass). This should include the development of a new state-of-the-art threat analysis decision support tool (software), in which impact forces can be calculated for a specific iceberg in near real-time.
- Iceberg drift models should be updated to use measured profiles to model underwater varying forces through the profile.
- Towing prediction should be integrated with drift prediction modeling, building on iceberg profile inclusion, RCM and enhanced drift developments. Since adding additional tools may add extra burden (even confusion) to operators, consideration should be given to removing archaic models such as the overly conservative dead-reckoning approach.

As rapid advances in satellite technology develop (i.e., quantity and quality of data), so too are the AI/ML based processing capabilities to maximize the use of the data. C-CORE is building an AI/ML based detection/forecast capability using RCM track data and advanced dynamic drift modeling. To assist in operational planning, this will allow, iceberg detection, tracking, forecasting, and threat analysis along the whole track from the Greenland glacier through the journey to its final melted fate in the Gulf Stream.

As noted earlier, ice management systems must be designed to operate at or a greater level than the performance modeled during design of the platform. It is imperative that designers engage with operational personnel to ensure operations are consistent with the assumptions made during design. The close of every ice season should be followed by a review, to identify successes, audit performance relative to bench mark and identify opportunities for improvement.

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