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Modelling iceberg grounding on the Grand Banks

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ABSTRACT

Grounding, scouring and deep draft icebergs pose a significant risk to pipelines, subsea production hardware and offshore oil loading facilities used for the production of offshore oil and gas, as well as other seabed installations such as cables on the Grand Banks off Newfoundland.

The approach outlined in this paper, originally developed in the late 1990's, was one of the first applications of simulation techniques to successfully represent iceberg contact with the seabed and used for pipeline risk assessments.

In this paper, iceberg grounding processes are simulated by modelling iceberg drift, deterioration and seabed contact processes. Icebergs with representative waterline length distributions are introduced at a latitude of 49°N. A reliable long-term record of icebergs crossing a latitude of 48°N has been collected by the International Ice Patrol and the starting point is extended northward to incorporate potential pipeline routes. Iceberg mass and draft are estimated based on relationships derived from Grand Banks data. Iceberg drift is modelled using a vector autoregressive process incorporating spatially varying mean iceberg drift rates and measured autocorrelations. Melting and calving processes are incorporated in a deterioration model driven by water surface temperature and local wave conditions. Iceberg grounding is assumed to occur when the draft exceeds the local water depth, determined from digital bathymetric data.

The above processes were incorporated in a Monte Carlo model, allowing the simulation of up to 5000 years of present iceberg and ocean conditions. The grounding model results have been compared with the seabed record over a limited area on the northeastern Grand Banks.

KEY WORDS: iceberg; grounding; scour; model; drift.

INTRODUCTION

A marine pipeline was proposed by North Atlantic Pipeline Partners (NAPP) in the late 1990's to link the northeastern Grand Banks to the Island of Newfoundland (Figure 1). Potential pipeline routes run through a region frequented by icebergs during the spring and summer. In this area, iceberg keels can come into close proximity to the seabed, potentially making contact with an exposed pipeline, or even make contact with the seabed and ground or scour. Iceberg interaction with the proposed pipeline could cause damage and result in down-time for repairs.

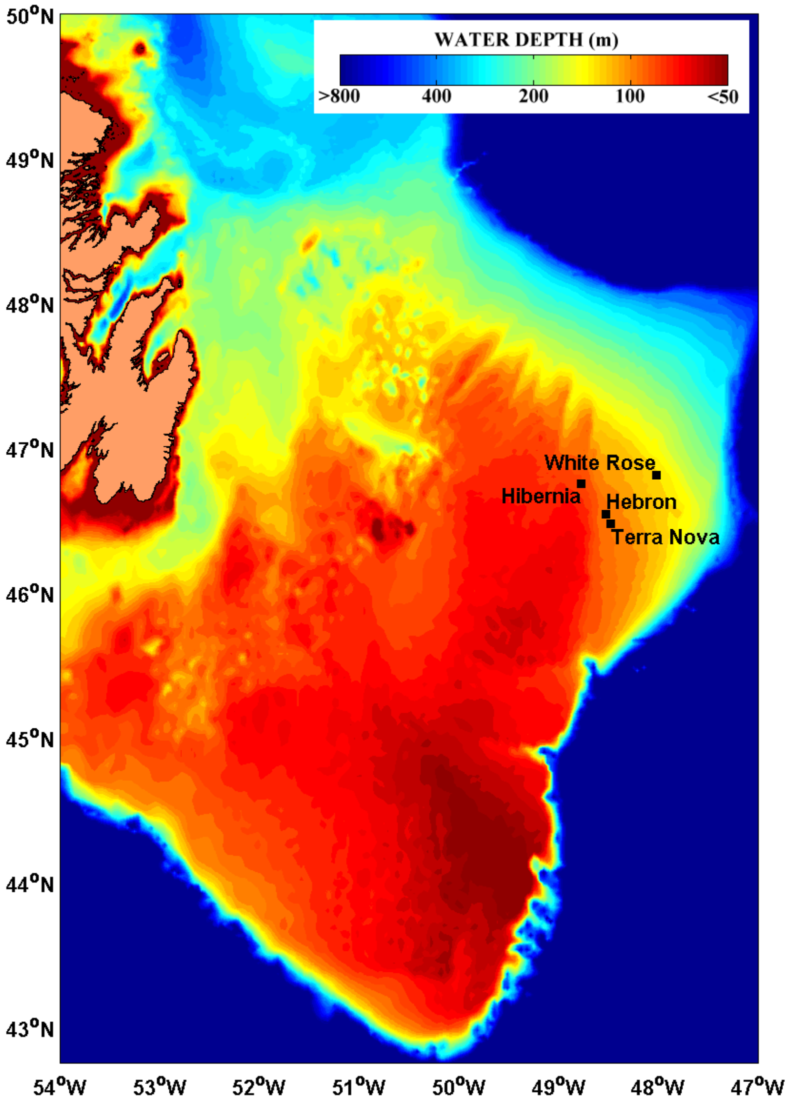

Figure 1. Digital bathymetry of the Grand Banks of Newfoundland. Potential pipeline routes cover the northern half of the mapped area.

A paper documenting this work was originally written in late 1999 but was not published at the time. Now, nearly 20 years later, the material is still of interest, not only from a historical context but also because the strategies are still relevant. For iceberg drift, we would now take advantage of many new drift tracks. Iceberg scours have not been documented by means of repetitive mapping on the northeastern part of the Grand Banks. Little work has been done to develop new models of iceberg deterioration because verification data are limited. In this paper, we have left the results as calculated but noted newer approaches and data sources as they might have been used had they been available in 1999.

In general, the best method for estimating iceberg risk to offshore pipelines is to derive contact frequency from the observed location and frequency of iceberg scour marks on the seabed. In the absence of such data, a simulation model was developed to estimate the areal density of iceberg groundings on the Grand Banks and adjacent areas. The results presented in this paper form the basis for a pipeline routing study outlined in a companion paper (Bruneau et al., 2019).

ICEBERG SIMULATION MODEL

Model Framework

In the simulation model, icebergs are introduced at a latitude of 49°N with specified waterline lengths and drift southward according to characteristic patterns. They deteriorate from wave action and local water temperature, and potentially make contact with the seabed. A grounded iceberg can then refloat and resume drifting before completely deteriorating. Grounding events are documented for use in assessing risk to pipelines on the seabed.

Iceberg Flux

The International Ice Patrol (IIP) has traditionally reported the iceberg flux drifting southward across a latitude of 48°N off Canada’s east coast. Since the early 1900s, the IIP has reported an average of 471 icebergs with waterline length 16 m or greater crossing 48°N per year. After discussions with the IIP, the use of data subsequent to the implementation of SLAR (side-looking airborne radar) in 1985 was recommended. The mean annual iceberg flux across 48°N reported by the IIP for the period from 1985 to 1996 is 940, which is the basis for the present analysis. In the period between 1985 and 2017, the average was 732, which is 22% less than 940.

Because of the northern extent of potential pipeline routes, icebergs were introduced to the simulation model at a latitude of 49°N. To correct the iceberg flux numbers from 48°N to 49°N, an algorithm was developed based on data from the PERD database (Fleet et al., 1998) for the 1985 to 1996 period. Once iceberg sightings east of the area being modelled were excluded (i.e. east of 46°30'W), the mean annual iceberg flux across 49°N with waterline lengths 16 m or greater was estimated to be 1045 for the 1985 to 1996 period.

The introduction of icebergs in the model reflected variations in flux across 49°N. Analysis of the PERD database indicated that approximately 32% of icebergs cross 49°N between 53°W and 52°W, 24% between 52°W and 51°W, 22% between 51°W and 50°W and 22% between 50°W and 49°W.

The proportion of icebergs crossing 48°N over the different months of the year for 1900 to 1997 was assumed to be representative of 49°N. Most of the icebergs reaching the Grand Banks do so during the months of March through June. In the simulation, icebergs were introduced randomly over the course of the month.

Iceberg Waterline Length

The PERD iceberg database (Fleet et al., 1998) was used to derive the waterline length distribution for icebergs at 49°N. The only records available in the latitude and longitude range of interest originated from the IIP. Iceberg records in the latitude range of 48°30'N to 49°30'N and in the longitude range 49°W to 53°W were examined. These records did not have specific waterline lengths listed, rather they were grouped into the size classes used by the IIP (15 m - 60 m, 61 m - 123 m, 123 m - 213 m, > 213 m). An algorithm was developed that produced a waterline length distribution with the same proportions of icebergs in the various size classes as the IIP data. The mean waterline is about 80 m and the standard deviation is about 45 m.

Waterline length data from more recent observations largely support the use of the above size distribution, except that very large ice islands have been observed in the last 20 years. Since these typically have drafts of about 50 m, their effect on grounding frequencies is not particularly significant.

Icebergs with waterline lengths of less than 40 m, which accounted for approximately 35% of the total population in the waterline length distribution, were excluded from the simulations because they do not have significant impact on the grounding frequencies. The number of icebergs used for the simulations was adjusted accordingly.

Iceberg Size Parameters

Available data were analyzed to derive relationships between iceberg length, draft and mass, each of which is used in the grounding simulation. Data derived from a variety of sources were used (e.g. Brooks, 1979; Hibernia, 1981), with the assumption that the basic shape relationships are essentially constant regardless of location.

Iceberg draft was estimated from waterline length using a best-fit relationship that also included random term to account for the variability in the data. From the waterline lengths and associated drafts, iceberg masses were generated using a similar relationship. In a recent paper by Stuckey et al. (2016), newer iceberg profile data suggest shallower drafts and a slightly decreased mass for the same waterline length (see Figure 2). The net result of including the new data would be slightly less iceberg grounding risk.

In the simulation model, the icebergs deteriorate, lose mass and reduce their draft. Iceberg draft is the primary variable of interest, since it is the iceberg draft that determines whether it contacts the seabed and grounds at a particular location.

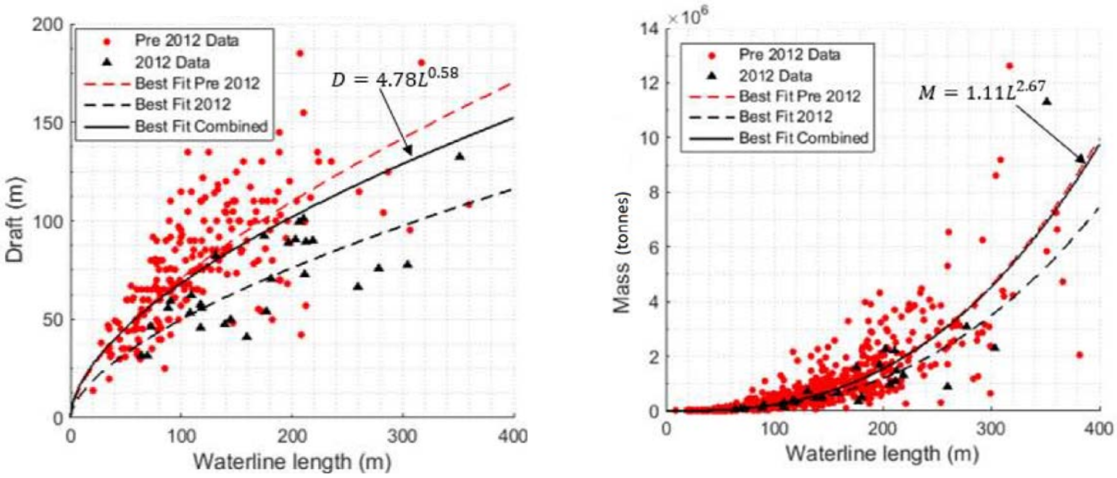

Figure 2. Iceberg length/draft and length/mass relationships, comparing 2012 data and iceberg data collected primarily in the 1980's (Stuckey et al., 2016)

Iceberg Drift

The primary role of the iceberg drift algorithm is to advect simulated icebergs southward onto the Grand Banks at realistic rates and directions from their initial positions at a latitude of 49°N. The drift model also needs to represent realistic variations in the drift velocities of deep draft icebergs to ensure realistic grounding locations.

Iceberg velocity data were obtained from the PERD Grand Banks Iceberg Database (Fleet et al., 1998). Repeated sightings were used to calculate gridded mean and standard deviation of drift velocity components. The mean field (Figure 3) was verified with a summary of drifter data obtained from the IIP.

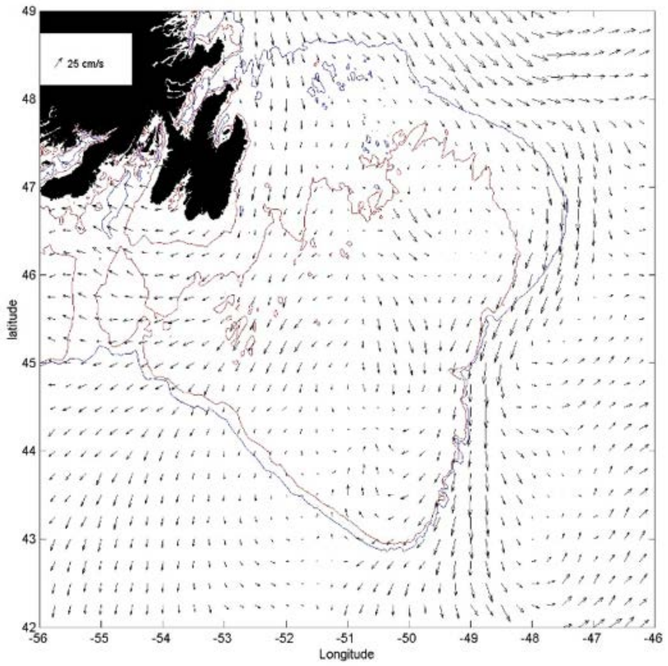

Figure 3. Mean iceberg velocity field derived from the Grand Banks iceberg database

Persistence in the iceberg drift was determined from iceberg positions documented in the MEDS Canadian Offshore Oil and Gas Environmental database (1997). These consist of drift tracks obtained during exploratory drilling activities in the mid-1980s. The above processes were captured using a lag-1 vector auto-regressive model to represent the covariance between iceberg velocities in the north/south and east/west directions. The model is given by

$$\begin{bmatrix} u_t \\ v_t \end{bmatrix} = \begin{bmatrix} \bar{u}_t \\ \bar{v}_t \end{bmatrix} + A \begin{bmatrix} u_{t-1} - \bar{u}_{t-1} \\ v_{t-1} - \bar{v}_{t-1} \end{bmatrix} + B \begin{bmatrix} N(0,1) \\ N(0,1) \end{bmatrix} \tag{1}$$

where u_t and v_t are the easterly and northerly components of the iceberg velocity at the present time step, u_{t-1} and v_{t-1} are the corresponding components at the previous time step, the overbars denote mean values, and $N(0,1)$ are unit normal random numbers. A time increment of 3 hours was used in the application of the model. The 2 × 2 matrices A and B combine both the standard deviations associated with iceberg velocity and the auto-regressive terms, and are calculated from the lag-0 and lag-1 covariance matrices S_0 and S_1

$$S_0 = \begin{bmatrix} \sigma^2_{xx} & \rho^0_{xy}\sigma_x\sigma_y \\ \rho^0_{xy}\sigma_x\sigma_y & \sigma^2_{yy} \end{bmatrix}, \quad S_1 = \begin{bmatrix} \sigma^2_{xx} & \rho^1_{xy}\sigma_x\sigma_y \\ \rho^1_{xy}\sigma_x\sigma_y & \sigma^2_{yy} \end{bmatrix} \tag{2}$$

where σ_x and σ_y are the easterly and northerly iceberg velocity standard deviations, σ^2_{xx} and σ^2_{yy} are the corresponding variances, and ρ^0_{xy} and ρ^1_{xy} are the lag-0 and lag-1 cross-correlations between easterly and northerly components. The A and B matrices are calculated from

$$A = S_1 S_0^{-1}, \qquad BB^T = \lambda \tag{3}$$

where λ is a diagonal matrix whose elements are the eigenvalues are the matrix

$$S = S_0 - S_1 S_0^{-1} S_1^T \tag{4}$$

The values for matrices A and B were determined for 0.25° grid squares on the Grand Banks and used as input to the simulation. As each simulated iceberg drifted from one grid square to the next, the appropriate values for *A* and *B* were used.

Newer data exist from production operations on the Grand Banks over the last 20 years that would change the mean drift speeds and directions as well as persistence. Some preliminary comparisons suggest a slight decrease in mean speed in the vicinity of the existing facilities (see Figure 1) and a slight clockwise drift direction change.

Tidal Effects

Including tidal heights in the simulation model allowed the grounded icebergs to refloat. A time series if tidal height was generated for each iceberg based on the twelve most significant tidal constituents. Tidal currents were not included directly in the model. Ignoring these higher frequency oscillations could result in some underprediction of grounding rates in areas with more complex bathymetry.

ICEBERG DETERIORATION

Deterioration Model

Forced convection melting, wave erosion and calving are the three primary mechanisms that influence the deterioration rate, size and life span of an iceberg. Components of the model proposed by White et al. (1980) were used in the formulation of the deterioration model. The various equations were simplified to obtain a mass loss rate in tonnes over 3 hours of

$$\Delta M = 0.047L^{1.8}\,T_s + 3.2L\,T_s\,H^{0.8} + 0.054L^{1.8}\,T_s\,H^{0.8} \tag{5}$$

where L is the waterline length in metres, T_s is the water surface temperature in °C and H is the significant wave height in metres. This type of model is still widely used in both operational and hindcast iceberg drift analyses, see Kubat et al. (2007). A rolling mechanism was also incorporated in the model to account for sudden changes in draft of an iceberg.

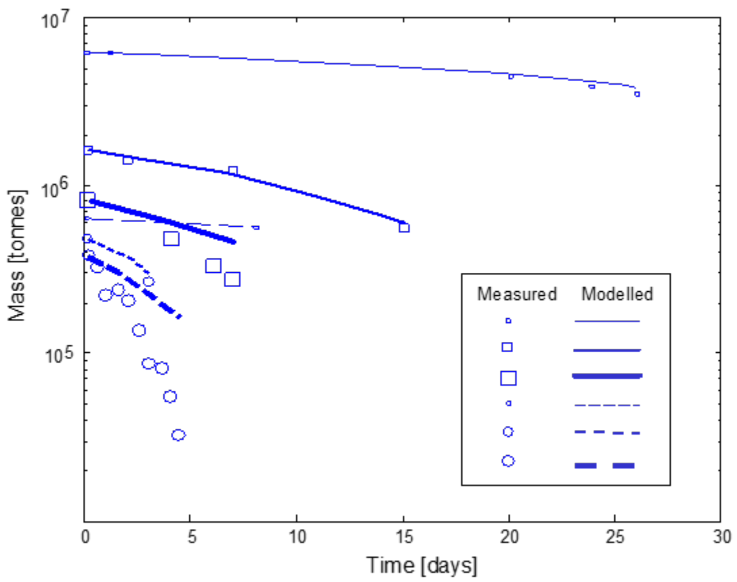

Figure 4. Comparison of observed and modelled iceberg deterioration rates

Six case studies of iceberg deterioration are available from IIP (1984), Venkatesh et al. (1985) and El-Tahan et al. (1987), which include measurements of iceberg above water volume (and mass) and measured or estimated environmental parameters such as water temperature, wave height, and wave period. Deterioration model predictions are compared with the observed mass reductions in Figure 4. In general, the correspondence is reasonable given the potential errors in estimating iceberg mass, and the fact that some of the environmental parameters were estimated, not measured. In two of the case studies, the deterioration model significantly underpredicted melt. In both cases, the iceberg calved multiple times and in one it also rolled repeatedly. The deterioration model does not account for large scale fracture, which potentially accounts for the poor correlation between predicted and observed deterioration.

The time required to reduce the mass of an iceberg with a waterline length of 125 m (in April to June) to 5000 tonnes predicted by the deterioration model was, on average, 91% of the estimate provided by Venkatesh and El-Tahan (1988) after correction was made for the differences between the mass to length relationships used in the two models.

Modelled life expectancies for a 100 m long iceberg in various water temperatures and 1.8 m seas were, on average, 81% of the White et al. (1980) model predictions. The latter model predictions have been tuned to generate realistic but conservative results based on the extensive experience of International Ice Patrol (IIP) scientists.

Waves

Wave action has a major influence on iceberg deterioration rate. Wave zone locations, mean monthly significant wave heights and variations in the wave heights were obtained from the Wind and Wave Climate Atlas (MacLaren Plansearch, 1991). In the simulation, each iceberg was assigned to a particular wave zone and significant wave height statistics were applied during a time step. Persistence was represented using an auto-regressive model to generate 3-hour wave series for each iceberg.

Ocean Surface Temperature

Water temperature is also a major factor in the deterioration of icebergs. Monthly water temperature data were obtained from the Bedford Institute of Oceanography for a number of geographical regions on or near the Grand Banks. Each modelled iceberg was assigned to the appropriate temperature zone as it drifted over the Grand Banks. Records spanning 22 years were analyzed to obtain the mean and standard deviations of the average monthly surface water temperatures for each temperature zone. An lag-1 auto-regressive model was developed to estimate monthly changes in the water temperature over the course of a simulation for each iceberg.

ICEBERG GROUNDING

Bathymetry

Considerable effort was made to develop a detailed bathymetric map of the Grand Banks and adjoining regions. This map included the shoreline and data for the various bays. The data were obtained from digital sounding data or digitized from charts published by the Canadian Hydrographic Service.

To convert the data into a format that could be used by the simulation model, the data were first transformed into regularly gridded data points using Delaunay triangulation. The resolution in the resulting data file was 0.02° latitude and longitude (approximately 2.2 km by 1.5 km). The data, covering a region from 42°30'N to 49°N latitude and 46°30'W to 56°30'W longitude, are illustrated by the bathymetric map shown in Figure 1.

Grounding Criteria

During each 3-hour time increment in the simulation, the draft of each iceberg was compared to the water depth at that geographical location and the tidal elevation. If the iceberg draft exceeded the water depth, the iceberg was considered grounded. While grounded, the simulated iceberg did not change position but was still subjected to conditions responsible for iceberg deterioration.

The iceberg remained grounded until it met the conditions required for refloating. Rolling of the icebergs was deemed to occur, on average, when the iceberg had lost 20% of its mass. If an iceberg rolled while grounded, and the new draft generated for the iceberg after rolling was less than the current water depth, including tidal effects, the iceberg was considered to be refloated and was then free to move again. Alternatively, if the iceberg draft was reduced sufficiently by melting, the iceberg also changed from a grounded to a floating state but only if it cleared a berm created around the point where the iceberg grounded. The height of this berm was deemed to be 82% of the difference between the iceberg draft and the water depth when grounding originally occurred, based on berm heights inferred from scour modelling tests in sand (Paulin, 1992).

MODEL RESULTS

In the base case simulation, a representative sample of 340,000 icebergs, with waterline lengths 40m and greater, was introduced to the model at 49°N. The sample of 340,000 icebergs represents a total population of 523,000 icebergs corrected to represent all icebergs with waterline lengths greater than 16 m. With an average of 1045 icebergs crossing 49°N annually, this represents a simulation period of 500 years.

A typical subset of drift tracks from the base case simulation is shown in Figure 5. Some of these icebergs drift southward down the Avalon Channel near the coast of Newfoundland, some drift directly onto the Grand Banks and some drift eastward. From a visual standpoint, the drift model seems to predict less east-west motion and possibly less channelling close to the Newfoundland coast and around the perimeter of the Grand Banks than observed tracks. The southerly flux of icebergs longer than 60 m was calculated as a percentage of the flux at 49°N and compared with IIP data. The modelled fluxes at latitudes of 47°N and 46°N were about 25% and 40% less than observed, which is consistent with the channelling effect.

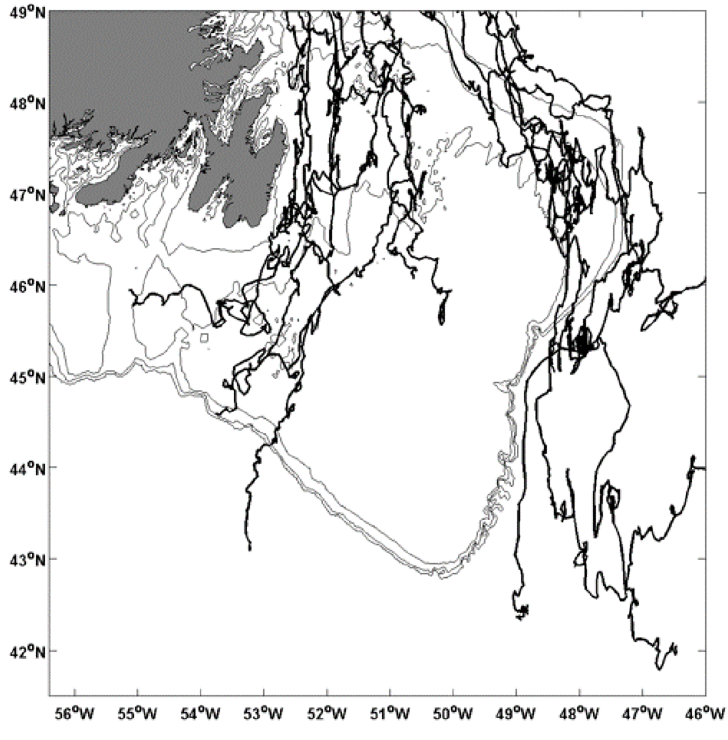

Figure 5. Typical modelled iceberg drift tracks

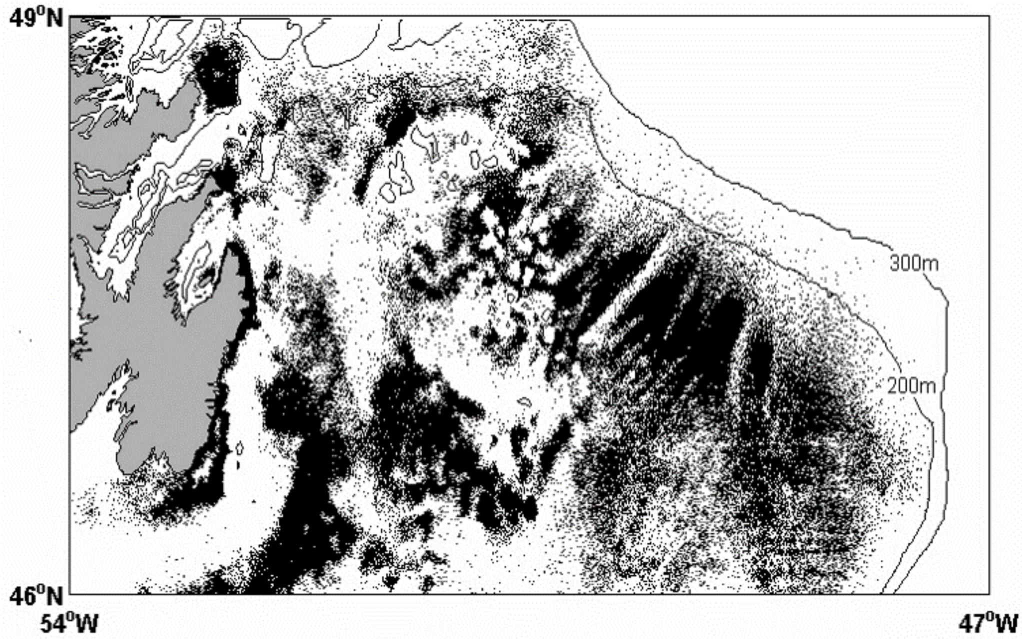

Figure 6. Modelled grounding locations for base case simulation

The modelled locations of iceberg groundings on the Grand Banks are illustrated in Figure 6. A total of 152,000 grounding events occurred in the base case simulation. The majority of icebergs grounded on the northern part of the Grand Banks and on the portion of the Banks adjacent to the Avalon Channel. The portion of groundings at water depths greater than 200 m was 0.3%. The mean duration of grounding events was 6.3 days, with a standard deviation of 13 days.

Sensitivity runs were conducted to assess the effect of a number of parameters on iceberg areal density and grounding frequency. A decrease in the deterioration rate of 20% resulted in more icebergs reaching the southern part of the Grand Banks. Other sensitivity runs had a modest influence on the numbers of icebergs reaching the southern Grand Banks, although reducing the standard deviation of iceberg drift speed and increasing the waterline length had significant effects on grounding.

MODEL VERIFICATION

Iceberg Velocity

The model output was processed to obtain velocity statistics for each 0.25° × 0.25° square for comparison with the mean velocity field that was input to the model in equation (1). Since the input mean iceberg velocity field was for freely-floating icebergs, only freely-floating model iceberg velocities were used in the comparison.

For the region bounded by 46°N to 48°N and 49°W to 51°W, the easterly mean velocity was 6.7 cm/s and the mean modelled velocity was 4.1 cm/s. For the same region, the southerly input mean velocity was 10.5 cm/s and the modelled mean velocity was 14.0 cm/s. The differences in these results are due to the persistence (or autocorrelation) component of the drift model. Each iceberg maintained a memory of its previous upstream velocity, therefore the modelled statistics for more southerly locations tended to reflect the input values upstream.

Although not used in the results shown in this paper, an iterative process was investigated for adjusting the model input velocity mean and variance fields to make the output fields match the observed data. This process was helpful when applying the model to the non-homogeneous iceberg velocity field on and adjacent to the Grand Banks.

Areal Density

The mean annual areal density of icebergs refers to the number of icebergs observed per degree square by an observer, viewing simultaneously the entire Grand Banks region. While areal density does not provide a direct measure of grounding frequency, it provides a check on the adequacy of the drift and deterioration components of the model.

To ensure that an equivalent range of sizes was used in the comparison of modelled and observed area densities (Jordaan et al. 1999, based on a compilation of IIP data), only icebergs with waterline lengths greater than 60 m were considered. The comparison is best on the northern portion of the Grand Banks, while the simulated areal densities were less than observed in the Flemish pass and the southern Grand Banks. The drift model tends to move too many icebergs directly onto the northern portion of the Grand Banks and too few eastwards through the Flemish Pass and onto the southern part of the Grand Banks.

Grounding frequency from observed scour marks

At the time of the study, several attempts had been made to estimate the frequency of iceberg contacts with the seabed:

- estimates iceberg scour densities by Geonautics (1987) from sidescan sonar and sub-bottom profiler and corrected by Davidson and Simms (1997) in an attempt to remove relict features.
- estimates of scour frequency made by Gaskill et al. (1985) based on scour density, depth distributions and estimates of infill rates;
- estimates of scour frequency from scour density and seabed mobility for the Hibernia area by Amos and Barrie (1982);
- groundings determined from IIP iceberg resightings (El-Tahan et al., 1985) and a similar analysis based on data in the PERD Grand Banks iceberg database;
- groundings determined from iceberg tracks (Banke, 1989a, 1989b, 1990); and
- grounding times for icebergs off the Labrador coast (El-Tahan et al., 1985).

The above estimates were not deemed to be sufficiently accurate to verify the modelled grounding frequency because of the inability to date the features with sufficient precision in the absence of repetitive mapping.

SUBSEQUENT DATA ACQUISITION AND MODEL DEVELOPMENT

Since the original pipeline risk study 20 years ago, considerable effort has been undertaken to improve and validate the iceberg grounding model. A new seabed survey conducted in 2004 (Sonnichsen and King, 2011) provided an opportunity to compare modeled iceberg grounding rates with scour formation rates inferred from the analysis of seabed survey data. The 2004 survey covered 610 km^2 on the northeast Grand Banks using multibeam sonar which overlapped an area of 424 km^2 previously surveyed using sidescan sonar in 1990. Ten scours were identified as potentially new with varying levels of confidence. Using the procedure described in Sonnichsen and King (2011), the inferred mean scour formation rate over the survey area over this 15 year period is 0.68×10^{-3} km^{-2} yr^{-1}. Since the modelled iceberg grounding rate over the same area is 2.1×10^{-3} km^{-2} yr^{-1}, the modelled rate is approximately three times more than the observed rate. In recent studies, the general modelling approach is to perform the grounding simulation and correct the results using known frequencies in areas where repetitive mapping data are available.

Recent research on iceberg areal densities (King et al., 2015; Habib et al., 2015) showed that iceberg densities based on aerial reconnaissance reports and satellite imagery analysis give values approximately 50% lower than values based on IIP iceberg bulletins.

The analysis of newly-collected 2012 iceberg profile data (Younan et al., 2016) and associated follow-up analysis resulted in additional modifications to the grounding model (King et al., 2016). Based on iceberg waterline lengths, drafts, and masses in the 2012 data the relationships for iceberg geometry were updated in the model. Based on a 2015 field program, a mean period of six days between rolling events was implemented in the model. Draft changes from a calving simulation based on the 2012 iceberg profile data were used to reduce the magnitudes of draft changes in the model.

Recent unpublished iceberg geometry data (McGuire et al., 2016) suggest changes in the iceberg length/mass/draft relationships, potentially in response to changes in environmental conditions. Iceberg grounding rates inferred from recent iceberg trajectory data also appear to be reduced from those observed during the 1980s (e.g. Banke, 1989a).

CONCLUSIONS

A comprehensive approach was used to model iceberg grounding processes on and adjacent to the Grand Banks of Newfoundland. The model includes iceberg drift, deterioration and grounding components, and is based on comprehensive site-specific iceberg, bathymetric and environmental data. Considering data collected by the IIP since the original study was conducted, the southerly iceberg flux across 48°N was just over 20% less than used in the previous calculations. The frequency of iceberg grounding would be decreased accordingly. With newer repetitive mapping surveys on the northeastern Grand Banks, the present simulation strategy is to scale simulated grounding frequency over the entire area according to predictions within surveyed areas. This consideration would decrease grounding rates by a factor of about 3 times compared to those predicted in the original study and summarized in this paper.

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