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An Operational Iceberg Deterioration Model

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ABSTRACT

This paper describes the iceberg deterioration component of an iceberg forecasting model. The model is intended for operational use by the Canadian Ice Service, and locally by offshore operators. The paper describes the formulation used to account for the various deterioration mechanisms, which consist of melting due to solar radiation, buoyant convection, and forced convection, as well as wave erosion and calving. The work also includes a sensitivity study that examines the role of the environmental input variables and model parameters. Tests examine the influence of water temperature, wind and current velocities, iceberg size, and wave height. The results indicate that wave height plays a major role in iceberg deterioration. Wind velocity and water temperature also play significant roles. In contrast, water current had little influence on iceberg deterioration. Finally, predicted calving intervals are found to be in reasonable agreement with field observations.

KEY WORDS: Iceberg forecasting, iceberg deterioration, iceberg calving.

INTRODUCTION

An iceberg forecasting model has been under development by the Canadian Ice Service (CIS). The development addresses iceberg drift, deterioration and calving, as well as the fate of the calved small ice masses. The model is intended for operational use by CIS to forecast iceberg conditions along the East Coast of Canada. Versions of the model are also adapted for local use by offshore operators over the Grand Banks. For example, the model is currently in use to provide information for iceberg management operations. Previous papers have described the drift component (Kubat et al. 2005), and the modeling of the size distribution and fate of calved ice (Savage et al. 2000, and

2001). The present paper concerns modeling of the deterioration of icebergs.

Knowledge of the deterioration of iceberg size is essential for forecasting the drift. Moreover, iceberg size is also an important factor in making decisions concerning iceberg management (e.g. towing) and evaluating the risks to offshore installations. Calving of small ice pieces presents an additional hazard to shipping. The small pieces are difficult to detect, and can inflict considerable damage if collisions occur. For these reasons, an operational iceberg forecasting model requires reliable modeling of deterioration processes. The model has to address several issues that complicate modeling of those processes. Difficulties arise, for example, from the irregular shapes of icebergs and the continuous changes due to calving and occasional rolling. There are also many environmental conditions (forcing) that influence iceberg deterioration, such as wind, water currents, waves, air and water temperatures, and solar and ocean heat fluxes. In view of such complexities, deterioration processes are usually modeled through semi-empirical parameterizations that capture the salient features of iceberg size evolution.

Josberger (1977) reported on detailed laboratory and field studies of the melting of icebergs. Another early study by White et al. (1980) gave estimates of the deterioration rates due to various processes. Their analysis became the basis for many of the subsequent modeling of iceberg deterioration. El-Tahan et al. (1987) also provided several empirical relations to describe iceberg deterioration, and verified their performance using field observations. In addition to the empirical formulas for iceberg deterioration, other studies addressed details of temperature distributions in icebergs. Loset (1993) gave a detailed analysis of temperature distributions, melt, refreezing and run-off in icebergs.

The present paper describes the formulation of the deterioration model. Results of a sensitivity study are also reported here. That study was motivated by the need to establish priorities and guide the efforts to acquire the environmental input. As can be seen from the following section of the paper, a wide range of environmental input is needed to account for the various deterioration processes. Some of that input can be difficult to obtain, particularly for local users with limited access to oceanographic and atmospheric forecasts. The following section of the paper describes the formulation used to model iceberg deterioration. A test case is also presented.

ICEBERG DETERIORATION

There are several processes that contribute to the melting, erosion, calving, and fracture of icebergs (see Job 1978, and El-Tahan et al. 1987). Savage (2001) gave a description of those processes. The present model considers the following:

- Surface melting due to solar radiation,
- Melting due to buoyant vertical convection,
- Melting due to forced convection,
- Wave erosion,
- Calving of overhanging slabs.

There are other deterioration processes that cannot be included in the present model. They include: convection due to overturning, calving due to differential melting along cracks in the iceberg, and fracture due to internal stresses. A brief description of the formulation used to estimate the deterioration due to each mechanism is given below. The contribution of each process to deterioration (except for calving) is expressed as a rate of change of the waterline length of the iceberg, L . The reduction in iceberg mass can be calculated using the relationship between iceberg mass and waterline length (Barker et al. 2004)

$$M = \kappa \rho_i L^3 \quad (1)$$

where ρ_i is ice density. The parameter κ has a value of approximately 0.45.

Surface melting due to solar radiation

The deterioration is expressed as a velocity representing the rate of change of the waterline length of the iceberg. The melting velocity (Savage, 2001) is given by

$$V_s = \frac{I}{\Gamma \rho_i} (1 - \alpha) \quad (2)$$

where Γ is the latent heat of melting of ice (334 J/gm), and α is the albedo. The measured insolation, I over Labrador Sea (De Jong, 1973) ranges from 30 cal/cm²/day in December and January to 420 cal/cm²/day in July. The values of the albedo range from 0.1 for clear ice surfaces to 0.95 for fresh snow.

Melting due to buoyant vertical convection

The water layer adjacent to an iceberg surface can experience currents induced by salinity and temperature gradients. Fresh water immediately next to the iceberg tends to rise against the denser saline ocean water. In the same time the colder water in the vicinity of the iceberg is heavier than the warmer more distant water. Thus, salinity effects dominate at the iceberg surface and cause the water to rise, while thermal effects become pronounced outside that layer and cause

the water to sink. Neshyba and Josberger (1979) gave the following empirical correlation to estimate the melt rate

$$V_b = 2.78(\Delta T) + 0.47(\Delta T)^2 \quad (3)$$

where ΔT is the difference between the far field water temperature, T_∞ and the freezing point temperature, T_{fp} ($^{\circ}\text{C}$); i.e. $\Delta T = T_\infty - T_{fp}$. The appropriate value for T_{fp} can be lower than the freezing temperature of fresh water. Loset (1993) noted that melting of iceberg keels takes place in water of -1.2°C temperature. He indicated that ‘‘Ablation of the submerged body continues well below the freezing point of fresh water’’.

The melting processes next to the iceberg surface are complex. The iceberg melting produces fresh water which mixes with the sea water; this in turn changes the freezing temperature that should be used in the model calculations. Josberger (1977) devised a expression for this based on his experiments. The equation for the freezing point to be used in the model is

$$T_{fp} = T_f(S) e^{-0.19(t_\infty - T_f(S))} \quad (4)$$

where T_∞ is the far field water temperature (away from the immediate surface of the iceberg), and T_f is the sea water freezing temperature based on the far field salinity, S . The ice freezing temperature depends on the salinity, S , (Loset, 1993) according to

$$T_f(S) = -0.036 - 0.0499S - 0.000112S^2 \quad (5)$$

where the salinity, S , is in ‘‘mils’’; i.e. grams of salt per 1000 grams of water. For a typical salinity of 33 mils, the resulting value is $T_f = -1.8047^{\circ}\text{C}$. These values of salinity and T_f are used in the present calculations. The corresponding values of the freezing point temperature, T_{fp} are usually a little larger than -1.8°C (and below 0°C). Using the appropriate value for the ice freezing temperature, T_{fp} becomes important for colder water temperatures, T_∞ (near zero $^{\circ}\text{C}$).

Forced convection

The relative velocity between the iceberg and water current contribute to the process of melting of the keel. The relative velocity maintains the temperature difference, which is needed for the melting process. Also wind can contribute to melting of the sail. The surface melt due to forced convection can be expressed as

$$V_f = \frac{q_f}{\rho_i \Gamma} \quad (6)$$

where q_f is the heat flux,

$$q_f = Nu k_f \Delta T / L \quad (7)$$

where k_f is the thermal diffusivity of the fluid (air or sea water), L is the water line length of the iceberg. The Nusselt number, Nu is given by

$$Nu = C Re^{0.8} Pr^{0.4} \quad (8)$$

where $C = 0.058$, and the Reynolds number, Re , and Prandl number, Pr , are defined as

$$Re = V_r L / \nu \quad (9)$$

and

$$Pr = \nu / k_f \quad (10)$$

where V_r is the relative velocity between the iceberg and the fluid and ν is the kinematic viscosity.

We note that in calculations of the drag forces, which are used in modeling the drift, the variation of water current with depth is taken into account (Kubat et al., 2005). However, for the above calculation of the relative velocity, V_r , a mean current was considered to give adequate accuracy.

Wave erosion

This is a major source of iceberg deterioration. White et al. (1980) developed the following equation to estimate the melt rate of a notch at the waterline

$$V_{we} = 0.000146 \left(\frac{R}{H} \right)^{0.2} \left(\frac{H}{\tau} \right) \Delta T \quad (11)$$

where V_{we} is the melt rate in m/s, R is the roughness height of the ice surface and τ and H are the wave period and height, respectively. According to White et al. (1980), the value of R is typically 10 mm. The melt rate V_{we} can be up to 1 m/day for a 1 degree C temperature difference.

Calving

Calving can be caused by several mechanisms. The major one appears to be the breaking of overhanging slabs of ice (Savage, 2001). A notch at the waterline usually forms due to wave erosion. As the erosion progresses, the notch deepens and size of the ice hanging above the notch increases. At a certain stage, the bending stresses cause fracture of the ice, and the overhanging slab collapses. White et al. (1980) conducted numerical analyses of stresses for several three-dimensional cases, and developed a parameterization of that calving process. Their results can be summarized as follows. The critical length of an overhanging slab at which fracture (calving) occurs, F_l , is given by

$$F_l = 0.33 (37.5 H + h^2)^{1/2} \quad (12)$$

where H is the wave height, and h is the thickness of the overhanging slab (both in meters). Savage (1999) conducted further analysis of the overhanging ice geometry, and using available estimates of calved ice mass developed a relationship between h and the waterline length of the iceberg, L . The expression for the overhanging slab thickness becomes

$$h = 0.196 L \quad (13)$$

For steady wave action, the calving interval, t_c , is given by

$$t_c = F_l / V_{we} \quad (14)$$

Savage (1999) also carried out an analysis of the shape of the overhanging ice and obtained the following expression for the calved ice volume,

$$\bar{V}_c = 0.64 L F_l h \quad (15)$$

The above correlations were verified using available estimates of observed calved ice masses (Savage 2001).

Aside from the mechanism discussed here, calving can occur due to fracture caused by internal stresses or overturning. Such mechanisms appear to have a minor contribution to calving (Savage, 2001). They are also too complex to include in a mechanical model.

TEST CASE

A test case is presented in some detail in the following section. The results of this case will be used to evaluate the role of each parameter. For this test case, an iceberg of 100 m waterline length is considered to drift in sea water temperature $T_\infty = 11.9^\circ\text{C}$ (Eq. 4), which is typical of fall conditions over the Grand Banks. This temperature is used because it produces relatively large deterioration, which makes it possible to examine the role of the various parameters. A colder temperature, as will be shown in the following section, produces substantially lower loss of iceberg mass. The run examines deterioration of the iceberg over a period of 4 days. For simplicity, waves, wind and water current are assumed to act steadily along the same direction for the period of the run. A wave height of 2.1 m, wave period of 8 s, wind velocity of 0 m/s, and water current of 0.5 m/s are used in the calculations.

The resulting decrease in the waterline length is plotted versus time in Fig.1, and the corresponding loss of mass is shown in Fig.2. The waterline length of the parent iceberg was reduced to 60 m and the mass decreased by 87% after 4 days.

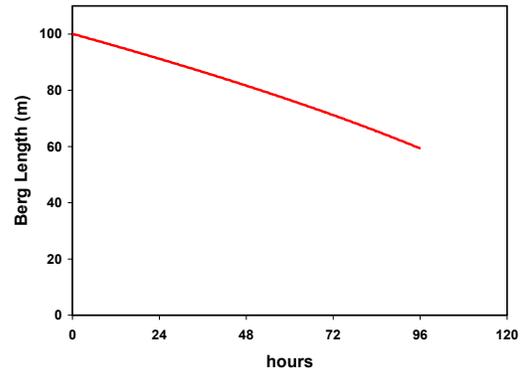


Fig.1 Iceberg waterline length decrease over 4 days

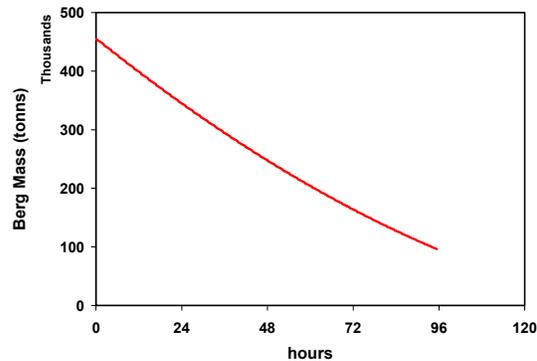


Fig.2 Iceberg mass loss over 4 days

A few tests indicated, as noted by El-Tahan et al. (1987), that wave erosion and calving are the predominant mechanisms of iceberg deterioration, followed by water forced convection. The combined contributions of solar radiation, vertical buoyant convection and air forced convection were typically less than 5% of iceberg mass loss.

We note that the estimated calving interval can be relatively large compared to the total duration of the simulation. Since the specific time of the first calving event (during a forecast) is unknown, the resulting deterioration estimates can be misleading if the calved mass is released all at once. Therefore, instead of choosing an arbitrary time for the first calving event, the calved mass was subtracted from the mass of the iceberg at every time step. The calculations were done by considering the rate of mass loss due to calving (calved mass/ calving interval). The resulting deterioration is thus averaged over the period of the simulation.

SENSITIVITY STUDY

The role of the various environmental and input variables is examined. This sensitivity study is intended to guide the operational use of the model. The variables include water temperature, iceberg size (waterline length), wind and current velocities, and wave height.

Tests were done using a water temperature of 1.1°C, which is typical for April over the Grand Banks area. Other input variables and parameters were kept similar to those of the above test case, which was done using a water temperature of 11.9°C (typical of September conditions over the Grand Banks). For the lower water temperature (1.1°C), the mass of the iceberg decreased by 19% after 4 days. The decrease was 79% for the case of 11.9°C water temperature.

Other tests were also done to compare the above two water temperatures, but using different values for the initial waterline length. The resulting decrease in length is plotted versus time in Fig. 3a and resulting decrease in iceberg mass versus time in Fig. 3b. The plots show that the effect of water temperature is pronounced. Moreover, the rates of deterioration of smaller icebergs are higher than those of the larger icebergs. The plot corresponding to the smallest iceberg in Fig 3a is truncated once the iceberg length decreased to 20 m. In implementing the model, a threshold of 20 m was set as the lower limit for iceberg waterline length. Below that limit, the present parameterization of deterioration mechanisms (e.g. wave erosion and calving) may not be valid. Smaller ice masses were considered to be *bergbits* or *growlers*. Their deterioration follows other formulations, which were presented by Savage et al. (2000) and (2001).

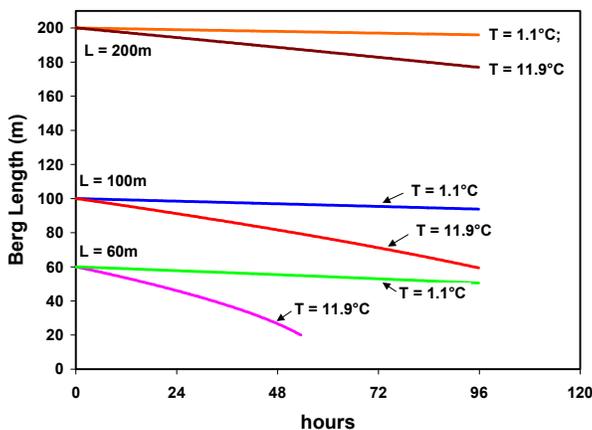


Fig.3a The influence of water temperature, *T* and iceberg *L* on iceberg deterioration – waterline length

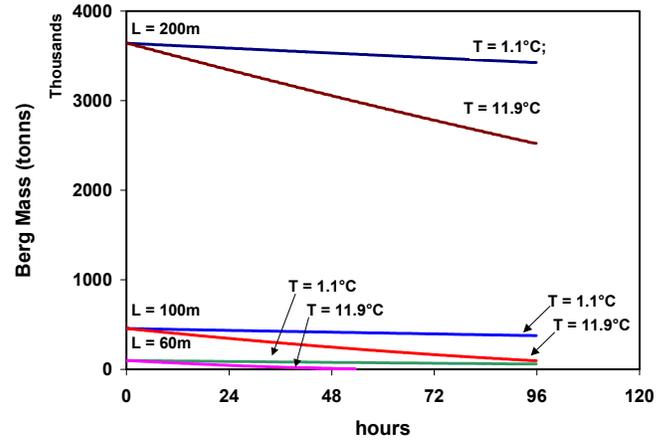


Fig.3b The influence of water temperature, *T* and iceberg *L* on iceberg deterioration - mass

The role of waves was tested using a range of values typical for the Grand Banks, obtained from the MSC50 Wave Atlas. Runs were then done for wave height values of 1.5, 2.0, 2.5, 3.0, 4.0, and 5.0 m. A number of wave periods ranging from 4 to 7 seconds were also tested.

Fig.4a shows the decrease of iceberg’s waterline length due to the action of wave heights of 1.5 m and 5 m. The results are presented for two cases representing *cold* and *warm* seawater of 1.1°C and 11.9°C temperatures, respectively. An increase in wave height from 1.5 m to 5.0 m in water of 1.1°C decreases the iceberg waterline length by 6.0%, and in water of 11.9°C by 51.5%. The iceberg with original waterline length of 100 m was reduced to 75.5 m in 11.9°C water with 1.5 m waves, and to 24 m in water with 5.5 m waves. Fig. 4b shows the decrease of the iceberg mass. An increase in wave height from 1.5m to 5.0m in water of 1.1°C decreases the iceberg mass by 15.5%, and in water of 11.9°C by 41.5%. The iceberg with original mass of 455,000 tons (100 m waterline length) was reduced to 43% of its mass in 11.9°C water with 1.5 m waves, and to 1.5% of its mass with 5.5 m waves.

A few tests indicated that the role of wave period is not as pronounced as wave height. The influence of wave period on iceberg deterioration, and the manner in which wave period should relate to wave height remain to be addressed in future work.

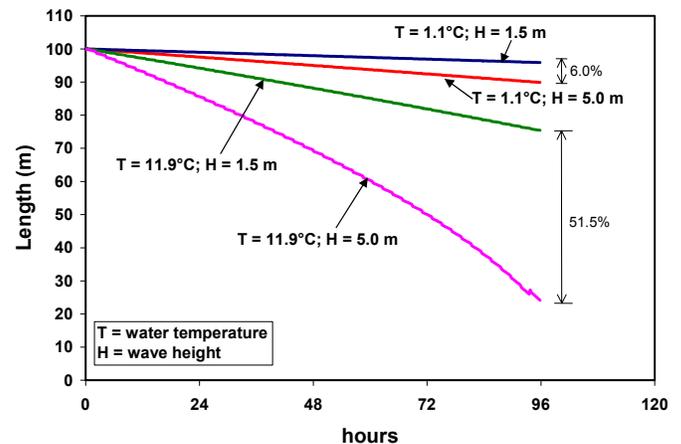


Fig.4a Effect of wave height, *H*, on iceberg waterline length

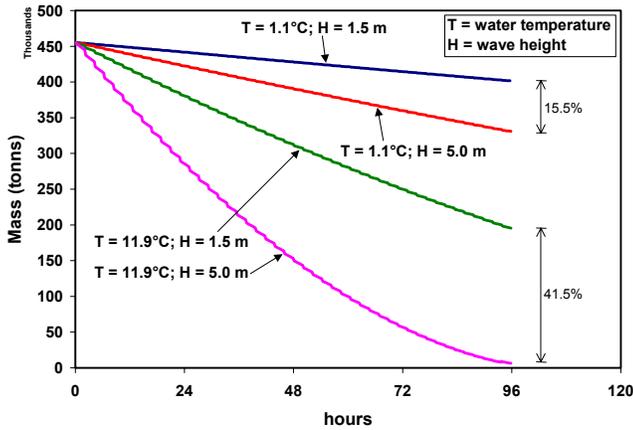


Fig.4b Effect of wave height, H , on iceberg mass loss

Another series of tests examined the role of water current and wind speed. Melt due to forced convection depends on the relative velocity between the iceberg and the water or wind velocities. Tests examined water current velocities of up to 1 m/s. In the absence of wind, there was very little influence on iceberg deterioration. The resulting iceberg velocities were very close to those of the water current, which explains the negligible impact on iceberg deterioration.

Tests of the role of wind speed were made using zero water current. Wind speeds of up to 15 m/s were tested. In those cases, the wind induced relative velocity between the iceberg and water produced an appreciable amount of melt due to forced convection. Figure 5 shows the reduction in iceberg mass for one case with no wind, and another with 5 m/s wind. Further increase of wind speed to 15 m/s had very little effect on iceberg deterioration.

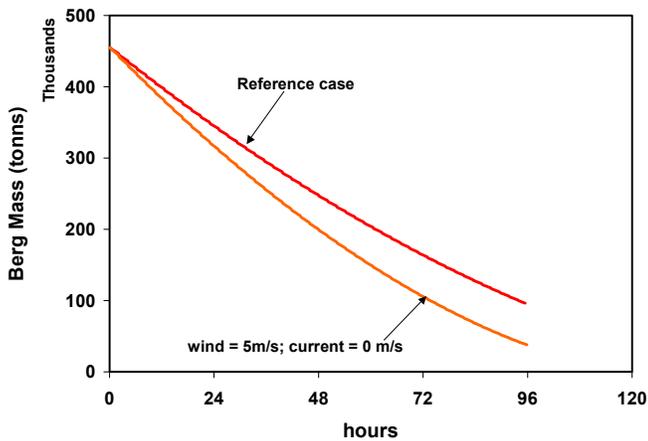


Figure 5: The influence of wind velocity on iceberg deterioration.

Finally, the calving interval is examined. The model is tested against data collected by Ballicater (2005). The data consist of observations of iceberg calving in Canadian and Greenland waters from 1998 to 2005. Recording the exact time of calving is very difficult. Photo and video records were used, however, to compile estimates of calving intervals. Other related observations including sea state (wave conditions), temperatures, and descriptions of iceberg shapes were collected. Table 1 summarizes the observations of Ballicater (2005). It includes estimates of the calving intervals, t_c , wave height, H , and wave period, τ , as well as iceberg parameters used in the present model: ice surface

roughness, R , height of the over-hanging ice slab, h , and water temperature, T_∞ , (Eqs. 11 and 12). The calculated and observed calving intervals are plotted versus water temperatures in Fig. 6. The calculations appear to be in relatively good agreement with the observations. At lower water temperatures, as expected, the calving interval increases. A small error in estimating water temperature can appreciably affect the fit of the data in that region. We note that calculations of the calving interval involves the value ΔT (Eq. 14) which is the difference between the water temperature and the freezing point temperature, T_{fp} (Eq.4). Using the appropriate value for T_{fp} becomes significant for lower water temperatures. Only one observation shows a relatively large calving period (approximately 95 hours) for colder water of 1°C. That discrepancy was probably the result of a different calving mechanism from what is considered in the model. Only the main mechanism of calving, which is the failure of overhanging ice, is taken into account in the model. Other mechanisms, such as fracture due to internal stresses or rolling of the iceberg, cannot be modeled at this stage. They take place less frequently and account for a minor portion of iceberg deterioration (Savage, 2001).

Table 1: Model parameters based on field observations

Year	T_∞ (°C)	t_c (hrs)	H (m)	τ (s)	h (m)	R (m)
1998	5.1	13	1.5	5.4	15	0.01
2000	5.0	30	1.0	4.4	15	0.01
2001	8.0	13	1.0	4.4	15	0.01
2002	1.0	50	1.0	4.4	15	0.01
2003	6.0	22	1.0	4.4	15	0.01
2004	10.0	8.6	0.5	3.1	15	0.01
2005	1.0	38.3	0.25	2.2	25	0.01

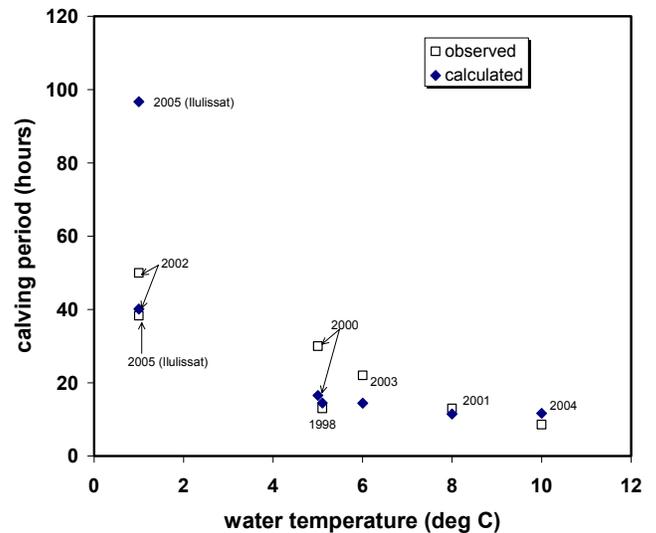


Fig. 6: Observed and calculated iceberg calving intervals.

CONCLUSION

The present paper has described an iceberg deterioration component of an iceberg forecasting model. The model is intended for operational use by the Canadian Ice Service, and locally by offshore operators. The present paper has compiled the formulas that describe the deterioration processes. In particular, expressions for calving interval and calved ice mass are included. The emphasis has also been on

examining the sensitivity of iceberg deterioration predictions to several environmental variables and input parameters.

The results indicate that wave action exerts the predominant influence on iceberg deterioration. Specifically, wave height is the primary factor. A few tests indicate that the role of wave period is not as significant. Waves contribute to iceberg deterioration in two manners. The first is direct erosion of ice near the water line. The second manner is through calving. As waves erode a notch at the waterline, the overhanging ice grows to a point at which fracture (and calving) takes place. Both those mechanisms are the primary source of iceberg deterioration.

The tests showed that water temperature has a significant effect on iceberg deterioration. Deterioration rates for a warm temperature of 11.9°C (typical of September conditions over the Grand banks) were substantially higher than those for a colder temperature of 1.1°C (representative of March conditions). It was also shown that wind induced iceberg motion enhances mass loss due to forced convection. The loss of mass due to forced convection is smaller for an iceberg moving predominantly under the action of water currents.

The predicted calving intervals were in agreement with the field observations of Ballicater (2005). This is remarkable since estimates of calving intervals and the ambient environmental conditions (e.g. wave) are difficult to measure. Both model predictions and field observations show a rapid increase in calving interval as water temperatures decrease, and approach the freezing point. It was found that an accurate estimate of freezing point temperature is necessary to obtain reasonable estimates of calving intervals.

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