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Determination of Iceberg Draft, Mass and Cross-Sectional Areas

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ABSTRACT

A new operational iceberg forecasting model is under development at the Canadian Ice Service (CIS). The model deals with iceberg drift, deterioration, and calving. One of the main features of the new model is the utilization of detailed environmental conditions. In particular, the vertical distribution of water current is used to calculate water drag forces. An accurate description of keel geometry is, therefore, needed in order to take advantage of the detailed water current information. This paper describes the analyses done to determine the geometry of iceberg keels and sails. The objective was to provide refined input for the iceberg drift section of the forecasting model. Available iceberg data were used to create empirical equations which describe keel cross-sectional areas at different depth intervals from a given waterline length. The equations also determine sail area, draft, and mass as functions of waterline length. This is the first investigation that determines geometry in detail.

KEY WORDS: iceberg forecasting; drift; iceberg geometry; draft; length; mass; area.

INTRODUCTION

The development of the Grand Banks of Canada for oil and gas production requires reliable forecasting of iceberg and bergy bit drift and deterioration, to ensure the safety of offshore structures and shipping operations. A new operational model has been developed at the Canadian Ice Service (CIS) in response to emerging forecasting requirements. The model deals with the drift, deterioration, and calving of icebergs. One of the main features of the model is employing detailed environmental forcing information in order to improve accuracy of the forecasts. In particular, detailed vertical profiles of water current are used to calculate water drag forces, which lead to significant improvements in predicted drift tracks. Previous prediction models assumed a uniform current independent of depth. Naturally, an estimate of keel area variation with depth is needed for appropriate evaluation of drag forces. At present, no such information concerning keel geometry is available in the literature.

The present investigation was primarily aimed at determining the detailed geometry of the keel. The observations of Smith and Donaldson (1987) provide the most comprehensive description of iceberg geometry, along with measurements of drift and environmental conditions. Those observations include the only available measurements of keel cross-sectional area variation with depth. This data set was used to develop a parameterization of iceberg geometry. The main objective of the study was to study the available data in order to determine the variation of keel width with depth. Additionally, sail width, keel depth, and iceberg mass were examined. Supplemental data concerning the draft and mass of the icebergs from other sources were also examined in the analysis (e.g. Canatec et al., 1999; Brooks, 1985; El-Tahan and Davis, 1985; Hotzel and Miller, 1985; Robe, 1976; among others). In turn, the results of the analyses were used to develop predictive formulas that describe the above aspects of iceberg geometry.

THE DATA SET

The measurements of Smith and Donaldson (1987) were conducted from 1983 to 1985 over locations covering the Strait of Belle Isle, the southern Labrador shelf, and the Grand Banks. The measurements were taken from a ship, which followed icebergs at relatively close distances (1 to 2 km). The data covers 12 track segments of 9 icebergs. Measurements recorded the track of the icebergs, vertical profiles of water current, wind speeds, and temperatures. The processed information of those variables was recorded at 10-minute intervals. To determine the geometry of the icebergs, sonar profiles of the keel were analyzed to produce cross-sectional areas at 10-m depth intervals. Sail cross-sectional areas were also surveyed, using photographs and taking vertical sextant angles above the horizon at known radar ranges. The cross-sectional areas were calculated along two perpendicular directions (length and width). Fourteen cross-sections were taken in total. Five of these were repeats of icebergs that had been previously observed.

ICEBERG DRAFT AND MASS

A summary of the Smith and Donaldson (1987) measured iceberg dimensions, mass and cross-sectional areas is given in Table 1. The accuracy of the data was ±5% above water and ±10% below water.

Table 1. Waterline dimensions, draft, mass, and sail cross-sectional area (CSA), from Smith and Donaldson (1987).

Iceberg	Type	Measured Height m	Measured Length m	Measured Width m	Measured Draft m	Estimated Mass kilotonnes	Mean Sail CSA m^2
83-1	pinnacle	19	66	37	54	85	445
83-2A	drydock	32	146	86	96	800	2646
83-2B	drydock	33	137	86	83	860	2510
83-3A	domed	25	129	71	84	620	1871
83-3C	domed	27	99	67	89	530	1548
83-5	drydock	20	77	56	67	147	624
84-5A	drydock	43	198	181	120	2100	4039
84-5B	drydock	44	204	136	110	1700	4254
84-6A	domed	19	90	70	70	320	1033
84-6B	domed	20	86	73	75	270	1191
84-7	domed	32	178	137	110	1700	4055
85-1A	blocky	23	118	92	110	570	1820
85-1B	blocky	23	118	92	110	570	1820
85-4	drydock	16	61	41	40	33	387

The focus was on using the waterline length (the largest horizontal distance across the iceberg at the waterline) of the icebergs to determine the variation of keel width with depth, sail width, keel depth, and iceberg mass. This waterline length was chosen because most observations of icebergs are determined from aircraft. Often iceberg length and shape are the only values estimated. Additionally, as icebergs are generally observed at weekly intervals, the length and geometry evolve between observations. This effect is included in the deterioration portion of the drift model, and it is essential to feed this information back into the model.

Initially, the data were plotted to examine relationships between draft and each of the iceberg length, width, height, mass and volume values. As there are no present means of determining these values theoretically, one must use curve-fitting techniques with what data is available. Fitting a power curve to the draft versus length data led to a reasonable definition:

$$D=2.91L^{0.71} \tag{1}$$

where D is the draft of the iceberg in metres, and L is the waterline length in metres. This is similar to other empirical relationships between draft and length found in the literature (see El-Tahran, 1982; Hotzel and Miller, 1983; Buckley et al., 1985; Canatec, 1999; for example). Equation (1), however, involves *dimensional* parameters. Subsequently, a satisfactory linear relationship, involving a dimensionless parameter, between draft and length was found from regression analysis to be:

$$D=0.7L \tag{2}$$

The advantage of Equation 2 is that it is dimensionless, which helps to minimize the effects of erroneous data, and makes better use of a limited data set.

A comparison of the results from Eq.1 and Eq.2 is shown in Figure 1. In comparing the two relationships for relating draft to waterline length, it can be seen in Figure 1 that the linear equation (Eq.2) underestimates the draft for smaller waterline lengths, and overestimates the larger lengths compared to Eq.1. However, the determination that iceberg draft is also 70% of the waterline length is in keeping with results from Hotzel and Miller (1985).

A similar analysis was carried out for the length-mass relationship, resulting in the equation:

$$M=0.43L^{2.9} \tag{3}$$

where M is the mass in tonnes and L is the length in metres. The equation was simplified to the following dimensionally correct form

$$M=0.5\rho_{ice}L^{3} \tag{4}$$

where ρ_{ice} is ice density, taken here to be 910 kg/m³. Figure 2 shows a comparison of the two empirical mass equations developed here, Eq.3 and Eq.4. It can be seen that Eq.4, the dimensionless equation, overestimates at waterline lengths greater than 100 m. For example, with a waterline length of 220 m, the calculated mass ranges from approximately 2 million tonnes to 4 million tonnes, depending upon whether Eq. 3 or Eq.4 is used.

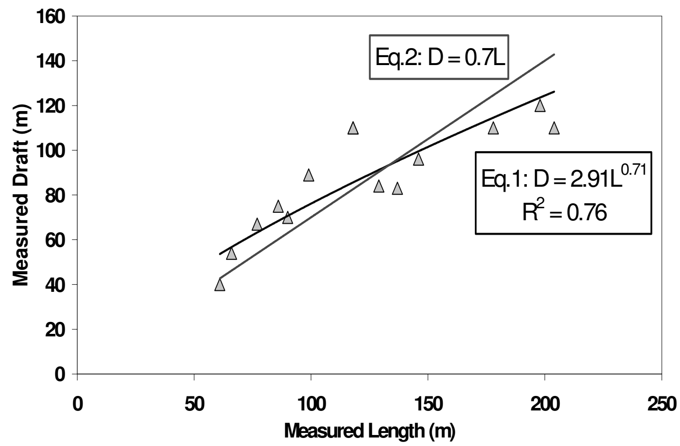

Figure 1: Comparison of Equations 1 and 2, relating iceberg draft to waterline length. The measured draft values used to calculate Eq.1 are indicated in the plot.

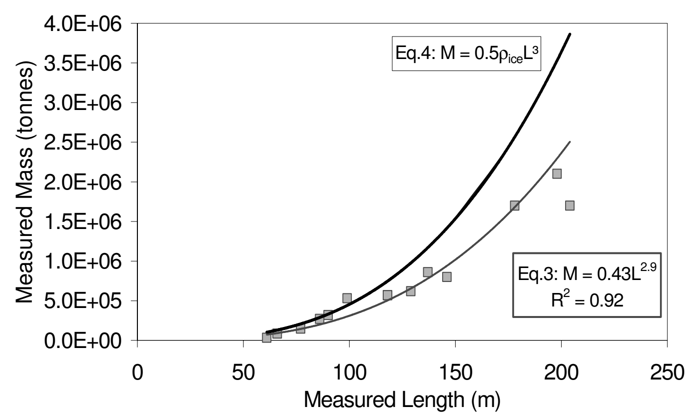

Figure 2: Comparison of equations relating iceberg mass to waterline length. The measured mass values used to calculate Eq.3 are indicated in the plot.

Previous empirical equations for relationships between draft and waterline length and mass and waterline length have yielded a variety of results, as shown in Table 2. Given the diverse data sets, scatter in the results is to be expected. This is especially evident in the mass calculations. Even so, the results had reasonable agreement and generally fell within ±10% of each other for icebergs less than 200 m. Large icebergs (with a waterline length greater than 200 m) encountered in the regions of interest to the present work are usually tabular. Non-tabular large icebergs would ground in the relatively shallow water depths. Obviously, geometry of tabular icebergs is not the focus of this study. Given this criteria, it was determined that the present study gave results that were in general agreement with the previous studies, within that range, for use as input into a numerical model for predicting iceberg drift.

Table 2: A sample of other empirical equations for determining iceberg mass and draft from waterline length, and their source reports

	Equation and Source Report
Mass	Hibernia, Canatec (1999): M=1.03L^2.67
	Labrador, Canatec (1999): M=2.25L^2.58
	Singh et al. (1998): M=0.97L^2.78
	Fuglem et al. (1995): M=0.81L^2.77
	Hotzel and Miller (1983): M=2.009L^2.68
Draft	Hibernia, Canatec (1999): D=1.95L^0.79
	Labrador, Canatec (1999): D=3.9L^0.63
	Hotzel and Miller (1983): D=3.781L^0.63

SAIL AND KEEL AREAS

The Smith and Donaldson (1987) data set included vertical cross-sectional areas of the keel of each iceberg at 10 m depth intervals, as well as sail areas, taken from two views. These area data were then averaged. An example of the reported average data for two of the icebergs is shown in Table 3. The focus of the work for the iceberg drift model was to establish a formulation for determining keel cross-sectional area(s) based upon waterline length. To establish a correlation, plots were made of waterline length versus cross-sectional area, for each of the vertical sections contained in the data set.

Table 3: Example vertical cross-sectional areas from data set. Areas are averages of two cross-sections taken at different angles.

	Iceberg 83-1		**Iceberg 83-3C**	
	Depth	**Area (m²)**	**Depth**	**Area (m²)**
Sail		445		1548
Layer 1	**0-10m**	546	**0-10m**	976
Layer 2	**10-20m**	500	**10-20m**	1071
Layer 3	**20-30m**	427	**20-30m**	1091
Layer 4	**30-40m**	403	**30-40m**	1115
Layer 5	**40-50m**	348	**40-50m**	1062
Layer 6	**50-54m**	51	**50-60m**	970
Layer 7			**60-70m**	795
Layer 8			**70-80m**	531
Layer 9			**80-89m**	221

A plot of sail areas versus waterline length is shown in Figure 3. The relationship representing the best fit of the data is expressed as

$$A_{sail} = a_0L+b_0 \quad (5)$$

where A_{sail} is the cross-sectional area of the sail (m^2), and a_0 (m) and b_0 (m²) are parameters determined by curve-fitting the data as shown in Figure 3.

For each layer of the keel, the area is expressed, in a similar manner, as

$$A(k) = a(k)L+b(k) \quad (6)$$

where $A(k)$ is the cross-sectional area of layer k, which extends from $(k-1) \times 10$ m depth to $k \times 10$ m depth. Figure 4 shows, as an example, a plot of the areas versus waterline length for Layer 1, and the associated best-fit line.

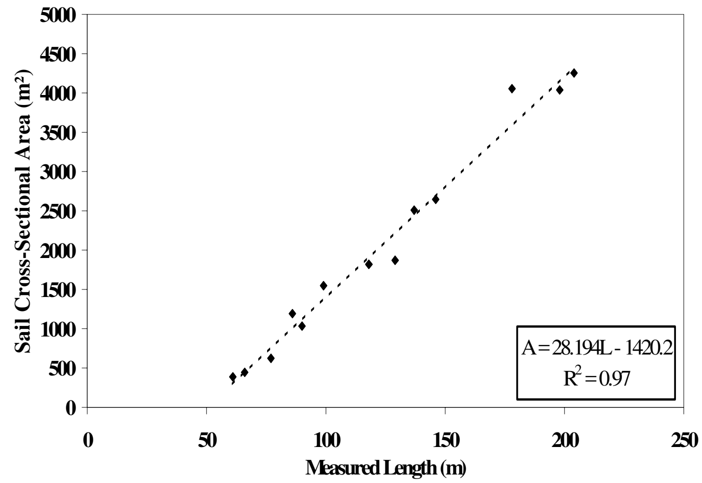

Figure 3: Plot of vertical cross-sectional area versus length for iceberg sail values, where R² is the correlation coefficient.

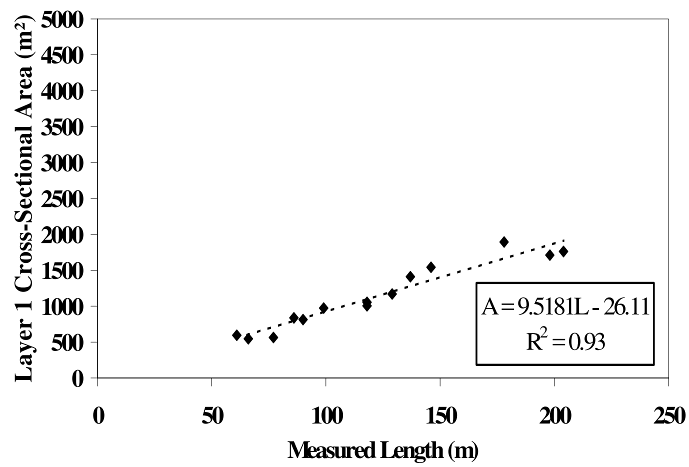

Figure 4: Plot of iceberg Layer 1 (0-10 m keel depth) cross-sectional area versus length, where R² is the correlation coefficient.

Curve fits were done for each layer to determine the parameters a(k) and b(k). The results showed that Eq. (6) represents the data with sufficient accuracy. Hence, a set of empirical equations was developed for each "layer" of an iceberg, based solely on waterline length. This set is shown in Table 4.

The largest draft in the data-set of Smith and Donaldson (1987) was 120 m. Drafts up to approximately 230 m, however, are reported in the Grand Banks area of Canada (e.g. Miller and Hotzel, 1985). In order to expand the equations for deeper drafts (but still less than 200 m, as previously discussed), plots of the slope and intercept values from the vertical cross-sectional area equations versus maximum draft depth for each layer were created (Figures 5 and 6). In these figures, an obvious change in slope of each graph occurs at the draft depth of 90 m. It was not evident why this change occurred. The data below these depths should be used with caution, as it is possible that the change is due to the small number of data points at these deeper depths. Fitting a power equation to each section of the plot above and below this 90 m depth gave equations for calculating the slope and intercept for a given layer depth. In this case, equations were developed for drafts up to 160 m, which are also shown in Table 4, for Layers 12-16.

Using the equations found in Table 4, combined with Eq.2 (the calculation for estimating iceberg draft based upon iceberg length), composite icebergs can be created. Two such icebergs, with drafts of 70 m and 105 m, are shown in Figure 7. The pictures show only the keel of the icebergs. These composites, and the equations they were derived from, were used in the calibration of the CIS iceberg drift numerical model, discussed in the following section.

Table 4: Parameters for calculating vertical cross-sectional areas

	Height/Depth (m)	a(k)	b(k)
Sail	0+	28.194	-1420.2
Layer 1	0-10	9.5181	-26.11
Layer 2	10-20	11.17	-107.42
Layer 3	20-30	12.482	-232.44
Layer 4	30-40	14.004	-407.02
Layer 5	40-50	14.327	-456.91
Layer 6	50-60	14.8	-599.7
Layer 7	60-70	14.68	-720.56
Layer 8	70-80	16.098	-1168.1
Layer 9	80-90	17.136	-1662.9
Layer 10	90-100	13.223	-1199
Layer 11	100-110	6.4432	-503.5
Layer 12	110-120	4.50	-319.1
Layer 13	120-130	3.05	-198.9
Layer 14	130-140	2.13	-128.4
Layer 15	140-150	1.53	-85.47
Layer 16	150-160	1.12	-58.39

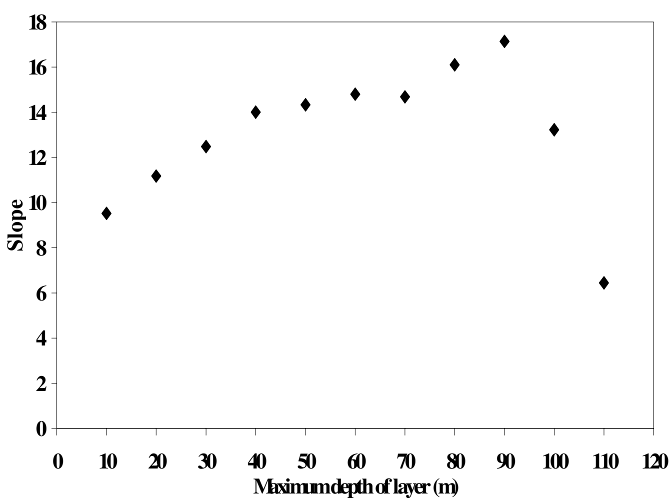

Figure 5: Plot of vertical cross-sectional area slope parameter versus maximum depth of layer

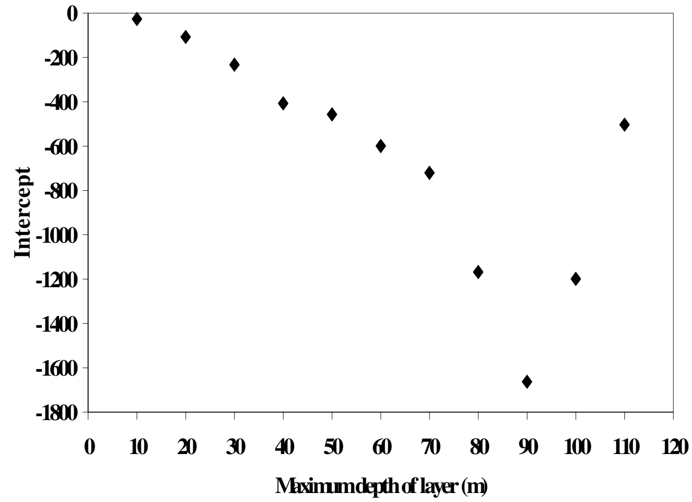

Figure 6: Plot of vertical cross-sectional area intercept parameter versus maximum depth of layer

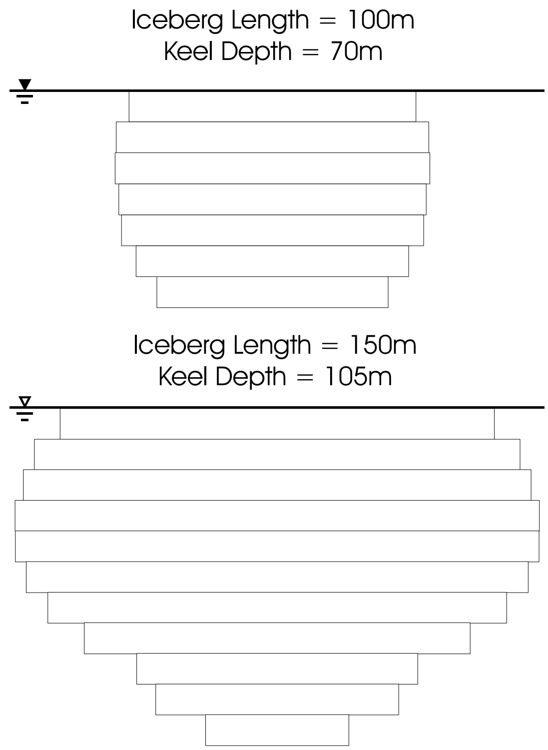

Figure 7: Composite icebergs, created using equations from Table 3

USING THESE RESULTS TO PREDICT ICEBERG DRIFT

The new Canadian Ice Service iceberg forecasting model deals with iceberg drift, deterioration and calving, as well as the drift and deterioration of calved bergy bits. The formulation of the model was discussed by Savage (2001). Carrieres et al. (2001) also gave an overview of the model implementation and testing. The analysis of iceberg geometry presented in this paper was used in the section for modelling iceberg drift, which is carried out by considering the various forces that act on each iceberg, and solving the linear momentum equations. This was incorporated into the model in 2000. The model includes forces resulting from water drag, air drag, wave radiation pressures, and water pressure gradient. The linear momentum equations of each iceberg include the sum of those forces. Added mass and Coriolis force are considered in the equations. An implicit solution is used in the present version of the program to obtain the velocities and update the positions.

The equation parameters shown in Table 4 were used to refine calculations of the air and water drag forces. Water drag forces are calculated over 10 m-depth sections of the keel. The present formulas are used to calculate the areas of those sections of the keel (using waterline length). Water current at those levels is obtained from an ocean model (see Carrieres, 2001), and is then used to calculate the drag forces. The vector sum of those forces gives the resultant drag force on the keel.

An example of a test of the model showing the predicted and observed drift tracks for one case from Smith and Donaldson (1987) is shown in Figure 8. In that test, measured water current and wind values were used as input. In Smith and Donaldson (1987), the iceberg's waterline length is listed as 66 m and the duration of the drift was 14 hours. A drag coefficient of 1.5 was used in calculations of both wind and water drag forces. The best fit to the observed track occurred when the value for L used in the model was chosen as an average value between the measured waterline length and the average of the waterline length and width values combined (in this case, 58 m, also shown in Figure 8). We note that recent parametric studies by Kubat and Sayed (2003) showed that using surface water current values leads to substantial inaccuracy. Their conclusions indicate that calculations of keel geometry are essential for acceptable forecasts.

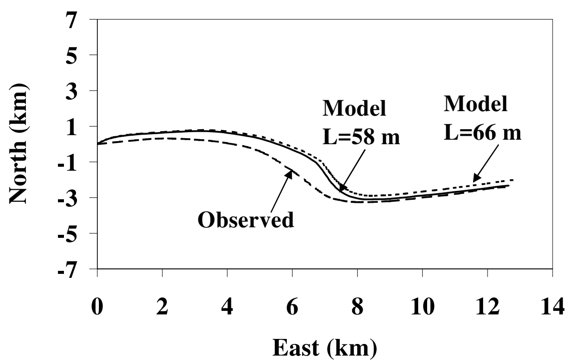

Figure 8: Predicted and measured iceberg trajectories, Smith and Donaldson (1987) iceberg 83-1, with a waterline length of 66 m and 58 m. It can be seen that the two results are very similar.

RECENT MODIFICATIONS TO THE EMPIRICAL MODEL

A number of refinements were made to the above empirical formulas of the geometry at CIS, in the four years after the model's initial development in 2000. These changes examined the effects of small sail areas, the bottom layer of keel areas and the extrapolation of larger keel depths from the existing data set. The above formulas are obviously limited to the range of waterline lengths of the Smith and Donaldson (1987) data. Considerably smaller lengths may cause inaccuracies. Based on the equations found in Table 3, the model can only accept input for icebergs with a waterline length such that the equations will not give "negative" heights or drafts. Rather than a linear equation, a power law relationship was fit to the smallest three icebergs in the data set. This resulted in the following equation for the cross-sectional area, A_{sail}, for icebergs with waterline length smaller than 65 m:

$$A_{sail} = 0.077L^2 \quad (7)$$

For the bottom keel layer of each iceberg, the area (of the bottom layer) was plotted versus length, regardless of depth. That led to a poor correlation. Subsequently, the amount that the keel projects into the bottom layer was included to created a new power law relationship:

$$A_b = 0.279(Ld_k)^{0.989} \quad (8)$$

where A_b is the bottom layer area and d_k is the amount that the keel projects into the bottom layer of the iceberg. Equation (8) was thus used to handle cases where the bottom layer of the keel was relatively small (depth smaller than 10 m).

The original data set contained only a few icebergs that had keel depths greater than 100 m. To improve on the equations found in Table 3, the relationship between keel cross-sectional areas at adjacent depths were examined. That was done for layers below the depth of maximum width, which produced the highest correlation (i.e. given the cross-sectional area of the upper layer, the lower layer may be calculated from a linear relationship - see Figure 9). Areas near the bottom of the berg were excluded (to remove the effect of partial keel projection into a layer depth). The resulting equation was:

$$A_L = 0.961A_U + 111.67 \quad (9)$$

where A_L is the cross-sectional area of the lower layer and A_U is that of the upper layer. Figure 10 shows a plot of the relationship between the areas of each two adjacent layers. From Equation (9), simulated keel areas for depths larger than 100 m were generated, and then used to refine equations describing the areas of sections of the keel up to 200 m in depth. Table 5 shows the effects of these modifications on the equations for vertical cross-sectional area with length. These changes helped to better define iceberg drift in the CIS model.

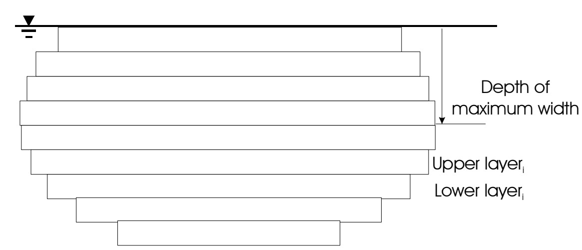

Figure 9: Variables used to study the relationship between cross-sectional areas at adjacent depths, below the depth of maximum iceberg width.

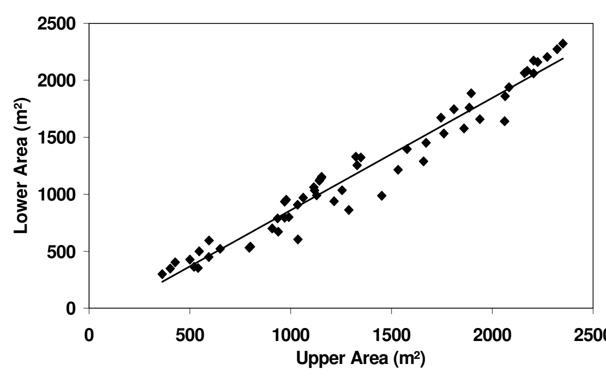

Figure 10: Relationship between cross-sectional areas at adjacent layers, below the depth of maximum iceberg width

Table 5: Modified vertical cross-sectional area parameters

	Depth (m)	a(k)	b(k)
Layer 1	0-10	9.5173	-25.94
Layer 2	10-20	11.1717	-107.50
Layer 3	20-30	12.4798	-232.01
Layer 4	30-40	13.6010	-344.60
Layer 5	40-50	14.3249	-456.57
Layer 6	50-60	13.7432	-433.33
Layer 7	60-70	13.4527	-519.56
Layer 8	70-80	15.7579	-1111.57
Layer 9	80-90	14.7259	-1125.00
Layer 10	90-100	11.8195	-852.90
Layer 11	100-110	11.3610	-931.48
Layer 12	110-120	10.9202	-1007.02
Layer 13	120-130	10.4966	-1079.62
Layer 14	130-140	10.0893	-1149.41
Layer 15	140-150	9.6979	-1216.49
Layer 16	150-160	9.3216	-1280.97
Layer 17	160-170	8.9600	-1342.95
Layer 18	170-180	8.6124	-1402.52
Layer 19	180-190	8.2783	-1459.78
Layer 20	190-200	7.9571	-1514.82

CONCLUSIONS

This paper documents an analysis of iceberg geometry. The objective was to improve the accuracy of estimating water and air drag forces on iceberg, which, in turn, would improve the forecasts of iceberg drift. The present analysis is the first to establish a detailed description of keel width variation with depth. It also provides reliable estimates of sail cross-sectional areas, and iceberg mass. The preceding analysis has primarily relied on the data of Smith and Donaldson (1987), which was the most complete and detailed information on iceberg geometry, drift, and environmental conditions available. These data were supplemented with other relevant information from various sources.

The analysis showed that geometry information could be adequately described using waterline length of the iceberg. That finding is particularly useful since waterline length is relatively easier to observe than other attributes of an iceberg. The mass and cross-sectional area of the sail were related to waterline length. For the keel, areas of sections, each 10 m in depth, were determined as linear functions of the length. Correlation was relatively high for all the formulas obtained in this analysis. Further refinement of the initial analysis correlated the areas of adjacent layers of the keel. That correlation was the basis for extending the data to describe keel geometry for larger depths (>100m), where the data is relatively sparse.

The present results are used in an operational iceberg forecasting model. Ongoing work aims at further validation of the results. Additionally, further data is being acquired through data mining and from profiling studies conducted in 2002 and 2003. This new data will hopefully cover waterline length values beyond those of Smith and Donaldson (1987) and would be of particular interest to add to this study. This would increase the confidence in the present analysis.

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