Geometry and Mass of Icebergs in the Russian Arctic

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ABSTRACT

In this paper, empirical relationships are derived to determine the mass and geometry of icebergs based on instrumental measurements and airborne data in the Barents, Kara and Laptev Seas. This work was performed during research expeditions conducted by Arctic and Antarctic Research Institute together with Rosneft Oil Company and Arctic Research Centre in 2012-17. The authors give regression dependencies between: 1D parameters of icebergs (length, width, height, draft); linear and area parameters of icebergs (cross section area of the above and underwater parts of icebergs); linear iceberg parameters and its volume and mass. Obtained empirical relations for the iceberg geometry and mass can be used to simulate the drift of icebergs and to estimate their impact on offshore structures and vessels.

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

INTRODUCTION

Icebergs present a serious danger for navigation, production and transportation of minerals in the offshore area. Provision of safe man activity on the shelf of the Arctic Seas requires development of a complex system of measures for detection, monitoring and forecasting of the drift of icebergs and risk assessment. The systems of forecasting and monitoring of motion of dangerous ice features are based on the numerical model of the drift of icebergs. The modern numerical model of the drift of icebergs presents a system of motion equations taking into account the impact on icebergs of wind, currents, water resistance, sea level tilt, sea ice impact, wind wave, soil and the Coriolis force (Klyachkin, May, 2012; etc.).

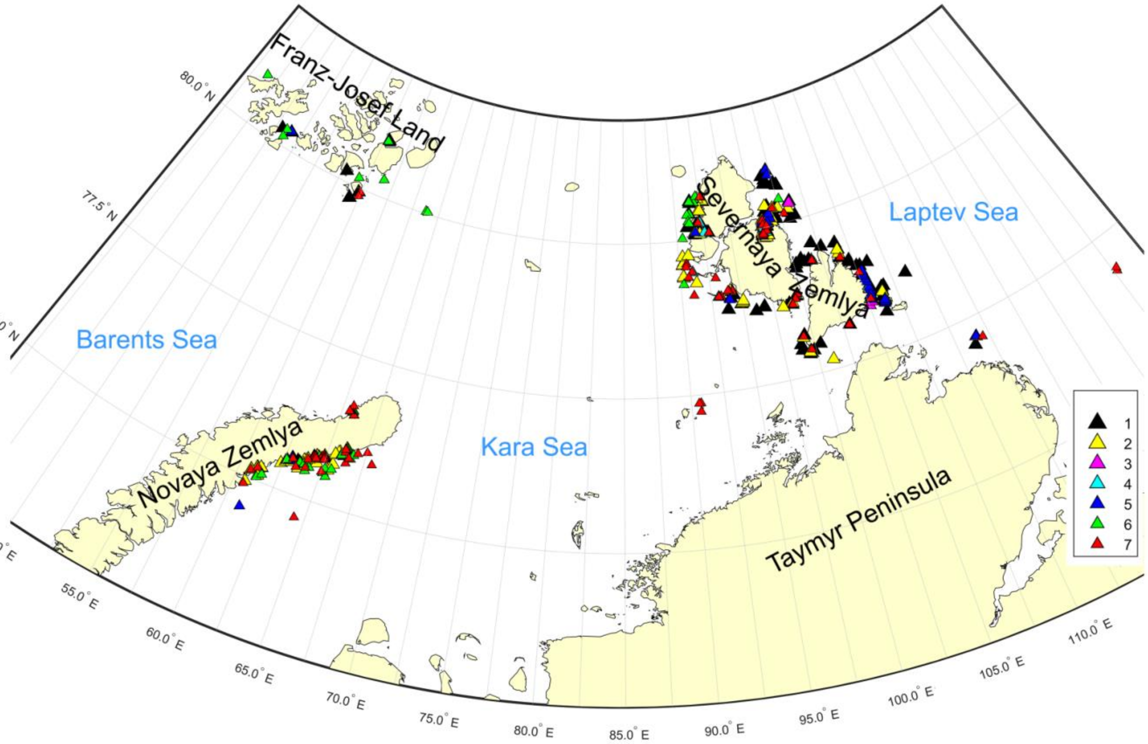
The wind impact force is comprised of tangential and normal stresses and hence for calculation of this force it is necessary to know the area of cross- (vertical) section Sva and the area of horizontal section Sha (iceberg area by waterline) of the iceberg above water part. To determine the water resistance force it is necessary to know the area of vertical cross-section of the iceberg underwater part Svw. Forces determined by the ice cover and wind wave impact are calculated depending on the iceberg linear dimensions (length L or width W). Finally, the force of soil impact on the iceberg depends on the sea depth and iceberg draft (D). So, for prognostic or diagnostic iceberg drift calculation one has to know the iceberg mass (M) and its following geometric parameters: L, W, D, Sva, Svw, Shw.

At present for detection of ice targets more often one uses satellite images at different electromagnetic spectrum ranges , which allow instantaneous coverage of a large area inaccessible for ship surveys. However from high-resolution satellite images one can estimate only the horizontal iceberg dimensions. For iceberg management objectives (including online use of the iceberg drift model) one needs the statistical regularities connecting the linear size of the above-water part with other iceberg parameters (normal and tangential drag, draft depth and mass).

MEASUREMENTS OF GEOMETRIC PARAMETERS OF ICEBERGS

As commissioned by the Rosneft Oil Company, the AARI made 12 comprehensive expeditions from 2012 to 2017 in the Russian Arctic Seas. One of the expedition goals was study of spatial distribution of icebergs, drift characteristics and assessment of their geometric size.

The expeditions were carried out onboard special research vessels, equipped with a helipad, small craft and ship radars. In the course of these expeditions, search of icebergs was based on satellite information reported to the ships, helicopter reconnaissance flights and ship radar and visual observations from the bridge. After iceberg detection, its coordinates and detection time were recorded and iceberg size and type were assessed visually. The iceberg type was determined visually by the shape of the sighted feature according to the national sea ice nomenclature (Sea-ice nomenclature …, 1974; Kazanskiy, Egorova, 1988). Icebergs in this nomenclature are subdivided by shape into the following types: tabular, wedged, dome, dry dock, pinnacle, weathered, bergy bit and growler. The indicated classification of icebergs coincides to some extent with the adopted international classification of icebergs of the World Meteorological Orgaization (WMO Sea Ice Nomenclature, 2014). The only important difference of the national sea-ice nomenclature is that tabular and blocky bergs in it belong to one and the same type.



1 – Tabular, 2 – Wedged, 3 – Dome, 4 - Dry Dock, 5 – Pinnacle, 6 - Weathered, 7 - Bergy bits and Growlers
Fig. 1. Geographical location and types of measured icebergs.

After determination of the iceberg coordinates and visual assessment of its size and type, the instrumental measurements of geometry of the above water and underwater parts were performed.

For determination of morphometric parameters of the above water part of icebergs, stereo-aerial photography was performed using special equipment mounted on helicopters and unmanned aircraft (Pavlov, et. al. 2018). Based on the obtained series of stereo photos one determined using specialized software the three-dimensional coordinates of the iceberg sail surface. By a three-dimensional field of points of the above water part of iceberg surface, three-dimensional digital models of surveyed icebergs were constructed, using which one estimated the linear dimensions (length (L), width (W), height (H), average height (Hm)), iceberg area by waterline (Sha) and volume of the above water part.

For examination of the underwater iceberg parts, a sonar survey by means of multi-beam echo sounder from small-size craft was performed. The small-size craft was lowered from the ship and made not less than two circles around an iceberg (as a rule, 3-5 circles were performed) at speeds of 3-4 knots at distances of 40-60 m or 70-120 m from an iceberg depending on its size (Pavlov, et. al. 2018). As a result of examination of the iceberg keel by a multi-beam echo sounder, a three-dimensional cloud of points of the iceberg lower surface relief was obtained using which a three-dimensional digital model of the iceberg keel based on special software packages was reconstructed. By this three-dimensional model, the draft (D), areas of random sections, volume and other geometric parameters were estimated.

As measurements of geometric parameters of the above water and underwater parts of iceberg require different labor efforts, a significant Imbalance is noted in the database of measurements of iceberg parameters: the number of measured sails exceed by 24 times the number of measured keels. In total for 2012-2017 using stereo-aerial photography, 599 sails of icebergs were surveyed, and by means of underwater echo sounding, only 25 keels of icebergs were measured

Figure 1 shows a geographic location of icebergs which were detected and surveyed in 2012-2017 at the time of the AARI expedition activities. As can be seen from the Figure, by the spatial location of icebergs one can identify icebergs that were calved from glaciers of Novaya Zemlya, Severnaya Zemlya and the Franz-Josef Land. In the area of Severnaya Zemlya Archipelago there were surveyed 395 icebergs (66%), 168 (28%) of measured icebergs originated from Novaya Zemlya glaciers and about 5 % (27 icebergs) were sighted in waters of the Franz Josef Land. The other small part of examined targets was observed at a significant distance from glaciers of the indicated archipelagos.

Of 599 icebergs, 217 (36%) targets were identified as tabular bergs (the National Nomenclature also includes block bergs into this category), 133 (22%) targets were determined as wedged bergs. The number of detected icebergs referred to the types dome and dry dock was 8 (about 2% in total), pinnacle - 52 (9%), 64 (11%) weathered bergs and 113 bergy bits and growlers (19%).

The distribution of measured icebergs by size showed the following: measurements of 171 (29% of the total number of targets) of small bergs and bergy bits (length up to 60 m), 206 (34%) medium bergs (length of 60-120 m), 105 (17%) large bergs (length of 120-200 m), and 117 (20%) very large (length of more than 200 m) were included to the database.

It should be noted that all estimates of probabilistic characteristics of size and type of icebergs presented in the article, are determined only for instrumentally measured icebergs (599 targets). We have not used information of en-route visual observations for determination of icebergs by types and size. We assume that sampling of icebergs, for which aerial photography was performed, does not necessarily coincide with the real distribution of types and geometric parameters of all icebergs. This can be explained by the fact that the number of surveyed icebergs was limited by the planned time of aerial photography and weather conditions and therefore as numerous targets were available, preference was given to larger icebergs.

STATISTICAL CHARACTERISTICS OF LINEAR DIMENSIONS OF ICEBERGS

The main objective of the study is to find the empirical dependencies between the linear dimensions of the iceberg above water part and other geometric parameters, which are necessary to prescribe in the numerical drift model. The predictor in these empirical dependencies is the iceberg length – the parameter, which is most simple to measure from the review of satellite images and instrumental and visual ship- or airborne observations.

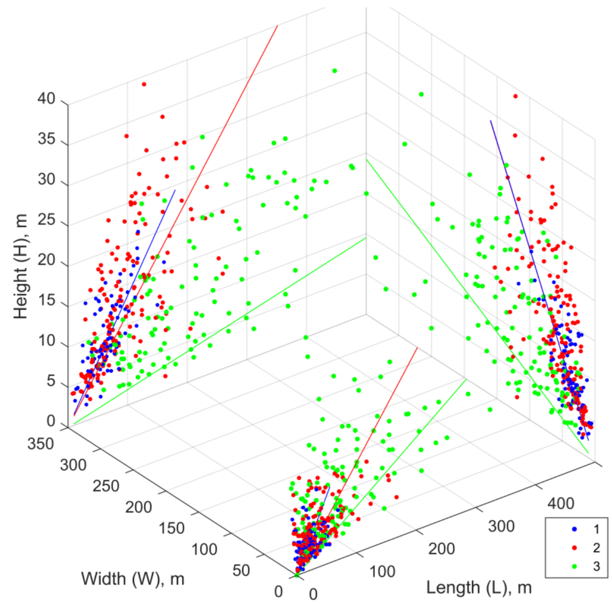
It is obvious that the regression equations cannot be universal for all dimensions and types of icebergs and all parts of the water area. To reveal the factors, which influence the distributions of linear dimensions of icebergs, the scatter plots were constructed in six-dimensional space (iceberg length, width, height, type by size, type by shapes and different water areas).

A comparative analysis of probabilistic characteristics of the linear dimensions of icebergs showed the icebergs formed by glaciers of Severnaya Zemlya and the Franz-Josef Land to have similar features, while icebergs of Novaya Zemlya in the Kara Sea differ significantly by their parameter. Icebergs in the Kara Sea have smaller dimensions and their significant part belongs by their dimensions to bergy bits and small bergs. Besides, differences in the length distribution of icebergs of different types were revealed.

The indicated regional differences have been known for quite a long time (Sailing Directions, 1992; Conditions…, 1988). Between the morphometric parameters of iceberg and glacier from which it originated there are specific dependencies, determined primarily by the prevailing type of glaciers at the archipelago (ice domes or outlet glaciers located in fjords). According to studies of Dowdeswell (Dowdeswell, 1989), the largest tabular bergs (several hundred meters in cross-section) are generated by ice shelfs and ice domes and their number is not as a rule large. The outlet glaciers situated in fjords produce icebergs of smaller size and frequently of irregular shape. It seems that depths at the fronts of glaciers also restrict the maximum dimensions of icebergs.

Systematization and generalizations made by Dowdeswell for the glaciers of Spitsbergen seem to be extremely important for understanding the morphometric peculiarities of icebergs formed and can be applicable to all sources of icebergs of the Eurasian Arctic. These generalizations are in good agreement with different descriptions of icebergs made at different time near Spitsbergen, Novaya Zemlya, FJL and Severnaya Zemlya (Sandford, 1955, Zubakin et al., 2006; Buzin et al., 2008). Thus the outlet glaciers of Russkaya Gavan' and Inostrantsev Bays in the northern part of Novaya Zemlya that have strong front crevassing form a moderate number of small and medium bergs of irregular shape (see in particular - Buzin, Glazovsky, 2005). Ice domes of the FJL and Severnaya Zemlya are characterized by generation of tabular bergs (Zubakin et al., 2007; Dowdeswell et al., 2002; Mironov et al., 2012).

Taking into account the above noted peculiarities we think it is advisable to calculate the probabilistic characteristics separately for tabular bergs and icebergs of other types. It is remarked that such classification is already used by the International Ice Patrol (IIP) and the Canadian Ice Service (CIS). In the IIP classification two types of icebergs are identified: tabular and non-tabular bergs. The non-tabular bergs are subdivided into sub-types, which are considered as independent types in the WMO classification (Manual of Standard Procedures, 2005).



1 – Icebergs of Novaya Zemlya. 2 – Non-tabular bergs in the area of Severnaya Zemlya and the Franz-Josef Land. 3 - Tabular bergs in the area of Severnaya Zemlya and the Franz-Josef Land.

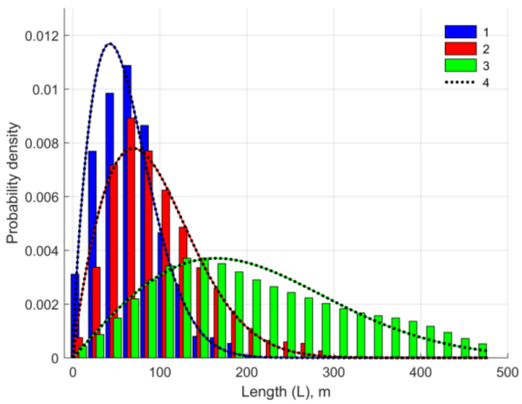
Fig. 2. 3D scatter plot and lines of regression dependencies between the parameters of linear dimensions of icebergs

As glaciers of Novaya Zemlya do not produce tabular bergs, only three groups of icebergs are identified in our study: icebergs of Novaya Zemlya of the Kara Sea and icebergs calved from glaciers of the Franz-Josef Land and Severnaya Zemlya, which are subdivided in turn into tabular and non-tabular bergs. Correctness of such division of the database into three groups is confirmed by the 3D scatter plot of linear dimensions of icebergs (Fig. 2.).

Table 1. Statistical characteristics of iceberg length by waterline (m) measured in the AARI expeditions in 2012-2017.

		All regions	Novaya Zemlya	Severnaya Zemlya and the Franz-Josef Land	
				Non-tabular	Tabular
Mean		121	61	93	205
Std		95	36	53	109
Quantile	p=0.05	22	12	30	63
	p=0.25	56	34	55	121
	p=0.50	90	57	79	177
	p=0.75	157	80	120	280
	p=0.95	344	118	198	410

Estimates of the probabilistic characteristics of linear dimensions of icebergs in the identified three groups are presented in Table 1 and in Fig. 3.



1 – Icebergs of Novaya Zemlya. 2 – Non-tabular bergs in the area of Severnaya Zemlya and the Franz-Josef Land 3 - Tabular bergs in the area of Severnaya Zemlya and the Franz-Josef Land 4 – Approximation of empirical distributions by Weibull's function

Fig. 3. Empirical (colored strips) and theoretical (dashed lines) functions of density function distribution of the probability of length of icebergs

Figure 3 presents kernel estimates of the empirical distribution density of probabilities of the linear dimensions of icebergs. All three groups of icebergs have a uni-modal function of the distribution density of probabilities with a positive asymmetry. The mode values of the distribution density of probabilities of the length of icebergs are at the range of 50-80 m for non-tabular bergs and at the range of 120-140 m for tabular bergs. The selection of theoretical distributions showed the empirical function of the distribution density of probabilities of iceberg lengths (L) to be well described by the Weibull's distribution:

$$f(L) = \frac{\mu}{\lambda}\left(\frac{L}{\lambda}\right)^{\mu-1} \exp\left(-\left(\frac{L}{\lambda}\right)^{\mu}\right), \qquad (1)$$

where λ – scale coefficient and μ - shape coefficient. For icebergs of Novaya Zemlya the scale coefficient λ=68, the shape coefficient μ =1.76. For non-tabular icebergs of Severnaya Zemlya and the Franz-Josef Land λ=105, μ =1.86, and λ=232, μ =2.01 for tabular icebergs.

METHODS OF APPROXIMATION OF GEOMETRICAL PARAMETERS OF ICEBERGS

In our work we will follow the same methodology of compiling empirical ratios as in (Barker, et al. 2004). We shall consider that the empirical ratios connecting the linear dimensions of iceberg with the mass or geometry of icebergs should have coincidence of physical dimensions: linear connection for linear measurements, quadratic – for areas and cubic for volumes. Such dependencies can be expressed only by the power function

$$\hat{Y} = k \times L^n, \qquad (2)$$

where $\hat{Y}$ – reconstructed values of iceberg parameter, *k* – sought for coefficient, connecting the iceberg length L with parameter $\hat{Y}$; n=1 – for linear characteristics (width, height, draft), n=2 - for quadratic characteristics (areas of different iceberg sections), n=3 – for three-dimensional characteristics (iceberg volumes and mass).

One can derive the formula of calculation of k coefficients at the known function in advance using the least-squares method:

$$\mathrm{k} = \frac{\sum Y \times L^n}{\sum L^{2\times n}}, \qquad (3)$$

where Y and L – known from measurements parameters of geometry of iceberg and iceberg length.

As quality estimates of the established dependencies one can use: coefficient of determination (R^2):

$$\mathrm{R}^2 = 1 - \frac{\sum(Y-\hat{Y})^2}{\sum(Y-\bar{Y})^2}, \qquad (4)$$

where $\bar{Y}$ – average value of measured parameters, root-mean-square error (RMSE):

$$RMSE = \sqrt{\frac{\sum(Y-\hat{Y})^2}{N}}, \qquad (5)$$

mean absolute error (MAE):

$$MAE = \frac{\sum|Y-\hat{Y}|}{N}. \qquad (6)$$

The statistical significance of regression coefficient k was determined by the Student's criterion (t-test), the significance of the regression equation itself was determined by the determination coefficient and Fisher's criterion (F-test), the significance level for both tests was prescribed equal to α = 0.05. All regression equations presented below in this article are statistically significant (i.e. with 95% probability the coefficients *k* and R^2 are not equal to 0).

EMPIRICAL RATIOS, DETERMINED FROM DATA OF AIRBORNE STEREO PHOTO SURVEY

Regression ratios between the iceberg length and width

In some cases, sea ice can influence icebergs. The ice impact force is proportional to the contact area between ice and iceberg. This area can be determined as a product of ice thickness and linear sizes of iceberg ($S_i=h_i \times L$ or $S_i=h_i \times W$). It is likely that neither the maximum distance between the iceberg tips (iceberg length), nor the distance orthogonal to it (iceberg width) will coincide with the iceberg motion direction relative to ice. In our opinion, it is reasonable to use some average parameter, which can be called an average iceberg diameter $2\times R=(L+W)/2$, and determine the area of iceberg/ice interaction by formula

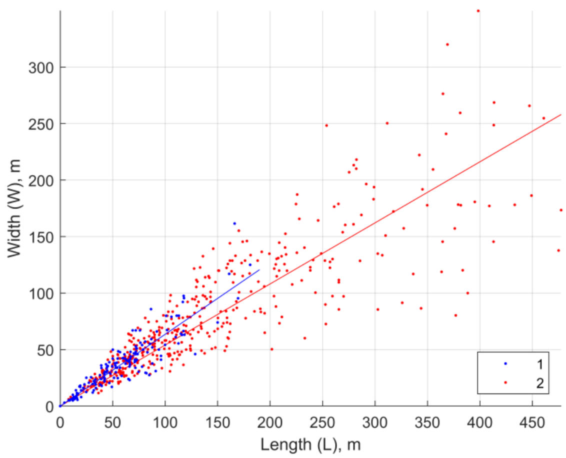
$$S_i=h_i \times (L+W)/2 \qquad (7)$$

A similar parameter, showing an average linear size, is used for determining the impact force of waves on iceberg. Thus for calculation of forces connected with linear dimensions of iceberg, it is reasonable to find the regression ratios between the iceberg length and width (Fig. 4).

For icebergs from Novaya Zemlya of the Kara Sea the width is determined by the ratio:

$$W = 0.64 \times L \qquad (8)$$

The accuracy of this approximation can be estimated by the determination coefficient values (R^2), root-mean-square error (RMSE) and the average absolute error (MAE) (equations 4~6): R^2=0.81, RMSE=11 m, MAE = 8 m.



1 – Icebergs of Novaya Zemlya. 2 – Icebergs in the area of Severnaya Zemlya and the Franz-Josef Land.
Fig. 4. Scatter plot of the iceberg length and iceberg width. Lines are values, calculated by regression equations 8 and 9.

For icebergs from Severnaya Zemlya and the Franz-Josef Land the regression coefficient for the iceberg width has the form

$$W = 0.54 \times L \quad (9)$$

For this equation the following estimates of the approximation quality were obtained: R^2=0.72, RMSE=29 m, MAE = 20 m.

Regression ratios between the iceberg length and height

The regression equation connecting the iceberg length with height strongly depends on the iceberg shape. The best coincidence with the height values of non-tabular icebergs gives formula (2) with coefficient value k=0.13 with the determination coefficient comprising only 0.11-0.22. The coefficient k of regression equation for the heights of tabular icebergs is equal to 0.05 at the determination coefficient of 0.18. The low quality of regression equations between the iceberg length and height makes it reasonable to use mean ratios between the iceberg length and height.

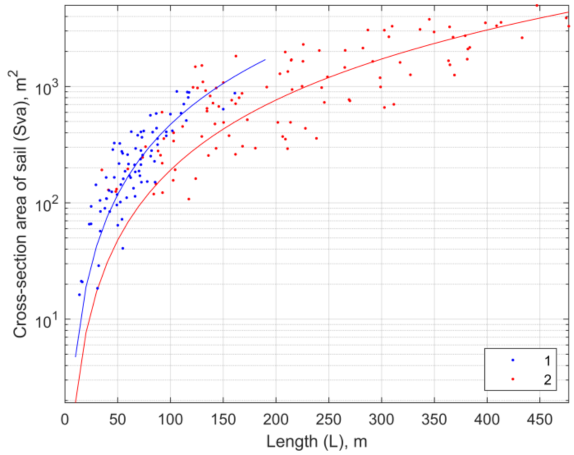
Regression equations for the iceberg sail cross-section area

One of the important parameters for calculation of the drift of icebergs is the sail cross-section area, which is influenced by wind. In our study the iceberg normal drag area is determined as a product of iceberg mean height and mean diameter. The iceberg mean height is calculated from data of airborne stereo photography.

The regression equation for the sail front cross-section should have a form of power function with a power of 2. The coefficient *k* in equation 2 was estimated by the least-squares method. Analysis of the change of the regression coefficient for different groups of icebergs showed it to be advisable to combine tabular and non-tabular bergs calved from glaciers of the Severnaya Zemlya and Franz-Josef Land archipelagos. Thus for icebergs of Novaya Zemlya to the Kara Sea the following expression was derived (Fig. 5):

$$S_{va} = 0.0472 \times L^2 \quad (10)$$

This equation has the following estimates of quality: R^2=0.68, RMSE=125 m^2, MAE = 88 m^2.



1 – Icebergs of Novaya Zemlya. 2 – Icebergs in the area of Severnaya Zemlya and the Franz-Josef Land.
Fig. 5. Scatter plot of the iceberg sail length and cross-section area. Lines denote the values calculated by regression equations 10 and 11.

For icebergs from Severnaya Zemlya and the Franz-Josef Land the following expression was obtained:

$$S_{va} = 0.0191 \times L^2 \quad (11)$$

Estimates of the accuracy of this equation have the following indicators: R^2=0.66, RMSE=638 m^2, MAE = 492 m^2.

Regression equations for the horizontal area of iceberg by waterline

One of the forces in the iceberg motion equation takes into account the tangential wind impact. For calculation of the impact of this force one takes into account the iceberg horizontal area by waterline. This parameter is directly determined from data of airborne stereo photography. A comparative analysis of dependence of the iceberg horizontal area by waterline on the length did not show differences between the icebergs of different geographical origin and types. Therefore it is reasonable to use the entire dataset without dividing it by groups (Fig. 6).

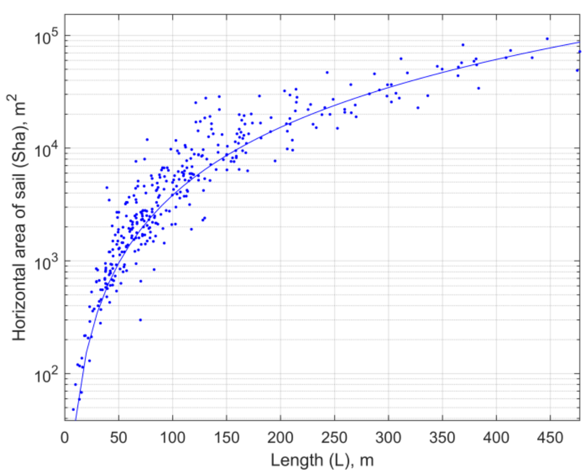


Fig. 6. Regression ratios between the iceberg length by waterline and its horizontal area. Line shows the values calculated by regression equation 12.

The regression equation connecting the length (L) and area S_{ha} has the form:

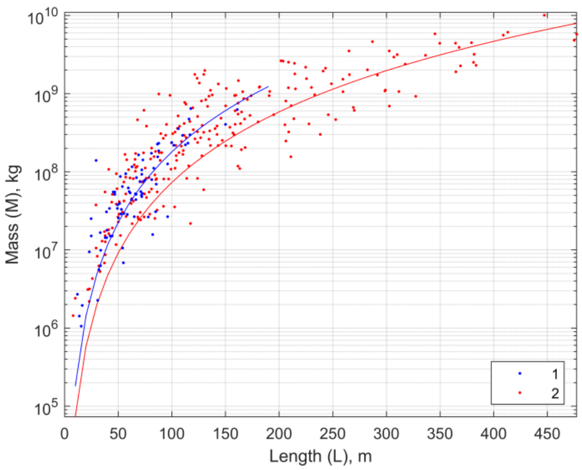
$$S_{ha} = 0.3828 \times L^2 \quad (12)$$

The determination coefficient (R^2) of this equation is equal to 0.85 and errors have the following values: RMSE=5590 m^2, MAE = 2888 m^2.

Regression ratios between the iceberg length and mass

The stereo aerial-photography survey makes it possible to estimate not only the iceberg sail linear dimensions (length, width, height), but also to create a 3-dimensional digital model and estimate the volume of the iceberg above water part. Unlike the ratio between the iceberg height and draft the ratios of the iceberg sail/keel volumes should correspond to the Archimedes buoyancy law at condition of iceberg being in drift. Knowing the ice and seawater densities we can calculate, by the volume of the above water part, the volume of the underwater part and the volume of the whole iceberg. The iceberg mass was determined as a product of ice density and the total volume of iceberg.

For all 599 surveyed features the volumes and masses were calculated. Based on these data the coefficient of regression equation to the third power was obtained for icebergs of Novaya Zemlya of the Kara Sea and icebergs of Severnaya Zemlya and the Franz-Josef Land (Fig. 7).



1 – Icebergs of Novaya Zemlya. 2 – Icebergs in the area of Severnaya Zemlya and the Franz-Josef Land.
Fig. 7. Regression ratios between the iceberg length and mass. Lines show the values calculated by regression equations 13 and 14.

For icebergs of the southwestern area of the Kara Sea the following equation was derived by the least-squares method:

$$M = 0.1975 \times L^3 \times \rho_i, \quad (13)$$

where ρ_i – ice density (ρ_i ~ 900 kg/m^3). Equation 13 has the following estimates of the quality of approximation: R^2=0.71, RMSE=75480 kg, MAE = 43860 kg.

For the rest of icebergs the mass is connected with the length by the following equation:

$$M = 0.0802 \times L^3 \times \rho_i \quad (14)$$

The determination coefficient of equation 14 is equal to 0.70, RMSE=792625 kg, MAE = 450470 kg.

EMPIRICAL RATIOS DETERMINED FROM DATA OF UNDERWATER ECHO SOUNDING

As a result of the expeditions in 2012-2017, the underwater parts of icebergs were also measured by means of sonar surveys using a multi-beam echo sounder. A total of 25 keels of icebergs located near the Severnaya Zemlya and the Franz-Josef Land Archipelagos were measured. For 23 icebergs it was possible to match the data of underwater echo sounding and airborne stereo photography (Fig. 8).

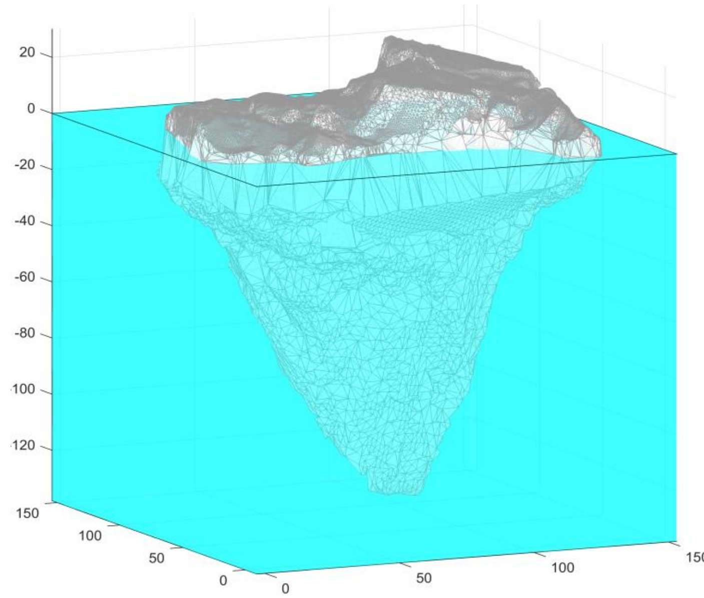


Fig. 8. Example of three-dimensional digital model of iceberg obtained from combined data of airborne stereo photography and underwater echo sounding.

The iceberg draft was determined as a distance between the waterline and the most distant from the waterline keel point estimated from data of underwater echo sounding. The average draft value of all 25 measured icebergs was 52 m, the maximum measured draft was 133 m and the minimum draft value was - 19 m. The standard deviation of the draft of measured icebergs is equal to 23 m with quartiles equal to $Q(_{p=0.25})$=37 m, $Q(_{p=0.75})$=63 m and median to 49 m.

Ratio between the linear dimensions of iceberg sail and draft

The average ratio of the iceberg max height to draft comprises 0.28, i.e., the iceberg draft is on average greater than its max height by 3.6 times. The ratio of the averaged iceberg height calculated from data of airborne stereo survey to the draft yields the average value of 0.14, which means that the iceberg draft is by 7.4 times greater than the iceberg average height. The latter value is more close to the theoretical ratio between the iceberg height and draft.

The iceberg length-to-draft ratio ranges from 0.83 to 5.35 and on average the iceberg length is twice as large as the draft. If one excludes from consideration a very large iceberg (more than 200 m long), the regression equation connecting the iceberg draft and length will have the form:

$$D = 0.52 \times L \quad (15)$$

The determination coefficient R^2 is equal to only 0.37, the root-mean-square error is equal to 19 m and the mean absolute error is 14 m.

Approximation of the iceberg keel area

The determination of the keel cross-section area for different sea depth level is necessary for correct taking into account the impact on iceberg of non-uniform by vertical currents. The iceberg underwater part has a complicated relief, which is practically impossible to approximate by the analytical function. This article analyzes the cross-section areas in the layer of prescribed thickness rather than the iceberg keel profiles.

The calculation of the iceberg keel cross-section areas was performed using the following algorithm. Separate surface points of the iceberg sail and keel were combined into a general 3-dimensional digital model. The keel area where the wind wave did not make it possible to determine the iceberg relief by hydro-acoustic methods was supplemented by information of three-dimensional interpolation. The obtained digital three-dimensional model of the iceberg keel (Fig. 8) was subdivided into the layers of equal thickness. For each layer the average weighted contour was determined by which the average contour diameter was calculated (Fig. 9).

The product of the average keel contour diameter and the layer thickness yields the iceberg keel area in the given layer. A set of cross-section areas presents a function from the distance between the waterline and the depth of location of the layer under consideration. The procedure described can be expressed as follows: a complex asymmetric shape of iceberg is approximated by a complex symmetric solid of revolution. The vertical distribution of the cross-section areas and volumes in the layer of prescribed thickness is preserved.

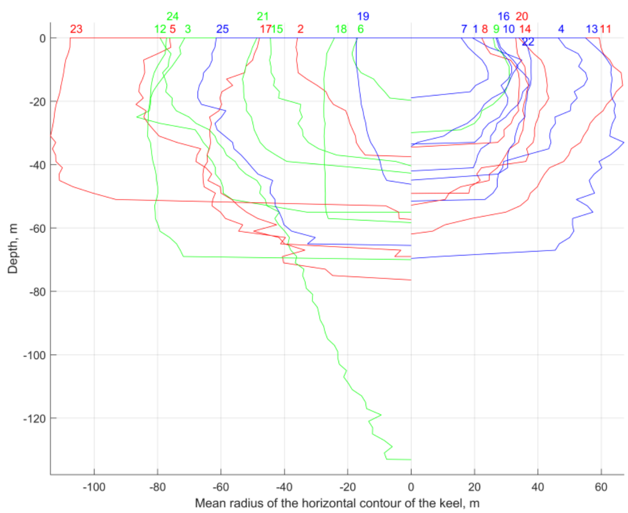


Fig. 9. Distribution by depth of average keel diameters of icebergs. Figures indicate the conventional numbers of icebergs.

As can be seen from Figure 9, we can conventionally subdivide icebergs by the keel shape into three groups: 1) icebergs in which the cross-section area does not change with depth (rectilinear keel), 2) icebergs in which the cross-section area decreases with depth (triangular keel) and 3) icebergs in which the cross-section area increases to some depth and then decreases to the draft depth (rhombic keel).

Of 25 targets, 3 icebergs have a triangle keel shape (targets No. 2, 12, 15), 6 targets (18, 19, 21, 22, 23, 24) have a rectilinear shape of the underwater part and the rest 16 icebergs have a keel with the maximum width at some depth. One of the targets (iceberg No. 23) strongly differs by its geometric parameters from the rest of the icebergs – by the length/draft ratio this feature looks more as an ice island. Therefore target No. 23 was excluded from data on which basis the regression equation between the iceberg length and keel cross-section area was derived. The total keel cross-section area is connected with the iceberg length by the following equation (Fig. 10):

$$S_{vw}^{tot} = 0.3652 \times L^2 \tag{16}$$

The derived regression equation has the determination coefficient of 0.76 and the following estimates of errors: RMSE= 1562 m^2, MAE = 1145 m^2.

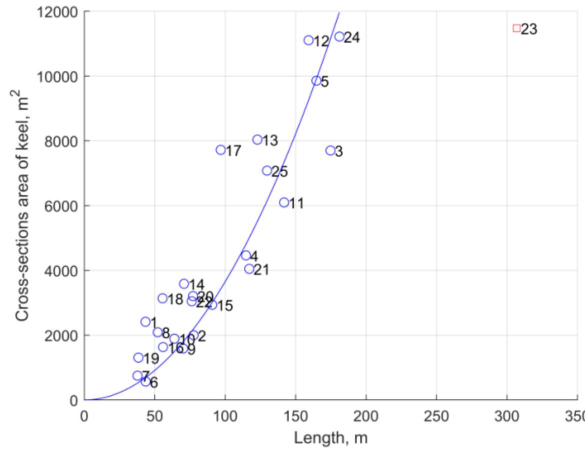


Fig. 10. Regression ratios between the iceberg length and the total keel cross-section area. Line denotes the values calculated by regression equation 16.

The empirical equation of reconstruction of the total keel cross-section area has a much higher quality of approximation compared to the equation for iceberg draft reconstruction. Therefore we recommend one to calculate the total keel cross-section area and then depending on the assessment of the iceberg draft and keel shape to distribute the total keel area by layers of numerical hydrodynamic model (*l*):

$$S_{vw}(l,\ \Delta h) = S_{vw}^{tot} \times \beta, \tag{17}$$

where $\beta(l,\ \Delta h(l))$ – distribution function of the total keel cross-section area by layers *l* and thickness Δh, $\sum_{l=1}^{D} \beta(l,\ \Delta h(l)) = 1$.

For icebergs with the keel rectilinear shape the total area of the keel front resistance is uniformly divided into the number of layers. For icebergs with the triangle shape of the underwater part, the function $\beta(l,\ \Delta h(l))$ decreases with depth.

CALCULATION OF THE CONFIDENCE INTERVALS OF THE DRIFT TRAJECTORY DETERMINED BY ICEBERG PARAMETERS

As the regression ratios were determined by the least-squares method, the approximation errors have a normal distribution, the values of which can be reconstructed by mean and standard deviation. The mean value will be the value of iceberg parameter reconstructed by the regression equation and the root-mean square error (RMSE) can serve as an estimate of the root-mean-square deviation. It is more likely that the suggestion about the uniformity of the root-mean square error for the entire series L in the derived regression equations does not correspond to reality: on the scatter plots (Fig 4-7) one can note that scattering of points relative to the regression equation line increases with the increase of the iceberg length. It is obvious that at the iceberg length close to zero, the mean and root-mean-square deviation of all iceberg parameters should also tend to zero. Based on this, we can suggest that the function of the change of root-mean-square deviation (RMSD(L)) can be estimated by means of the regression analysis of errors or based on the suggestion of linear model of the RMSD function change. After determining the mean value (by equations 8~17) and standard deviation of all necessary iceberg parameters of prescribed length, we can calculate the confidence intervals of the drift trajectory, determined by changes of the iceberg mass and geometric parameters.

We have developed two methods of calculation of confidence intervals of the iceberg drift trajectory. The first calculation method is based on modelling three iceberg trajectories: first trajectory is calculated for an iceberg with the average mass and other parameters; second trajectory is calculated for an iceberg with parameters contributing to the maximum drift (minimum mass, maximum areas of horizontal and cross-sections); third trajectory is calculated for icebergs with parameters contributing to the minimum drift. The mass and geometric parameters of icebergs of the second and third trajectories are calculated by a normal law of the distribution of probabilities at the prescribed confidence interval. The iceberg drift trajectory with the average mass and geometric parameters will be considered as an average trajectory and its confidence intervals of prescribed probability will be determined by circles inscribed between the points of extreme drift trajectories. The second calculation method of confidence intervals of the iceberg trajectory is based on numerical drift modelling of multiple targets, the parameters of which are calculated by the Monte-Carlo method by the normal distribution law and the known values of their mean and standard deviation. The mean value of iceberg coordinates will correspond to one of the points of average trajectory. The isoline of 2D probability density of iceberg's coordinates can be interpreted as a boundary within which there will be located a prescribed portion of all simulated icebergs.

Testing of the described methods of calculation of the confidence intervals of the drift trajectory of icebergs will be made in a series of subsequent articles devoted to operational prognostic modeling of the drift of dangerous ice features.

CONCLUSIONS

Based on the statistical analysis of the set of measurements of geometric dimensions of icebergs, the functions of the distribution of probabilities of linear dimensions for icebergs of different origin and different shapes were estimated. For each group of icebergs the regression ratios connecting the iceberg linear size with its other parameters were determined, which should be by all means taken into account in the drift model (horizontal iceberg area by waterline, average sail cross-section area, average keel cross-section area at different horizons, iceberg draft).

The reconstruction of all necessary iceberg characteristics only by its length can be compared with determination of the height, age and weight of man by the size of its footprints. In spite of the fact that the accuracy of the obtained regression dependencies between the length and other iceberg parameters is far from being ideal, the derived equations are probably the only information source for implementation of the numerical model of the drift of icebergs.

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