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ON THE SIZE DISTRIBUTION OF ANTARCTIC ICEBERGS

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ABSTRACT

Composites are given of six reported Antarctic iceberg size distributions and theoretical Rayleigh distributions are fitted with reasonable small errors. A modal length of 0.4km is found for observations in East Antarctica; this increases to 0.7km when size data for icebergs observed by satellite in or near the pack ice in the Bellingshausen Sea are added. Results of model investigation of the equilibrium or standing population size distribution, based on the Gordienko observations of sizes near the Amery Ice Shelf as initial conditions and annual input together with the constraints of uniform sidewall wastage rate and that length/width ratios be maintained within the range 1.1 to 2.2 by iceberg fracturing into equal parts, show a distribution much unlike the Rayleigh in that the highest probability of occurrence is of icebergs of widths 0 - 0.2km. The model size distribution attains equilibrium after 21 years, at which time it is fitted very well to a Weibull distribution with parameters $\beta = 0.5, \eta = 1.6$ and $\gamma = 0$. A method is outlined by which the size distribution of freshly-calved icebergs might be assessed for use as the initial condition to such models.

INTRODUCTION

There are now available a number of reported distributions of iceberg sizes in Antarctica, some based on lengths and others on widths. The majority of these are reported by Russian authors and are based upon both ship sightings and aircraft photography; distributions are given in probability of occurrence by length classes. More recently, two distributions of iceberg widths are reported based on LANDSAT satellite imagery. This paper compares and composites these observed data, discusses a matching theoretical distribution, presents a model which yields an equilibrium distribution from assumed first-year iceberg generation, and outlines an experiment by which a statistical estimate of the true distribution of first-year icebergs sizes might be found.

DATA

Listed below are the principal available size distributions by source. Each is based upon different numbers of observations and covers different areas and times.

Romanov 1973[1]: The Romanov data are of iceberg lengths and given in two groups, one for sightings south of 65°S, the other north of this latitude. Since most of the other available data are for regions south of 65°S, only the former group is used here. The $\bar{L}_{s.65°S}$ = 0.38km (derived from Romanov's probability distributions) is based on 395 sightings in all; 89% of these are contained in the interval $L \leq 3$km.

Gordienko 1960 [2]: This distribution derives from observations made near the Amery Ice Shelf on 397 icebergs, of which 75% are contained in lengths up to 3km. Mean length is estimated at 1.9km.

Nazarov 1962 [3]: The Nazarov distribution (reported in Husseiny, 1978) results from sightings of 407 iceberg lengths; however, the specific locale in which the sightings occurred is not known to this author.

Dmitrash 1965 [4]: This group contains observations of 139 icebergs off the Antarctic Coast between 11°E and 94°E. The majority were sighted between the coast and 64°S; a sub-group were observed between 54° and 60°S. These data are given in widths of icebergs.

LANDSAT 1978 [5]: These are iceberg width distributions produced from satellite imagery and reported in Husseiny (1978). One distribution is given of icebergs sighted within the ice pack (648 sightings); the other is for icebergs (74) at the edge of the pack ice in the Bellingshausen Sea.

Figure 1 shows the above described distributions, each normalized to total number of icebergs observed. Where observations of widths are reported, these data are converted to lengths using a Dmitrash [6] value of 0.64 as the ratio of the average width of an iceberg to its average length. Only lengths to 3km are shown but these account for about 93% (1925 icebergs) of all sightings used in all distributions.

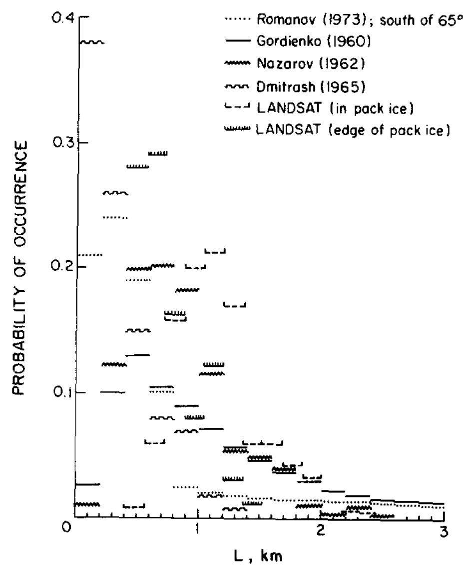

Fig. 1. Size distributions of Antarctic icebergs.

A COMPOSITE SIZE DISTRIBUTION

Composite size distributions, shown in Fig. 2, are formed from the above data by weighting each according to quantity of icebergs sighted. In Fig. 2a all six of the listed distributions are combined; Fig. 2b shows the composite obtained without the two LANDSAT [5] distributions. The graphs are in terms of the probability of occurrence within length classes of 0.2km.

There is a fundamental difference in the method of observation between the satellite-derived data and the others. The former show no icebergs of size (width) less than 0.250km; this translates to no icebergs of lengths less than 0.4km. In contrast, some of the direct and photographically-derived distribution show high probability of sighting icebergs of lengths less than 0.4km, particularly the Romanov [1] and Dmitrash

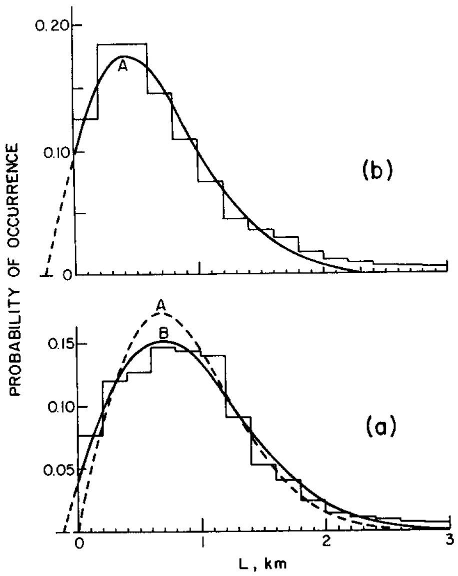

Fig. 2. Composite size distribution of Antarctic iceberg lengths:
(a) Weighted composition of all six size distributions of Fig. 1; (b) weighted composition excluding the two LANDSAT distributions.
A - Rayleigh distribution with standard deviation of 0.35 km; B - Rayleigh distribution with standard deviation of 0.40 km.

[4] reports. Thus the composite which excludes the LANDSAT [5] data shows a modal length of 0.4km while the addition of the LANDSAT [5] distributions increases the modal length to 0.7km. A further difference is that the LANDSAT [5] data derive from observations in the Bellingshausen Sea while the other pertain to observations mainly in East Antarctica.

FITTED RAYLEIGH DISTRIBUTIONS

Both composites in Fig. 2 strongly resemble the Rayleigh distribution

$$F\ (L) = \frac{L}{4b^2} \exp(-L^2/8b^2) \qquad (1)$$

where $b = (\overline{L^2})^{\frac{1}{2}}$ is the standard deviation and F (L) is a distribution such that

$$P\ (L> L_x) = \int_{L_x}^{\infty} F(L)\ dL \qquad (2)$$

is the probability that an iceberg length will exceed the value L_x.

The usual method of fitting the Rayleigh is to derive the value of b as one-half the mode value of the observed distribution. A better fit is obtained here by selecting b values larger than the observed $L_{mode}/2$ but displacing the Rayleigh toward the origin by an amount equal to the difference in observed and Rayleigh mode values. In Fig. 2a the best fit Rayleigh has a mode of 0.8km (b = 0.4km) but is displaced 0.1km; in Fig. 2b the best fit Rayleigh has a mode of 0.7km (b = 0.35km) but is displaced 0.3km toward the origin. Both of the Rayleigh curves of Fig. 2 are normalized to the number of icebergs in the respective observed length distributions.

DISCUSSION

The principal question is...why is the Rayleigh an apparent fit to observed iceberg lengths? The answer is not clear and clearly not proven, but the fact of the fit coupled with the knowledge that the Rayleigh is known to describe other distributions associated with natural processes makes the question non-trivial. For example, the Rayleigh is used to describe the distribution of radial miss distance from a target center when the distributions of projectile strikes along each of two coordinates are (a) independent and (b) normal. Another example, more appropriate to this discussion, is had from ocean surface wind wave theory; when sea surface elevations are narrowly Gaussian in distribution and of random phase, the Rayleigh describes the distribution of wave heights (cf. Kinsman [7]). In both cases, the Rayleigh is a non-directional scalar representation of the natural phenomenon. It is noted later that the Rayleigh is a special case of the more general Weibull distribution.

The displacement toward the origin of the best-fit Rayleigh curves in Fig. 2 may have a logical explanation based upon melt (and wastage) rate for icebergs whose widths approach draft dimensions. For example, assuming that sidewall melt rate is the dominant mechanism (top and bottom melt neglected), an iceberg of cube dimensions which periodically rolls to its most stable condition requires up to 1.5 times longer to melt to, say, one-half of its initial width than will the same berg when restrained from rolling. Therefore, observed size distributions would be skewed toward the smallest width class intervals. Stated another way, observed distributions of horizontal dimensions would be distorted at small sizes due to relatively rapid changes in iceberg drafts. This factor is illustrated in Fig. 2a where the Rayleigh of $b = L_{mode}/2 = 0.35$km is statistically correct but not a best fit.

Relations to surface waves: It follows that a pertinent question is...does the observed size distribution of iceberg lengths reflect directly from an implicit relation between the wastage rate and some surface wave characteristic? Ordinary wind waves for which the Rayleigh height distribution holds are short waves of lengths about 100m or less, and are probably of no importance in iceberg sizing. Extremely long gravity waves, sometimes called infragravity waves, have periods between ½ and 5 min and wavelengths of several kilometers. Weeks and Mellor [8] state that a maximum in stress is induced in infinite ice plates of typical Antarctic thickness by waves of about 6km. In icebergs less than 6km width, the maximum quasi-static stress occurs in response to a wave of length equal to berg width in the direction of wave travel. There is also the possibility of resonance induced in the iceberg or ice shelf from excitation by wave trains of special frequencies. Little is known of the distribution of wave lengths in infragravity range. In view of possible influence on iceberg sizing, these waves should be studied definitively in Antarctica.

Relations to observation technique: The LANDSAT [5] data clearly discriminate in favor of larger iceberg dimensions; similar discrimination is probably present in the other reported size observations by other techniques, but there is no satisfactory way to evaluate this. Plausible models of iceberg deterioration should lead to steady-state size distributions with monotonically increasing numbers as size dimension decreases; this is discussed further in a later section.

Relation to iceberg age: With respect to iceberg age or equilibrium, steady-state size distribution, does the Rayleigh describe the sizes of bergs newly formed from ice shelves? The corollary is... independent of the shelf calving size distribution, does the process of iceberg fracturing and melting move the ensemble of sizes into the Rayleigh over the average lifetime of the berg?

Of all the distributions shown in Fig. 1, the Gordienko [2] derives from icebergs sighted near the Antarctic Coast and the apparent source, the Amery Ice Shelf. It has a mode length of 0.5km but an average length of about 1.9km; in contrast, the Rayleigh with mode value of 0.5km has an average of only 0.63km. Clearly, the Gordienko size distribution contains substantial numbers of large size icebergs and, if it is representative of the ensemble of sizes of newly formed icebergs, the answer to the first question above is negative.

The second question is an important one since it bears directly upon the processes of iceberg deterioration. Neshyba and Josberger [6] show that Morgan and Budd [10] estimates of iceberg melt rate, based on observed size distributions and transit time during dispersion away from the Antarctic continent, may be considered in two independent parts: one due to fracturing along edges and apparently independent of ambient temperature, and the other due to melting within the convective boundary layers along sidewalls. The latter rates are found to be consistent with extrapolated laboratory results (Josberger [11]) and have a power dependency upon ambient temperature. Further, wastage rate due to edge fracturing exceeds convective melt rate in ambient water temperatures less than about 4°C. Since average ocean surface layer temperatures of 4°C are found north of about 48°S, it follows that the major cause of size decrease with age is due to fracturing and not melting, hence the equilibrium distribution of sizes will show maximum numbers in the smallest size categories.

<u>A simple model for steady-state size distribution</u>: A relatively simple model can be constructed to verify the conclusion of the previous section. The model conditions are:

1) sidewall wastage is assumed sufficiently dominant over top and bottom melt rate such that the latter are neglected; a uniform sidewall wastage rate of 100m yr^{-1} and an average draft of 200m are used here.
2) iceberg fracturing is modeled by division of the berg into two equal parts such that the length/width ratio is constrained within the limits

   $$1.1 \leq L/W \leq 2.2$$

   which bound the 1.6 average value reported by Dmitrash [6]. Fracture occurs when uniform wastage increases the L/W ratio to the upper limit.
3) the model describes distributions of widths, not lengths. This condition provides continuity to the dimension being tested; the iceberg is assumed to fracture across its shortest dimension.
4) the initial condition is the size distribution of newly-formed or first-year icebergs.
5) The initial ensemble of all iceberg sizes are assumed to be of dimensional ratio L/W = 1.6.

This model has been run using the Gordienko (see Fig. 1) observations as the initial distribution of sizes; each year an additional input of Gordienko-type berg sizes is injected. Figure 3 shows the distribution of widths after 21 years at which time equilibrium is reached. An iceberg of original 4.1km width is then totally dissipated. The model accounts for about 97% of a total of about 11,000 bergs of all sizes; this is about seven times less than the total contained in the Shil'nikov [14] report.

The equilibrium distribution is clearly not of the Rayleigh type. The Weibull distribution (Mann et al. [12]) given by

$$f(x) = \frac{\beta}{\eta}\left(\frac{x-\gamma}{\eta}\right)^{\beta-1} \exp\left[-\left(\frac{x-\gamma}{\eta}\right)^{\beta}\right], \quad (3)$$

where β, η are shape parameters and γ is a location parameter, is used for example to describe the distribution of failure when the hazard rate is not constant with the independent parameter. With $\gamma = o$, $\beta = 2$ and $\eta = b\sqrt{8}$, the Weibull specializes to the Rayleigh. For the model in Fig. 3 the Weibull factors are $\beta = 0.5$; $\eta = 1.6$, with $\gamma = o$. The applicability of the Weibull is reasonable since in the real iceberg world, melt rate and wastage are clearly not uniform over time because of the gradual dispersion of icebergs away from the continent into increasingly warmer waters. Also shown in Fig. 3 is the model result after only 10 years.

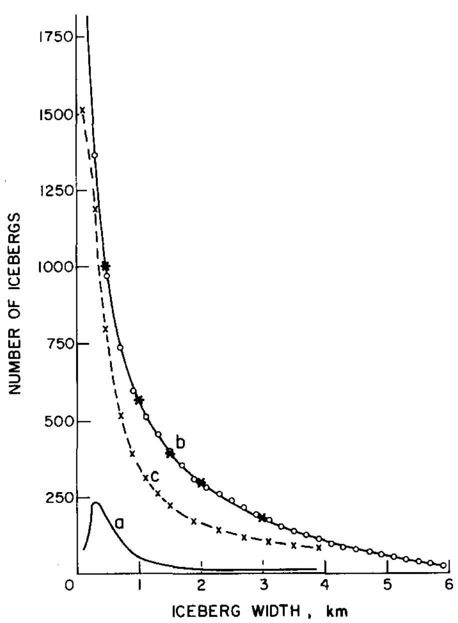

Fig. 3. Iceberg width distributions: (a) Gordienko 1960; initial condition for model. (b) Distribution of model sizes after 21 years and equilibrium. (c) Distribution of model sizes after 10 years.
*Weibull distribution with $\beta = 0.5$, $\eta = 1.6$, $\gamma = 0$.

SUMMARY

Previously reported iceberg size distributions are not useful in modeling Antarctic iceberg deterioration because they fail to observe the quantity of smallest icebergs. A model similar in nature to that reported here, but which allows for fracturing of new icebergs over a suite of sizes, appears to be the logical approach. Further, the Weibull distribution appears to be a suitable theoretical test of the model results.

The real fracturing process is probably an edge effect, hence independent of the shape of the berg; in fact, the shape (L/W) appears to be the dependent factor. However, the orientation of the major iceberg axis to the prevailing direction of surface long wave propagation may not be random since waves and wind directions are usually not independent and there is a tendency for elongate icebergs to "sail". Therefore, random edge fracturing would not necessarily result in round icebergs.

It is not yet clear that the equilibrium distribution of Antarctic iceberg sizes will be independent of the distribution of sizes of freshly-calved bergs, but this may well be the case. Very large icebergs, such as the TROLLTUNGA which calved in 1973 and has been tracked by satellite imagery since then (McClain [13]), may have to be treated as simple extensions of the ice shelves rather than as members of the ensemble of icebergs. However, it is of interest to note that during the first 4 years of its life, TROLLTUNGA maintained a length/width ratio of 1.7 to 1.8, i.e., very close to the average value previously discussed; more recently (since 1977) the L/W ratio has exceeded 2. In any case, it is worthwhile to determine if possible the statistics of the ensemble of first-year generations of icebergs and, further, to compare such statistics for the production from the several major sources.

A suggested method to achieve this goal is to take photographs of substantial sections of the edges of each of the major ice shelves and to analyze these for the numbers of cusps of various dimensions. The resulting distribution may also be in error in the smallest size categories because the very large iceberg will have carried away a part of the historical record of smaller-scale calving. A partial solution to the latter difficulty is to photograph the larger bergs and apply the same analysis to these, i.e., treating these as shelf extensions. It will be useful to compare the results obtained from different ice shelves, and attempt to explain such differences in terms of ice thickness or variations in tide or other wave forcing. A useful concomitant experiment would be to install pressure gages on the ocean floor near the major shelves to assess the long wave environment to which each is subjected.

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