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SEA ICE THICKNESS DATA: THE MANY VS. THE FEW

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Abstract. During May 1988 a 1230-m ice thickness profile was drilled across a floe in Fram Strait. The probability density function of this data set corresponds closely to extensive ice draft measurements from submarines and the thickness distribution of floes sampled randomly in the area. The observed similarity is attributed to the topography of the pack ice in Fram Strait where each floe is composed of a spectrum of smaller components. This may imply that mutual independence and representativeness of thickness measurements can be satisfied to some degree even for short profiles.

1. Introduction

How many samples of sea ice thickness are needed for a reasonable estimate of the distribution and probability density function of ice thickness? Studies on the energy and mass balance of the polar oceans and on sea ice dynamics rely on the determination of draft and thickness of sea ice as important geophysical parameters. Yet, facing the statistical alliance between the principle of large numbers and the demand for mutual independence of data points, researchers seem compelled to cover a lot of sampling ground. This is reflected in the extensive data sets that exist for the Arctic sea ice cover, mostly collected with upward-looking sonar onboard submarines, in fewer cases by drilling holes through the ice [e.g. Ackley et al., 1974; Wadhams, 1981; Key and McLaren, 1988].

As part of the ARK V/1 cruise with R/V *Polarstern* in May 1988 we had the opportunity to acquire a small ice thickness data set while the ship was moored to a floe which drifted with the surrounding pack between 80°50'N, 4°00'E and 80°20'N, 0°05'E in Fram Strait [Spindler, 1989]. Holes were drilled with a 2"-auger at 5-m intervals across the entire floe of approximately 1250 m width and the thickness of snow and ice cover along with the position of the water level within the hole (freeboard) were recorded.

2. Results

2.1. Measurements and probability density function

A plot of ice and snow thickness along the profile is shown in Figure 1. The mean ice thickness amounts to 2.97 m with extreme values of 1.12 and 6.50 m, respectively. If P(h)dh is the probability that an ice floe is between h and h+dh thick at a random point, then P(h) is called the probability density function (pdf) of ice thickness. The pdf is computed as the ratio between the relative frequency of ice of a certain thickness and the width of the thickness bins. The pdf for the data gathered by us is shown as the solid curve in Figure 2. The overall shape of the curve approaches that of a bimodal distribution exhibiting one well defined maximum at a thickness of approximately 1.4 m and a broader crest between 2 and 4 m, topped by three secondary peaks. A small shoulder is discernible at ice thicknesses between 4 and 5.5 m. The pdf marked by a stippled outline in Figure 2 is that of a modified data set with only every second value along the profile, i.e. 123 points at 10-m spacing, taken into account.

To complement thickness measurements, ice cores were extracted along the profile at selected sites. Determination of their textural and physical properties revealed that the peak in the pdf at around 1.4 m corresponds to undeformed first-year ice, made up by more than 90% of columnar ice. The broad maximum between thicknesses of 2 and 4 m is composed of second- and multi-year sea ice without prominent signs of deformation, yet with a higher percentage of granular ice. A minor contribution is made by recent (i.e. not yet consolidated) pressure ridges. The portion of the pdf above a thickness of 4 m represents mostly ridges older than one year. In the field these appear as rounded hummocks on the surface of the ice floe.

The average snow thickness amounts to 0.41 m. Snow and ice thickness are not significantly correlated with each other, yielding a correlation coefficient of -0.49. Thus thin young portions of the floe do not exhibit a shallow snow cover in proportion to their age, as one might expect. The data rather indicate that wind erosion may result in diminished snow thickness above elevated, thicker segments of the floe, with drift snow accumulating in depressions on top of younger ice.

2.2. Comparison with other data

Figure 3 shows the pdf of ice draft as obtained by submarine sonar along a 2845-km-track from 84°50'N, 70°W via the North Pole to the ice edge in Fram Strait (at 78°53'N, 0°W) during October 1976 [Wadhams, 1981]. The shape of the pdf corresponds essentially to the one presented in Figure 2, with two maxima representing first-year ice and second-/multi-year ice, respectively, and gradually decreasing probability density towards drafts larger than 4 m. However, the position of the first peak in Figure 3 is located at a much lower value than the corresponding one in Figure 2. On the one hand this is due to the fact that ice thickness exceeds ice draft by that fraction of floes which extends above the waterline. On the other hand, the submarine profile was taken in October, a time of year when first-year ice has not yet

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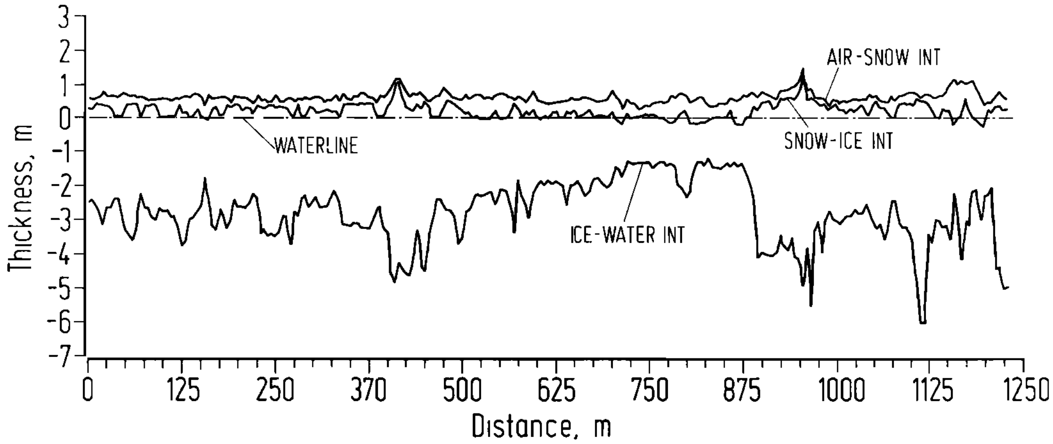

Fig. 1. Ice and snow thickness along the profile across the ice floe. The Water level is at 0 m.

reached substantial thickness. Thus one would expect an even closer resemblance had the submarine profiling likewise been conducted in May at the end of the growth season. The position of the main peak of Wadhams' data around 3.2 m is located at slightly higher values than the corresponding one in Figure 2. The same is true for the contribution of ridged floes which does not appear as a proper maximum in Figure 3. It is also important to keep in mind that the drilling profile does not take into account areas of open water and nilas between floes that are shown as ice of zero or low thickness in Figure 3.

During June and July of 1984 Gow et al. [1987] drilled ice cores on 40 randomly selected floes in Fram Strait. Their work can thus be regarded as a good survey of the different categories of sea ice floes occurring in the area discussed by us. Figure 4 depicts the pdf computed from the lengths of the samples extracted by Gow and co-workers. Again, a correspondence between this pdf and that of Figure 2 is evident. The two principal maxima of first-year and older ice are only shifted towards slightly lower values for the data of Gow et al. [1987]. This may partly be explained by the fact that Gow and co-workers tended to sample undeformed ice [op. cit., p. 10].

3. Conclusions

What conclusions can be drawn from this? Does the determination of ice thickness along a 1230-m profile represent an acceptable alternative to a continuous scan of ice draft for thousands of kilometers? This is certainly not the case. Yet, when comparing the two, one might ask in what way particular floes along a sonar sampling track contribute to the overall ice thickness distribution.

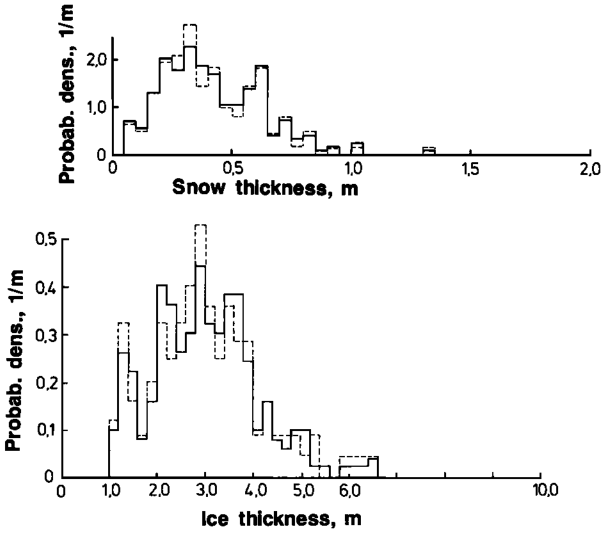

Fig. 2. Probability density function (pdf) of ice thickness (below) and snow thickness (above). The solid curve represents the complete data set (247 points at 5 m distance), the stippled curve every second value along the profile.

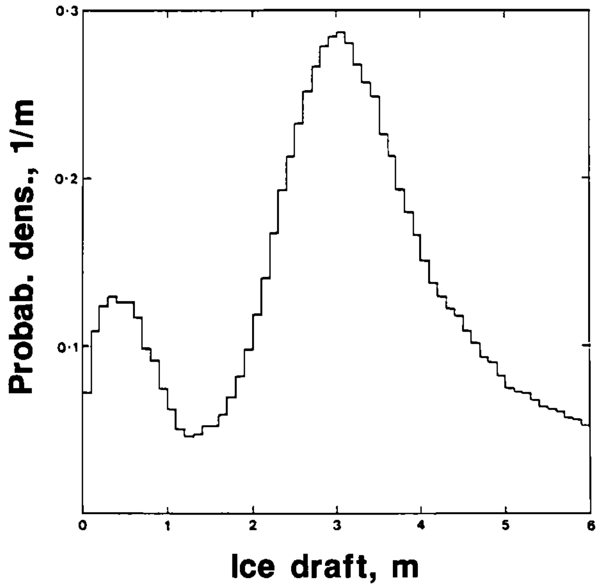

Fig. 3. Pdf of ice draft determined with submarine sonar along a 2845-km-track from 84°50'N, 70°W via the North Pole to the ice edge in Fram Strait (at 78°53'N, 0°W) during October 1976 [after Wadhams, 1981].

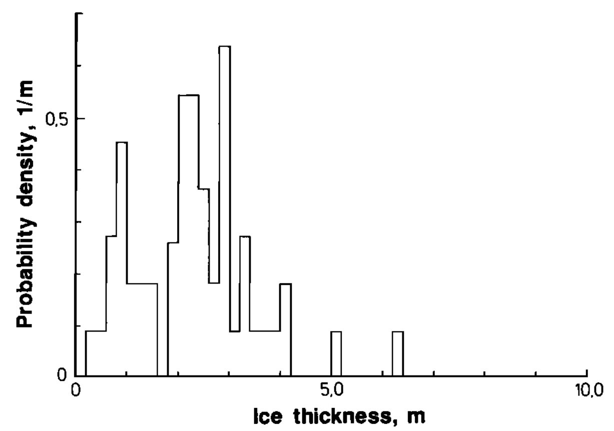

Fig. 4. Pdf of core lengths (i.e. floe thicknesses) sampled at random on 40 floes in Fram Strait during June/July of 1984 by Gow et al. [1987].

The similarity between the thickness pdf resulting from random sampling of floes in Fram Strait by Gow and co-workers [1987] or the continuous submarine profile of Wadhams [1981] on the one hand and the pdf obtained for one particular floe in this study on the other could point towards a general similarity between the whole, i.e. a certain pack ice region of the Arctic, and the parts, i.e. the floes that it is composed of. The floe sampled by us was a conglomeration of smaller subunits, each of different history and thickness, welded together by various deformational and metamorphic events. A particular region within the Arctic pack ice should be composed of floes that are similar to one another because each one in turn is made up of smaller elements in the same fashion. As a consequence, ice floes should have a composition, i.e. a thickness pdf, that is essentially the same as that of the surrounding pack ice. This is particularly true for the Fram Strait region where sea ice exits the Arctic Basin after several years of growth and ablation, transport and deformation. The compound nature of the profile in Figure 1 is a manifestation of these processes. Thus, at least in Fram Strait it seems not a matter of mere luck to encounter a particular floe that matches the characteristics of the surrounding pack, as most floes are "veterans" all alike. In addition, rather than forming large sheets, new ice grows attached to or in between older floes. Yet, for a better, thorough understanding of the problem, data of a wider range of floes are needed.

With this context in mind we return to the question regarding determination of ice thickness pdf's in general. Inherent in the definition of the pdf is the assumption that data points represent continuous random variables that are mutually independent of one another. This mutual independence is not necessarily true for ice thickness measurements because adjacent data points sampled on an ice sheet will within certain limits exhibit similar thicknesses. Just what are these limits? Investigations in the central Weddell Sea [Wadhams et al., 1987] suggest that for that region it is not sufficient to sample, however closely spaced, one particular floe only, as the thickness variability within floes apart from ridging is not very large. This is explained mainly by the homogeneity of the floes which are essentially vast sheets of pancake ice aggregations, each floe representative of a certain age and thickness class.

The autocorrelation function (acf) can provide further information on the spatial structure of the sampled profile. Figure 5 depicts the normalized acf, defined as

$$\text{acf} = [E(x_1x_2) - E(x_1)E(x_2)] \,/\, s_1s_2$$

for expected ice thickness $E(x_i)$ with standard deviation s_i [Davenport and Root, 1958], plotted against different lags $L=x_1-x_2$. The minimum distance between statistically independent points corresponds to the lag at which the acf has its first zero [cf. Davenport and Root, 1958; Rothrock, 1986]. In this case, the condition is satisfied for lags larger than 185 m, whereas the data points of a study by Rothrock and Thorndike [1980] in the Beaufort Sea are independent only for distances larger than 1 km. This again implies that 1 km of profile sampled in Fram Strait may comprise several subunits of completely different statistical and glaciological provenance. The spectral analysis by Key and McLaren [1988] of 940-km draft data from the Canada Basin may point to a similar segmentation, as they found periodicities of 50 to 150 m to occur most frequently, with few wavelengths exceeding 1000 m.

As regards the required minimum distance between drillholes, Figure 2 shows that sample spacings of 5 m (solid curve) and 10 m (stippled curve) yield very similar pdf's. For studies of small-scale ice roughness under meteorologic or oceanographic aspects this spacing may prove too wide; the acf values for small lags (cf. Figure 5) indicate a significant loss of roughness information for a 5-m spacing of data points. On the other hand, a comparatively short profile may represent the roughness spectrum of an entire region owing to the composite nature of floes discussed above.

The data collected by Gow et al. [1987] are mutually independent of one another because they were obtained at random on different floes. The resulting pdf (Figure 4), which represents a good large-scale estimate of the floe thickness distribution in Fram Strait, parallels that of Figure 2, again pointing to a correspondence between

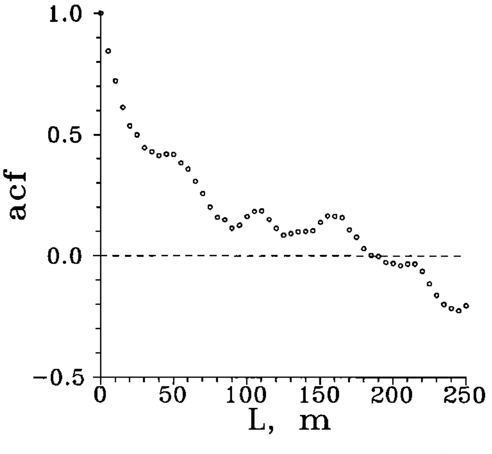

Fig. 5. Normalized autocorrelation function (acf) of ice thickness plotted against different lags L.

local and regional measurements. This correspondence does not imply the equivalence of long profiles obtained through submarine sonar and highly local measurements; yet, it may indicate that mutual independence and representativeness of thickness measurements can be satisfied even for short profiles because single floes may embody the characteristics of an entire geographic region.

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