

SOME PHYSICAL PROPERTIES OF SNOWCOVER ON  
EVOLVING FIRST YEAR SEA ICE

Gregory B. Crocker

Scott Polar Institute  
Cambridge University  
Cambridge, England

and

John E. Lewis

Department of Geography  
McGill University  
Montreal, Quebec H3A 2K6

ABSTRACT

Spatial and temporal variations in the physical properties of snowcover that forms on first-year sea ice are measured, over a 50-day period, on a study site near Resolute Bay, N.W.T. The data indicate that while spatial variability is relatively small, temporally the snowcover is very dynamic. Snow density, salinity, temperature and brine volume are found to undergo large fluctuations as snowcover evolves from a cover of discontinuous frost flowers, to a shallow, high-density snowpack. Some implications of the observed physical properties, in particular the brine volume, on heat flux through the snowcover are discussed.

INTRODUCTION

Snowcover is integral part of the thermal regime of arctic sea ice. Because of its low thermal conductivity, small quantities of snow can play a major role in determining the flux of heat through the ocean-ice-atmosphere system. The importance of a snowcover is particularly great over young ice, where the thermal resistance of the ice itself is low, and heat flux is large. Maykut (1976) predicts that the net heat loss over 10 cm thick ice decreases by 25% with the addition of only 1 cm of snow, and by 65% when the snow depth is 3 cm. Yet none of the physical properties of the snow are known with any degree of certainty during the period when the ice is thin (Nakawo and Sinha, 1981). As a result, in many heat flux and ice growth studies snow depth and density measurements made in late winter or early spring have been assumed to be representative of conditions during the entire period of ice growth.

The validity of this assumption has not been rigorously tested. First, very little systematic information of the spatial and temporal variations of the physical properties of snowcover on sea ice has appeared in the literature. Secondly, since the snow properties are not known, the applicability of existing empirical or theoretical thermal conductivity formulae to the snowcover on sea ice has not been demonstrated.

Variations in the crystal structure, depth and density of the snowpack will all

influence the flux of heat through an ice sheet, but of particular interest in this case is the salt content of the snow. The upper portion of young sea ice has a layer of concentrated brine. When a snowcover develops on the ice surface the brine is drawn up into the snow by capillary tension, or by mixing during periods of drifting or blowing snow. However very few measurements of snow salinity have been made. Martin (1979) gives some spot measurements of the bulk salinity of snow over sea ice of several thicknesses. The only systematic studies of the salt content of snow on sea ice was conducted by Lapp and Prashker (1981). Their data set consists of snow depth and salinity values taken roughly once per week near Pond Inlet, N.W.T. between December, 1974 and April, 1981. In both studies the data set is discontinuous and no attempt has been made to quantify the spatial variability. Despite these limitations, the measurements indicate that at certain times during the year the snow may contain appreciable quantities of salt (in excess of 45 ppt).

In addition to the presence of brine, the snowcover on sea ice differs from other snow types where frequently in the initial stages of development it forms entirely from a type of surface hoar, commonly referred to as frost flowers. Soon after an ice sheet has formed the frost flowers, which consist of small hemispherical clusters of long plate-like ice crystals, begin to grow on the ice surface. Over a period of about two weeks the clusters may grow to form a continuous cover several centimeters in thickness. Gradually, scour and deposition by wind, and constructive and destructive metamorphosis produce a hard, high density cover on the surface of the sea ice.

This paper presents detailed measurements of the spatial and temporal variations of snow depth, density, salinity, total salt content and brine volume over young/first year sea ice in the central high arctic. No attempt is made to quantify the effects of these properties on heat flux; refer to a recent article by Crocker (1984b).

#### FIELD MEASUREMENTS

Field measurements were made on the ice located in Resolute Passage, N.W.T., during November and December of 1982 (figure 1). On November 8, a nine point (3x3) grid network with 15 m spacing between grid points was established at 74° 42' 18" N, 95° 07' 30" W. At this time the ice was 14 cm thick and already had a well developed cover of frost flowers. Between November 8 and 15 the salinities of the frost flowers and the ice surface were measured at randomly selected sites originating from each of the 9 grid points. Daily snow densities and ice surface temperatures were measured at a single location, using an acrylic tube sampler and a calibrated thermistor probe.

On November 15 the frost flower cover had grown sufficiently to constitute a continuous cover and permit the use of the snow sampler. This device, designed specifically for the project, allowed snow samples to be taken at 1 cm depth intervals. The sampler consists of rectangular, brass sections, stacked to form an open ended box (figure 2). The bottom section is tapered to a 45° angle to provide a sharp cutting edge, and all four sides are fitted with guides to allow easy stacking. The guide at the 'rear' of each section is dove-tailed so that the spill arms ('A' in figure 2) can be easily slipped into place and firmly held.

To sample the snowpack the required number of sections were stacked and pushed down through the snow until the bottom section rested flush with the ice surface. The snow immediately surrounding the sampler was then cleared away and the top section was removed and replaced with the spill arms. A sharp edged sheet metal plate was used to slice off the snow section held by the spill arms. The snow on the plate was then dumped directly into a numbered sample bag. This procedure was repeated until the entire snowpack had been sliced into 1 cm thick sections and bagged. The samples were immediately transported to Resolute where the laboratory analyses were performed.

In conjunction with daily temperature profiles, weighing the samples and determining the electrical conductivity of the melt allowed the density, salinity, total salt content, and brine volume of each 1 cm thick layer at each of the 9 sample points to be calculated. This information was collected on a daily basis from November 15 until December 30.

## RESULTS

### I. Mass and Density

Although density is the parameter normally used to characterize the ice content of a snowpack, in cases such as this where the snow is shallow, small errors in determining the level of the snow surface may lead to large errors in the calculated density. For this reason the ice content of the snowcover has been expressed as the mass in grams per cm<sup>2</sup> of surface area, as well as in the conventional g/cm<sup>3</sup>.

The total mass of the snowpack (figure 3) fluctuated through cycles of erosion and deposition, with a general trend towards increasing as the winter progressed. Most of this increase resulted from the addition of mass to the snow surface, either the 1-2 cm or 2-3 cm layer (all snow depths were measured from the ice/snow interface). During the first 2 weeks of snowcover development most of the mass increase in the surface layer was due to sublimation. Throughout the remainder of the study period deposition of windblown snow accounted for the majority of the mass increase. The formation of faceted crystals near the ice surface indicates that mass transfer from this region may also contribute to increasing the mass of the upper layers of the snowpack, but evidence of this can not be seen in the data.

The 95% spatial variability with confidence limits for the mean of the 9 daily measurements are shown in figure 4. There was a general decrease in spatial variability after the first major redistribution of snow by strong winds that occurred on November 26 and 27. The spatial variability was particularly high in the surface layer in late December, due to the presence of small drifts which had begun to form on the ice surface at this time. The large dot and error bars shown on December 11 represent the mean and 95% confidence limits of eight sample points measured on a transect across Resolute Passage on that date (see figure 1).

The density of each layer and the bulk snowpack density are shown in figure 5. For reasons mentioned above the values for the surface layer and bulk densities should be considered accurate to only  $\pm 10\%$ . The density of the 1-2 cm layer underwent the most dramatic changes. In mid November it was substantially less dense than the surface layer, reflecting the structure of the frost flowers from which it developed. After the storm of November 26 and 27, wind induced mixing left both the 0-1 cm and 1-2 cm layers with similar densities. Densification of the 1-2 cm layer proceeded gradually through the rest of November and early December, and by mid December the layer had a substantially greater density than the 0-1 cm layer.

It is interesting to note that the bulk density of the snowpack never exceeded 0.30 g/cm<sup>3</sup>. Several authors (Bilello, 1957, Williams and Gold, 1958, Nakawo and Sinha, 1981) have reported much higher density values for snow on sea ice in the same region, often in excess of 0.35 g/cm<sup>3</sup>. The discrepancy is undoubtedly due to seasonal and locational factors, and indicates the importance of properly assessing the spatial and temporal variability in the snowcover properties.

### II. Salinity

Large decreases in the salinity of all of the layers of the snowpack occurred during the first month of ice growth (figure 6). The salinity of both the frost flowers and the ice surface were initially high, with concentrations in excess of 100 ppt. While the surface salinity remained fairly constant, the salinity of the frost flowers dropped markedly during the first week due to the addition of new ice crystals via sublimation. By mid November all layers in the snowpack had reached quasi-stationary levels. In the 0-1 cm layer this level was quite high, showing salinities between 40 and 50 ppt even at the end of December.

The rapid increase in the salinity of all the layers between December 5 and 16 is puzzling. Peak salinity values were reached in the 0-1 cm layer on December 12, in the 1-2 cm layer on December 13, and on December 16 in the 2-3 cm layer, suggesting a steady upward migration of brine from the ice surface during this period. Although there were no

significant deviations in the mean daily temperature during this period, relatively strong winds did prevail. This suggests that the salinity increase may have been caused by brine being drawn up into the snow by an increased capillary tension associated with the deposition of fresh wind blown snow. The rapid decrease in salinity which follows the peak values would then be the result of destructive metamorphism reducing the snow's ability to hold the liquid. If this is in fact the cause of the salinity increase then it is not clear why such a dramatic rise should occur specifically at this time, while no change in salinity was observed during other similar periods of strong winds and drifting snow.

Figure 7 shows the variability for the daily salinities. In general salinity appears to be much less spatially variable than mass. The only instance where the confidence limits are large is in the 2-3 cm layer immediately after it reappears in mid December. This is due to differences in salinity between the existing snow surface and the drifts of 'fresh' snow which had begun to form at this time.

### III. Total Salt Content

Since salinity is a function of both the amount of salt and ice in the snow matrix, changes in the actual salt content may be hidden by changes in snow density. Therefore the total mass of salt per square centimeter of surface area is a better indicator of the movement of salt in the snowpack (figure 8). Several trends which do not appear in the salinity curves are revealed here. In almost every case salt was transported upward during periods of blowing snow, most likely the result of the increased capillarity associated with the deposition of fresh snow, as discussed previously. Also, it appears that the initial transport of brine to the ice surface took place during the first 5-6 days of ice growth. After this period there was a net removal of salt from the ice surface as brine drainage mechanisms become active in transporting salt down through the ice block and out into the water below.

Figure 9 indicates that the variability in the daily mean salt contents for the 0-1 cm layer was fairly constant throughout the study period, but there was an increase in variability in the upper 2 layers after the upward migration of salt in mid December.

### IV. Brine Volume

By combining measured snow temperatures, densities and salinities, the brine volume of the snowpack can be calculated using brine volume tables (Assur, 1960) or equations (Frankenstein and Garner, 1967) developed for sea ice. Figure 10 shows the temporal variations in brine volume expressed as a percentage of the volume of ice in the snow matrix. The graphs reflect many of the same trends seen in the density and salinity curves, but are far more variable on a day to day basis because of the influence of temperature. They also demonstrate that a large portion of the snowpack was in a liquid state, especially when the ice was thin and temperatures were warmer in the snowpack.

## DISCUSSION AND CONCLUSIONS

Qualitatively the snowpack was observed to be composed of three distinct layers. Immediately above the ice surface there was a thin layer with a very high brine content. Above this was a layer of small, low-density depth hoar crystals overlain by a thin dense surface crust. The metamorphosed hoar layer contained many large cavities, which appeared to be remnants of the open areas between individual frost flowers. Although this stratigraphy can be seen from the density, salinity and brine volume curves, the 1 cm depth interval was too large to discern many of the finer details of the snow structure. For example the 0-1 cm layer contained portions of both the brine rich bottom layer and the dry, faceted crystals above. This causes some averaging of the properties of the individual layers, and produces conservative estimates of the variability of these properties with depth.

The layered structure of the snowpack can have a considerable influence on its ability to conduct heat. Goodrich (1976) points out that in a system of series connected conduc-

tors, conduction is most strongly influenced by the least conducting layers. Therefore in a snowpack that is composed of several layers, each with different physical properties, the bulk thermal conductivity will be less than that of a homogeneous snowpack with the same average or 'bulk' properties. In cases where the bulk properties are used as the basis for estimating the thermal conductivity of a layered snowpack, an overprediction of the thermal conductivity will result. For the Resolute Passage data this overprediction is at times as high as 80% (Crocker, 1984a) when Abels' (1892) empirical thermal conductivity formula is used.

In addition to the influence of layered structure, the liquid may effect the snow's ability to conduct heat. The presence of brine changes the geometry of the snow matrix, which is a crucial determinant of thermal conductivity. Also, the thermal conductivity of the brine is less than that of ice but substantially greater than that of still air, the other two components of the snowcover, and therefore may either increase or decrease thermal conductivity depending on which of these media it is displacing. A model to predict the thermal conductivity of wet snow, based on the findings of this study, is presented in Crocker (1984b).

The physical properties of snowcover on young and first year sea ice are unique from those of any other type of natural snowcover. Consequently the assumption that its thermal (and dielectric) properties can be adequately represented by relationships developed for 'conventional' snowpacks may not be valid. The density, salinity, salt content, and brine volume measurements presented in this paper provide a basis from which these relationships can begin to be evaluated and the influence of the snowcover on atmosphere-ocean energy exchanges properly assessed.

#### REFERENCES

- Abels, H., 1882. «Beobachtungen der täglichen periode der temperatur im schnee und bestimmung des wärmeleitungsvermögens des schnee als function seiner dichtigkeit.» Rep. Meteorol., Bd. XVI, no. 1, pp. 1-53.
- Assur, A., 1960. «Composition of sea ice and its tensile strength.» CRREL, RR 44, 49 pp.
- Bilello, M.A., 1957. «A study of arctic snow-cover properties as related to climatic conditions.» CRREL, RR 39, 9 pp.
- Crocker, G.B., 1984a. «The physical properties of snowcover on young sea ice in the central high arctic.» M.Sc. Thesis, McGill University.
- Crocker, G.B., 1984b. «A physical model for predicting the thermal conductivity of brine-wetted snow.» Cold Regions Science and Technology, Vol. 10, pp. 69-74.
- Frankenstein, G., and R. Garner, 1967. «Equations for determining the brine volume of sea ice from  $-0.5^{\circ}\text{C}$  to  $-22.9^{\circ}\text{C}$ .» Journal of Glaciology, Vol. 6, no. 48, pp. 943-944.
- Goodrich, L.E., 1976. «A numerical model for assessing the influence of snowcover on the ground thermal regime.» Ph.D. thesis, McGill University, 555 pp.
- Lapp, D., and S. Prashker, 1982. «Sea ice salinity and temperature data Pond Inlet Northwest Territories.» Unpublished report submitted by Polar Research and Engineering to Dr. R.O. Ramsier, Senior Ice Research Scientist, Atmospheric Environment Service.
- Martin, S., 1979. «A field study of brine drainage and oil entrainment in first year sea ice.» Journal of Glaciology, Vol. 22, no. 88, pp. 473-502.
- Maykut, G., 1976. «Energy exchange over young sea ice in the central arctic.» AIDJEX Bull. no. 31, pp. 45-74.
- Nakawo, M., and N.K. Sinha, 1981. «Growth rate and salinity profile of first-year sea ice

in the central arctic.» Journal of Glaciology, Vol. 27, no. 96, pp. 315-330.

Williams, G.P., and L.W. Gold, 1958. «Snow density and climate.» Transactions of the Engineering Institute of Canada, Vol. 2, no. 2, pp. 91-94.

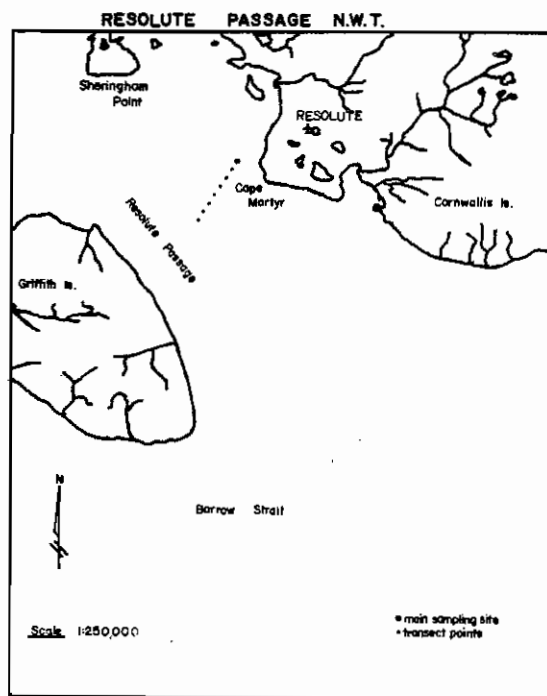


Figure 1. Study site on Resolute Passage, N.W.T.

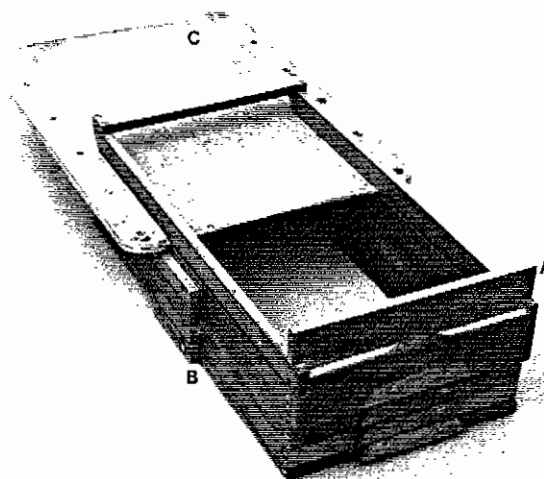


Figure 2. Photograph of snow sampler showing: A. Spill arms, B. Tray sections, C. Cutting plate.

MEAN SNOW LAYER MASS PER  
1 cm<sup>2</sup> SURFACE AREA

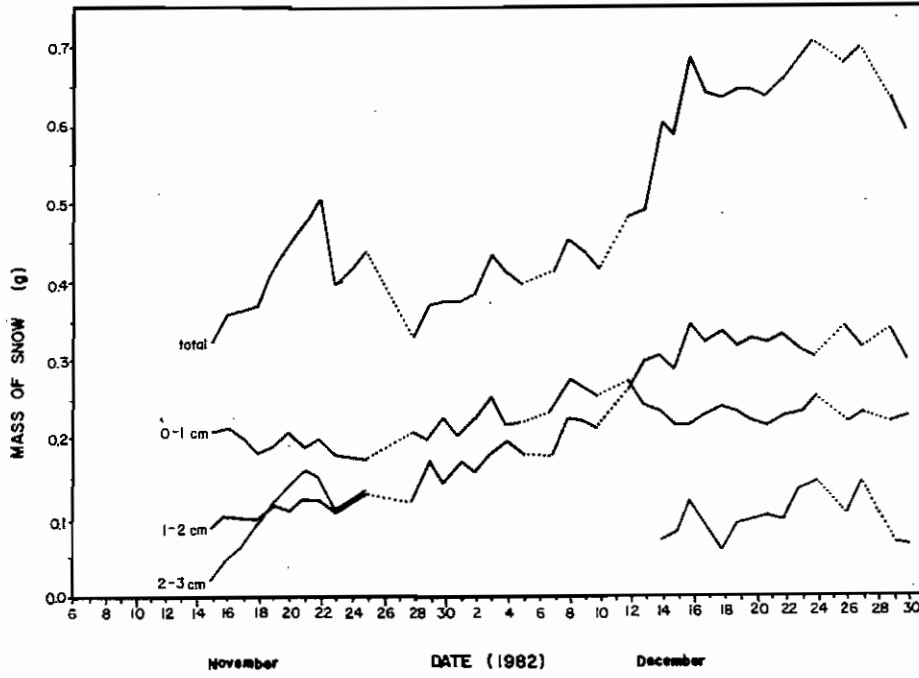


Figure 3

MEAN SNOW LAYER DENSITY

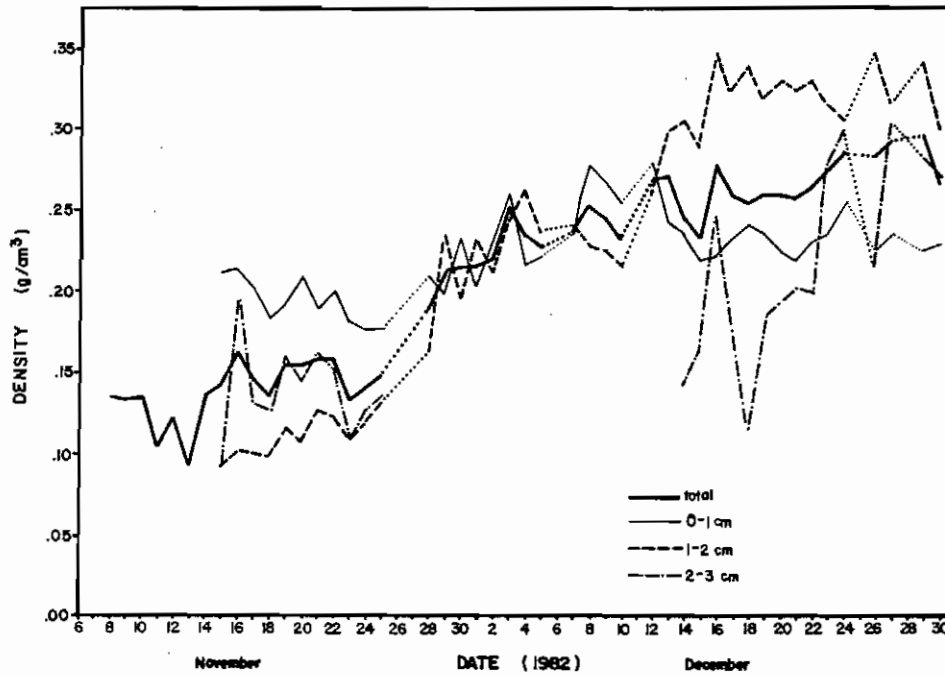


Figure 5

MEAN SNOW LAYER MASS WITH  
95% CONFIDENCE LIMITS

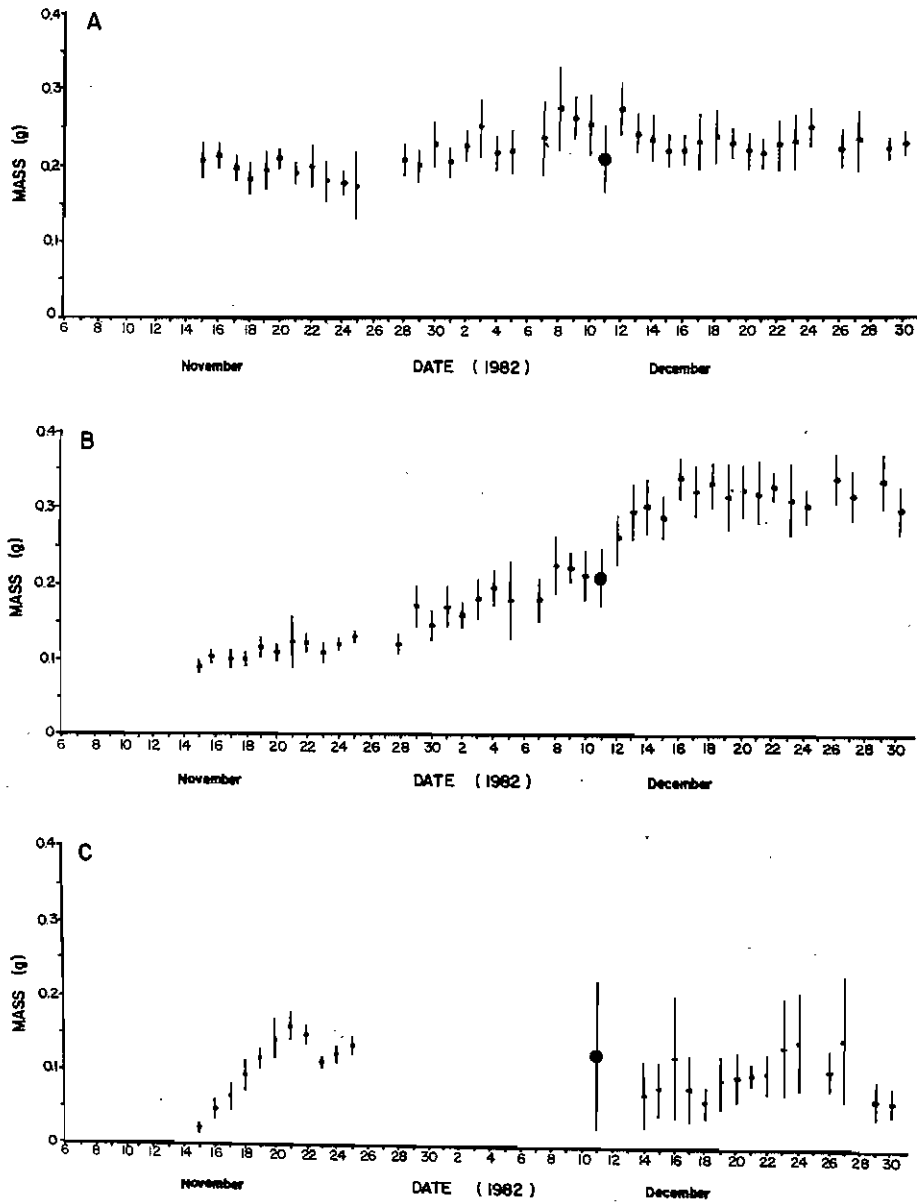


Figure 4. The 95% confidence limits for the mass of snow in the 0-1cm layer (A), the 1-2 cm layer (B), and 2-3 cm layer (C). The large dots represent transect values.



MEAN SNOW LAYER  
SALINITY

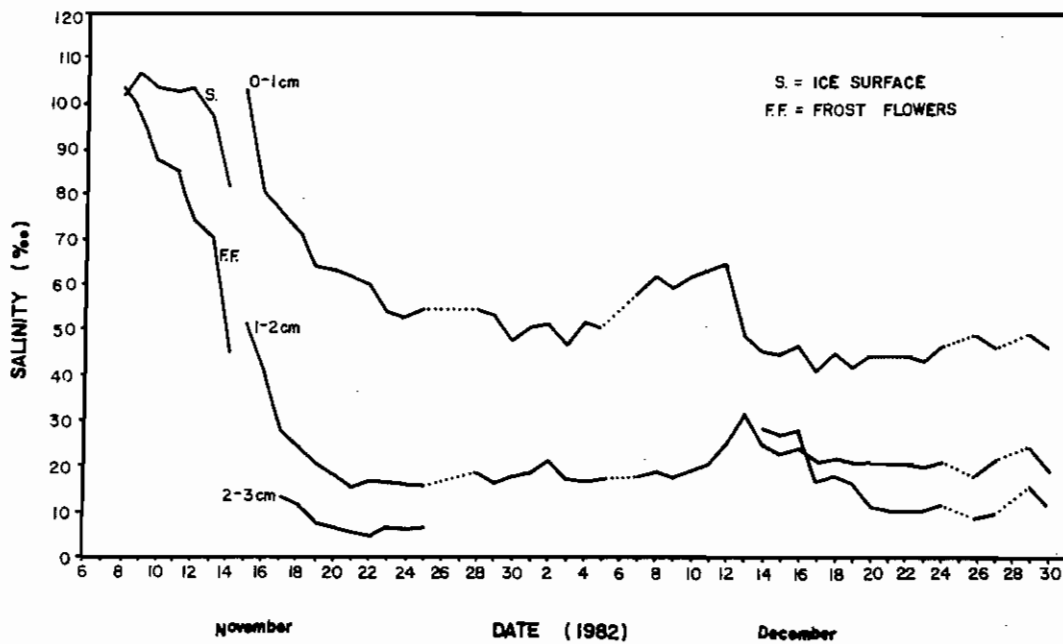


Figure 6

MEAN SNOW LAYER SALT CONTENT  
PER 1 cm<sup>2</sup> SURFACE AREA

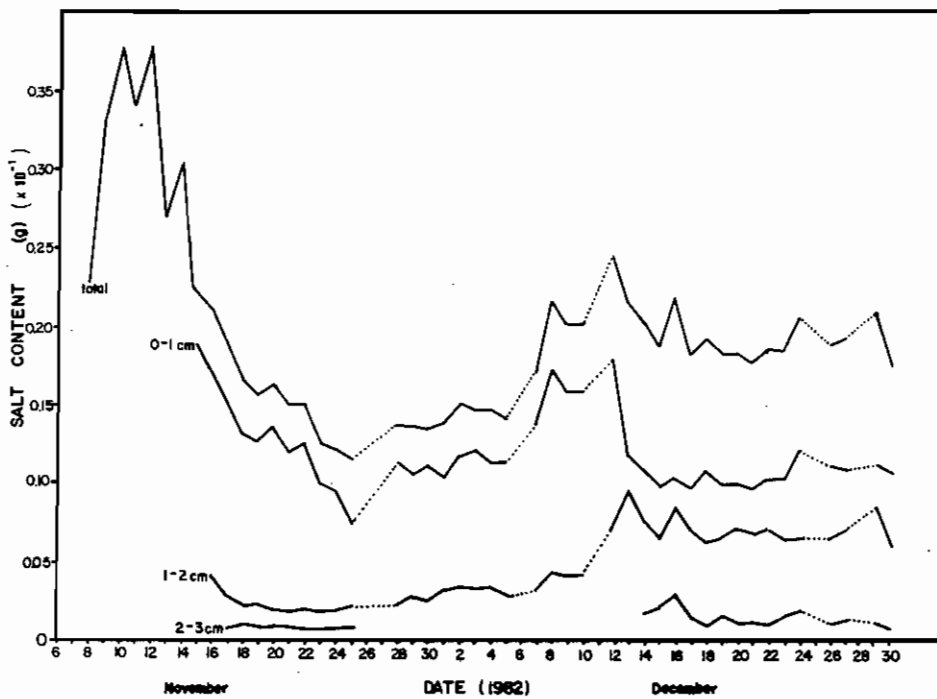


Figure 8

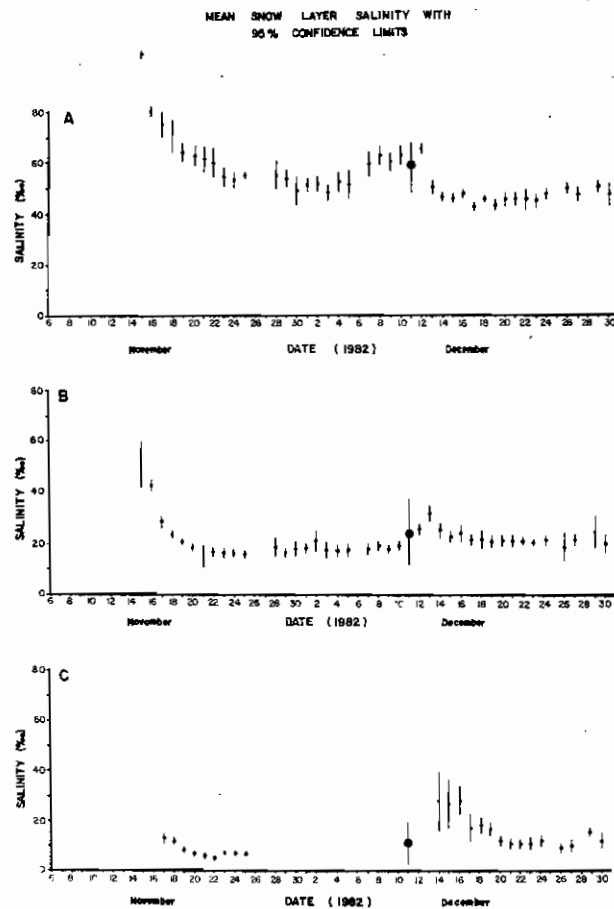


Figure 7. The 95% confidence limits for the snow salinity of the 0-1 cm layer (A), the 1-2 cm layer (B), and the 2-3 cm layer (C). The large dots represent transect values.

MEAN SNOW LAYER SALT CONTENT  
WITH 95% CONFIDENCE LIMITS

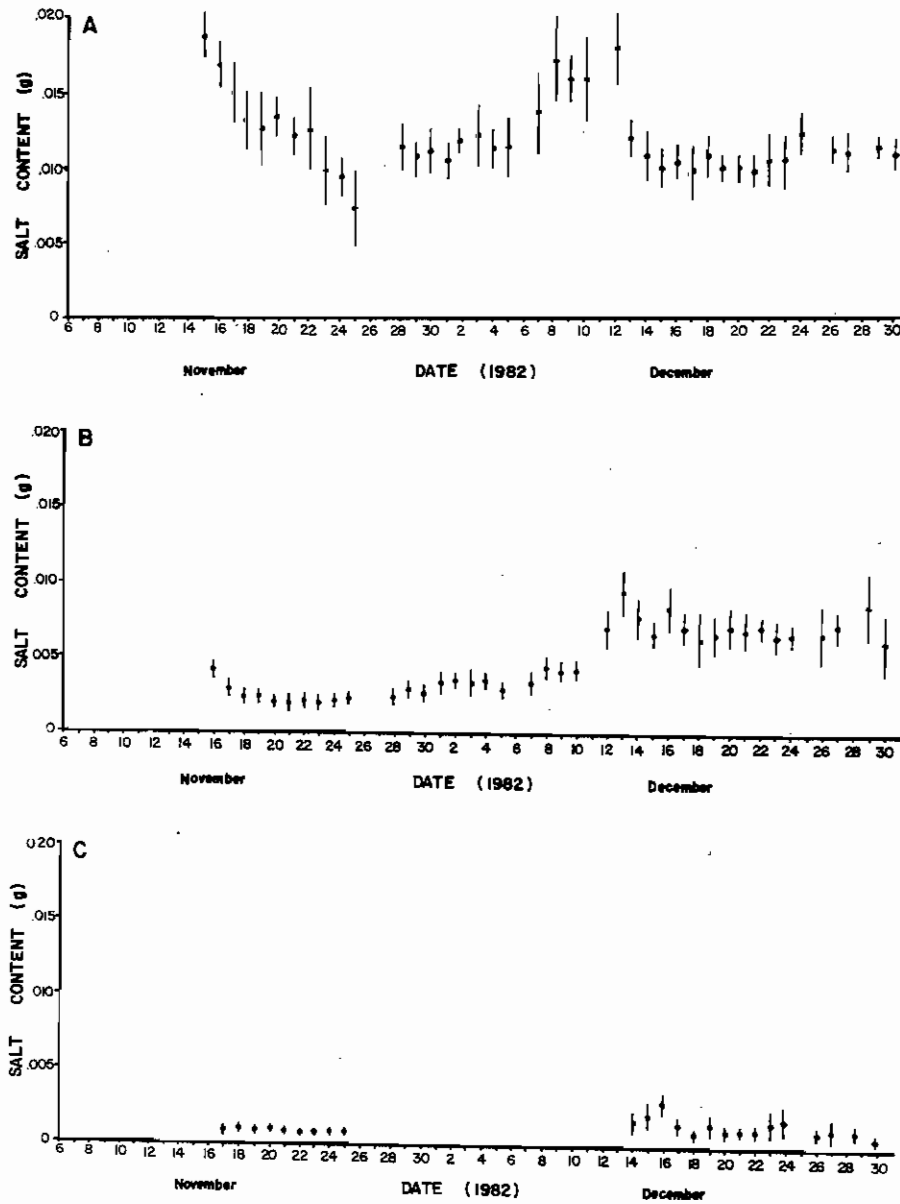


Figure 9. The 95% confidence limits for the total salt content of the 0-1 cm layer (A), the 1-2 cm layer (B), and the 2-3 cm layer (C).

MEAN SNOW LAYER BRINE VOLUME

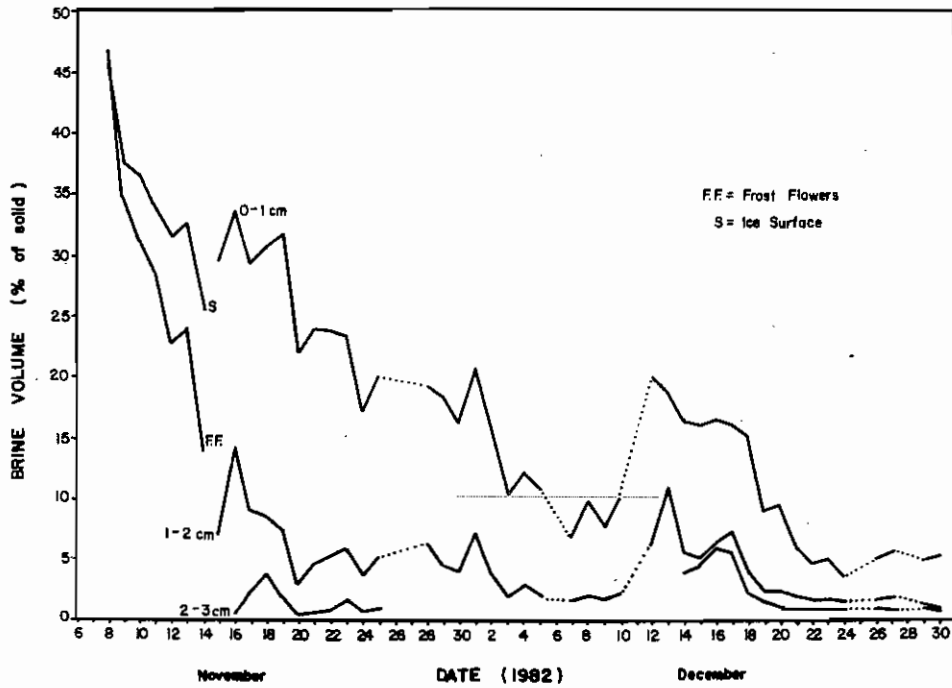


Figure 10. The mean brine volume of each snow layer as a percent of the volume of solid in the ice matrix, calculated using standard sea ice brine volume equations, in combination with data on snow density, salinity, and temperature.