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Growth of first-year sea ice, Eclipse Sound, Baffin Island, Canada

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A simple numerical integration method has been developed for predicting growth of ice under snow cover where solar radiation does not play a dominant role. The method is capable of incorporating variations in snow conditions and physical properties of ice and snow during the growth period. Theoretical predictions compare favourably with field observations in Eclipse Sound, Baffin Island, for the winter seasons of 1977–78 and 1978–79.

Une méthode simple d'intégration numérique a été mise au point pour la prédiction de la croissance de la glace sous un champ de neige, dans les situations où le rôle du rayonnement solaire n'est pas déterminant. Cette méthode permet de tenir compte des variations dans les conditions de la neige et des propriétés physiques de la glace et de la neige durant la période de croissance. Les observations qui ont été effectuées au cours des hivers 1977–78 et 1978–79 à Eclipse Sound, terre de Baffin, ont confirmé, dans une large mesure, les prédictions théoriques.

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Introduction

Geotechnical activities in the north involving ice-covered water masses are on the increase. The safe use of floating ice sheets under static (e.g., drilling platform) and moving loads (e.g., ice bridges and air strips), the use of ice-breakers for moving through ice-covered waters, and the reaction of structures to a moving ice sheet are examples of engineering problems for which it is essential to know the thickness and temperature distribution. These are influenced by the past as well as the prevailing climatological conditions.

Several attempts have been made in the past to predict the growth of sea ice from climatological data (e.g., Zubov 1938, 1945; Tabata 1958; Billelo 1961; Assur and Weeks 1963; Michel 1972). These investigations have resulted in the development of successful empirical equations relating ice thickness to accumulated degree-days of frost. The empirical approach was taken mainly because necessary and reliable information on the growth conditions such as snow thickness and its properties, ice characteristics, data of freeze-up, etc. was lacking.

More recently, during the winters of 1977–78 and 1978–79, it has been possible to collect a large volume of data on weather, snow and ice characteristics, and temperature distribution in the ice at Eclipse Sound (72.7°N, 78.0°W) near Pond Inlet, Baffin Island, Canada. These field data have permitted the development of a simple theory for predicting the growth of first-year sea ice. Ice thickness in the High Arctic can be predicted reasonably well if the daily mean temperatures, snow thickness, and its density are known.

Theory

Consider a growing ice sheet of thickness h_i with a snow cover of thickness h_s subjected to an ambient air temperature of T_a. If, for simplicity, the upper snow surface temperature is assumed to be the same as T_a, and if T_b is assumed to be the snow–ice interface temperature, then under steady-state conditions

$$[1] \quad G_i = (T_m - T_b)/h_i$$

and

$$[2] \quad G_s = (T_b - T_a)/h_s$$

where G_i and G_s are temperature gradients in ice and snow, respectively, and T_m is the melting point of sea ice. It is implicit in the assumption that the physical properties of ice and snow are uniform throughout their respective depths.

If the increase in thickness of the ice sheet is Δh_i in a time period Δt, then the quantity of heat released during freezing is $L\rho\Delta h_i$, where L is the latent heat of fusion and ρ the density of ice. This amount of heat must flow through the ice and snow to the atmosphere, assuming that there is no flow to the water underneath. Thus

$$[3] \quad L\rho\Delta h_i = k_i\left(\frac{T_m - T_b}{h_i}\right)\Delta t = k_s\left(\frac{T_b - T_a}{h_s}\right)\Delta t$$

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where k_i and k_s are the average thermal conductivities of ice and snow, respectively.

The second equality in [3] gives, after rearrangement,

$$[4]\quad T_b = \frac{k_i h_s T_m + k_s h_i T_a}{k_s h_i + k_i h_s}$$

Substitution of T_b from [4] in [1] and [2] gives, respectively,

$$[5]\quad G_i = \frac{T_m - T_a}{h_i + (k_i/k_s)h_s}$$

and

$$[6]\quad G_s = \frac{T_m - T_a}{(k_s/k_i)\, h_i + h_s}$$

Substitution of T_b from [4] in [3] and rearrangement gives

$$[7]\quad \Delta h_i = \frac{k_i k_s}{L\rho}\frac{T_m - T_a}{k_i h_s + k_s h_i}\Delta t$$

Suppose that $T_{a,N}$ is the mean air temperature of the Nth day from the date of freeze-up and Δt is a period of time equivalent to 1 day, that is $\Delta t = 1$. Equation [7] then gives a daily growth rate of

$$[8]\quad \Delta h_{i,N} = \frac{k_i k_s}{L\rho}\frac{(T_m - T_{a,N})}{(k_i h_{s,N} + k_s h_{i,N-1})}$$

where $h_{i,N-1}$ is the ice thickness at the end of $(N - 1)$th day and $h_{s,N}$ is the average snow thickness on the Nth day.

The total ice thickness for a given day is then given by the sum of all the daily growth increments from the first freeze-up day to the day under consideration

$$[9]\quad \sum_1^N \Delta h_{i,N} = \sum_1^N \frac{k_i k_s}{L\rho}\frac{(T_m - T_{a,N})}{(k_i h_{s,N} + k_s h_{i,N-1})}$$

Equation [9] can be rearranged to give

$$[10]\quad \sum_1^N (T_m - T_{a,N}) = \sum_1^N \frac{L\rho}{k_i k_s}(k_i h_{s,N} + k_s h_{i,N-1})\,\Delta h_{i,N}$$

The left side of the above equation is the accumulated degree-days of freezing. Thus [10] describes growth of ice in terms of accumulated degree-days of freezing. The integral form of [10] is given by

$$[11]\quad \int_0^t (T_m - T_a)\,dt = \int_0^{h_i} \frac{L\rho}{k_i k_s}(k_i h_s + k_s h_i)\,dh_i$$

If the snow thickness is assumed to be constant, then [11] reduces to

$$[12]\quad \int_0^t (T_m - T_a)\,dt = \frac{L\rho}{2k_i}h_i^2 + \frac{L\rho h_s}{k_s}h_i$$

which further reduces in the absence of snow cover to

$$[13]\quad \int_0^t (T_m - T_a)\,dt = \frac{L\rho}{2k_i}h_i^2$$

Equation [12] bears close resemblance to Zubov's (1938) empirical formulation

$$[14]\quad \sum(T_m - T_a) = Ah_i^2 + Bh_i$$

where A and B are constants.

Equation [13], on the other hand, is similar to widely used empirical equations of the form

$$[15]\quad \sum(T_m - T_a) = Ch_i^D$$

applied successfully to field data by several investigators (for example, Tabata, 1958; Billelo, 1961). In [15] C and D are constants and D is usually found to be close to 2.

As this theory neglects the effect of incoming solar radiation, it should be applicable to the conditions of near absence of sunlight in the High Arctic during most of the season of ice growth and the low elevation of the sun during the rest of the period.

Methods of Field Observations

An observation area in the ice cover 100 m² was selected and marked each year at Eclipse Sound soon after the ice was safe. These areas were 0.5 km from the nearest shore where the main camp and laboratories of the Arctic Research Establishment were located, and the depth of water underneath was about 150 m. The selection was made during the first week of November for the 1977–78 season and towards the end of October for the 1978–79 season.

Ice cores were recovered from the chosen site at intervals of about a week during the first season and were recovered almost daily during the first 2 months of the second season. The coring locations were about 10 m apart to ensure undisturbed samples. Ice thickness and snow depth at the coring locations were recorded each time a core was removed. Each was taken to the main camp soon after recovery and sectioned into segments of 2.5 cm and then the salinity of each segment was measured by a standard method. Salinity profiles through the thickness of the ice sheet were thereby obtained as regularly as the cores were taken.

Snow density in the observation area was measured at regular intervals of about a week. This was accom-

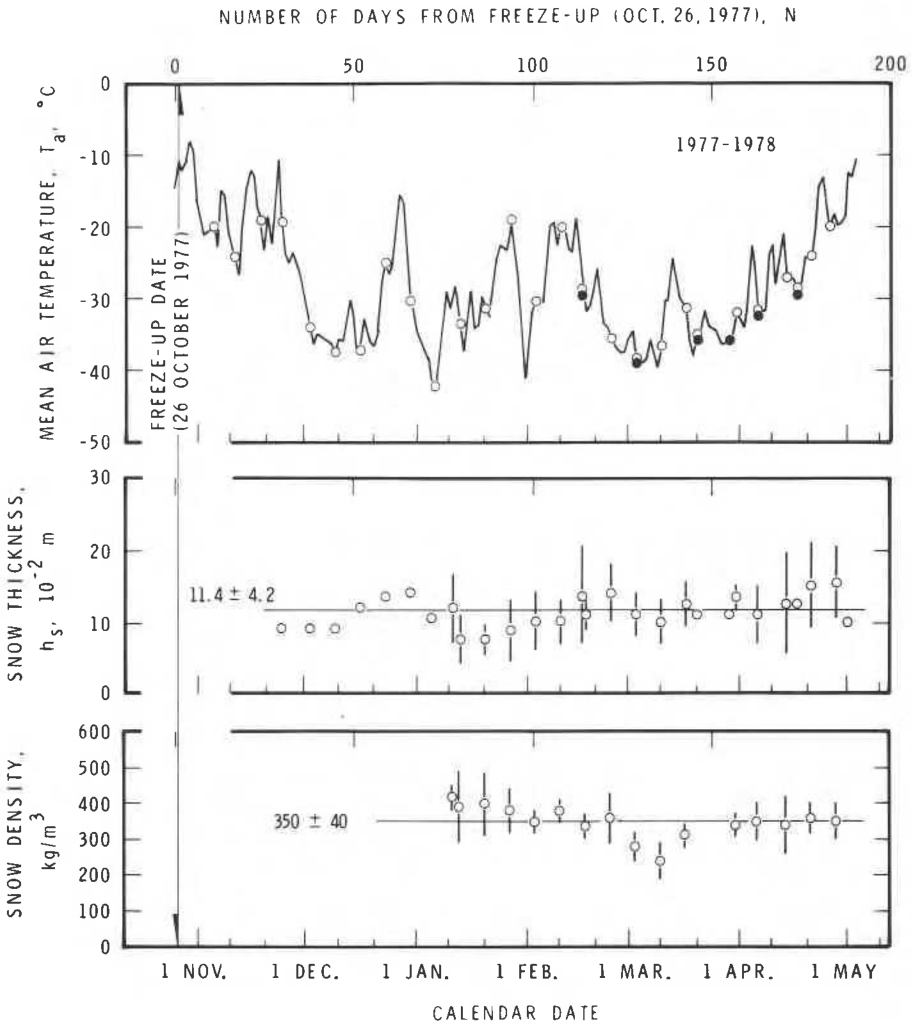

FIG. 1. Variation of daily mean air temperature, snow thickness, and snow density during the winter of 1977–78 at Pond Inlet. Open and solid circles in the recorded temperature variation indicate dates on which ice cores were taken and ice temperatures measured respectively. Single circles for snow thickness and density indicate single measurements, and circles with standard deviation bars describe the mean of about 6 measurements.

plished by taking snow cores of fixed diameter and known depth and determining their mass. During the latter part of each season six vertical snow cores were taken at a time (Figs. 1, 2), providing additional data on snow depth.

Daily maximum and minimum, and hence mean, air temperatures were recorded at the main camp for both the seasons under consideration. Temperature distribution through the ice thickness was also measured several times (Figs. 1, 2) by means of a 2 m long probe with waterproof thermocouple junctions placed 10 cm apart; the topmost sensor was placed in the ice only a few millimetres below the snow–ice interface.

General Field Results

Variations of daily mean air temperature for the major part of the two winter seasons are shown in Figs. 1 and 2, along with the recorded data on snow depth and density. Also shown are the dates on which ice cores were taken and ice temperatures measured. Figure 3 gives examples of measured ice temperatures.

Although the variation in snow depth did not suggest any specific pattern during the first season, the second was marked by a tendency towards gradual thickening of the snow cover. In general, the thickness of the snow cover varied widely not only with time but also with location. It was decided,

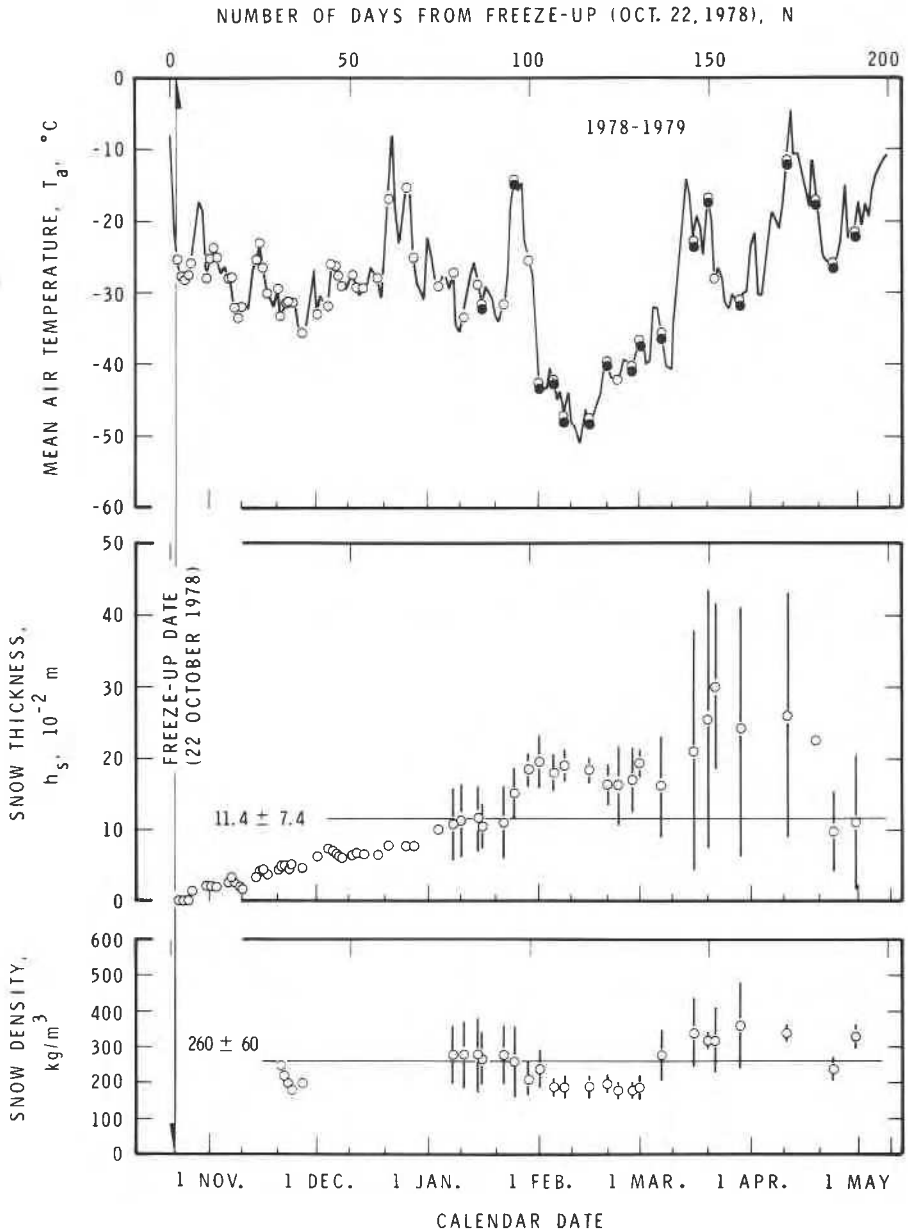

FIG. 2. Variation of daily mean air temperature, snow thickness, and snow density during the winter of 1978–79 at Pond Inlet. Open and solid circles in the recorded temperature variation indicate dates on which ice cores were taken and ice temperatures measured respectively. Single circles for snow thickness and density indicate single measurements, and circles with standard deviation bars give the mean value of about 6 measurements.

therefore, to estimate an average annual snow thickness for both seasons in order to represent the general snow condition in the test area. Average snow depth for 1977–78 was 11.4 ± 4.2 cm; for 1978–79 it showed the same value as for the previous year with a different scatter (11.4 ± 7.4 cm).

The average seasonal snow density was 350 ± 40 $kg\ m^{-3}$ in 1977–78 (Fig. 1) and 260 ± 60 $kg\ m^{-3}$ in 1978–79 (Fig. 2). The first measurement agreed with an earlier survey by Williams and Gold (1958) of 356 ± 52 $kg\ m^{-3}$ at Resolute Bay, about 400 km from Pond Inlet, whereas the second differed significantly.

In agreement with innumerable previous observa-

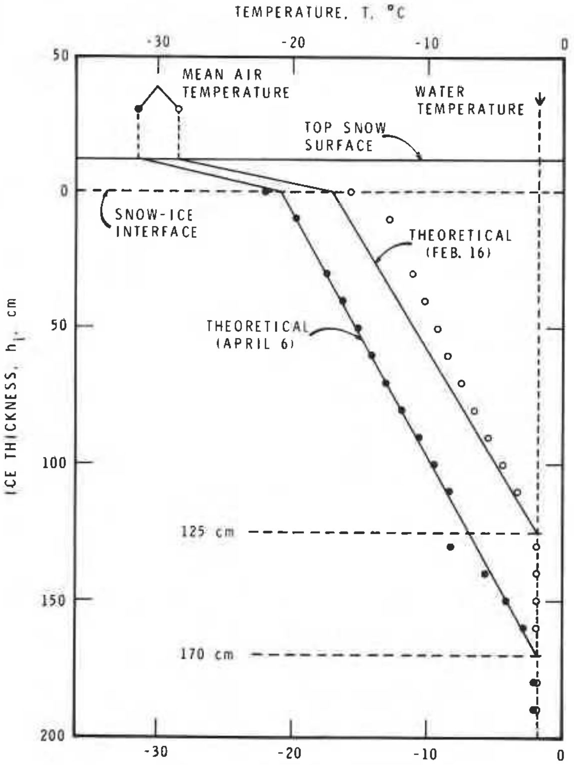

FIG. 3. Comparison of measured and theoretical temperature distributions in the ice sheet for 2 days in 1978.

TABLE 1. Physical properties of snow and ice

Average salinity of water in the test area in Eclipse Sound = 32‰	
T_m	= −1.8°C for sea water with salinity of 32‰ (see also the measured water temperature in Fig. 3)
ρ	= 900±10 kg m^{-3} (density of sea ice at Eclipse Sound, measured at DBR/NRC)
L	= 70 cal g^{-1} (293 J g^{-1}) (Anderson 1960; Schwerdtfeger 1963; Ono 1968)
k_i	= 5×10^{-3} cal cm^{-1} s^{-1} °C^{-1} (2.1 W m^{-1} °C^{-1}) for sea ice of about 6‰ salinity (Schwerdtfeger 1963; Ono 1968)
h_s	= 11.4±4.2 cm (average snow thickness for 1977–78)
	= 11.4±7.4 cm (average snow thickness for 1978–79)
Snow density	= 350±40 kg m^{-3} (average value for 1977–78)
	= 260±60 kg m^{-3} (average value for 1978–79)
k_s	= 6×10^{-4} cal cm^{-1} s^{-1} °C^{-1} (0.25 W m^{-1} °C^{-1}) for snow density of 350 kg m^{-3} at −20 to −30°C (Pitman and Zuckerman 1967; Mellor 1977)
	= 4×10^{-4} cal cm^{-1} s^{-1} °C^{-1} (0.17 W m^{-1} °C^{-1}) for snow density of 260 kg m^{-3} at −20 to −30°C (Pitman and Zuckerman 1967; Mellor 1977)

tions on first-year sea ice, salinity was observed to be high at the top as well as at the bottom of almost all the ice cores. The average bulk salinity of the ice was high during the early growth period in October–November, but decreased to a quasi-stable bulk value of about 6‰ from December on. Evolution of the salinity profile in the ice during 1977–78 is shown in Fig. 4, in which the vertical solid lines at a value of 6‰ are given as a reference. Similar observations were made in 1978–79. It is perhaps important here to mention that the distribution of salinity through the thickness has been shown to be related to previous climatological conditions (Nakawo and Sinha 1981).

Analysis

Theoretical analysis, given earlier, was simplified by assuming steady-state heat flow or, in other words, linear temperature distributions in both the snow

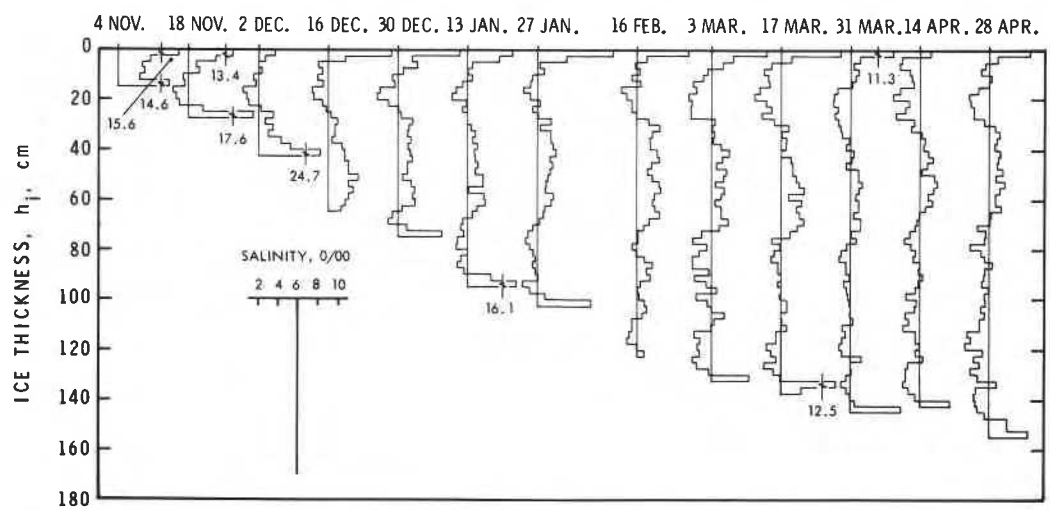

FIG. 4. Salinity profile in the ice at Eclipse Sound at intervals of 2 weeks during the winter of 1977–78; the scale for salinity is shown in the insert; vertical solid lines represent a value of 6‰ and are given as a reference.

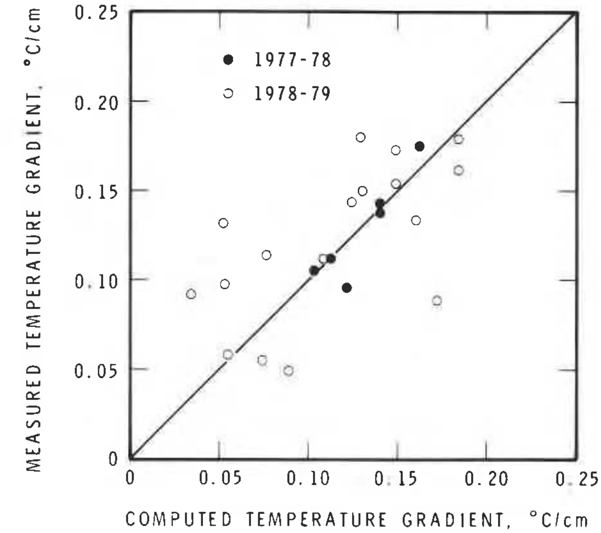

FIG. 5. Comparison of calculated and measured temperature gradients in the ice sheet for 6 measurements carried out February–April 1978 and 17 measurements carried out January–April 1979 at Eclipse Sound.

cover and the ice sheet below the snow. There was a need, therefore, to examine the applicability of this basic assumption using the field data.

Computed temperatures of the snow–ice interface and the temperature distributions in the snow and ice are compared with measured data in Fig. 3. Calculations were made, using the illustrated ice thicknesses estimated from the observed temperature distributions, snow thickness of 11.4 cm, and the material properties relevant to the observed snow and ice conditions (Table 1). Theoretical prediction for 16 February 1978 (Fig. 3) indicates that some consideration should be given to the thermal history previous to the days of measurement because the warm week prior to 16 February (see Fig. 1) led to a warmer ice sheet than that predicted.

A complete analysis must take into consideration the effects of wind and cloud cover, if any, on the heat transfer conditions at the exposed snow surface, the disturbance that might be introduced in temperature distribution by the presence of the probe, and the uncertainty of the thermal conductivities of snow and the highly saline upper and bottom layers of the ice, etc. These refinements are necessary for short-term comparisons of theoretical and measured quantities. The general agreement between estimated and measured temperature gradients in the ice (Fig. 5) supports reasonably well the validity of the assumptions over a long period. Figure 5 presents 6 tempera-

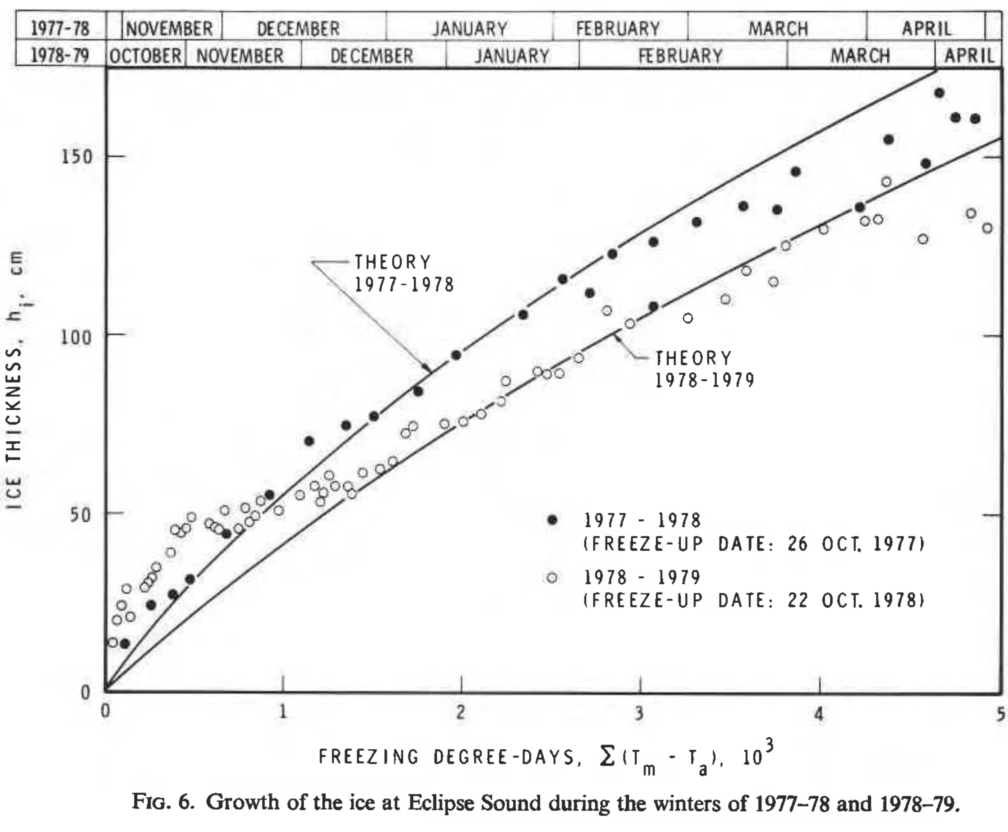

FIG. 6. Growth of the ice at Eclipse Sound during the winters of 1977–78 and 1978–79.

ture measurements from the first season (Fig. 1) and 17 measurements from the second season (Fig. 2). In all these calculations a constant snow cover of 11.4 cm was used with, however, different k_s values to take account of differences in snow densities from one year to another, as given in Table 1.

Growth of ice in the test areas at Eclipse Sound during the two seasons under consideration are shown in Fig. 6 as a function of accumulated degree-days of freezing. Dates given at the top of the figure indicate the time of the season. Calculated results, based on [10] and constant snow thickness of 11.4 cm and appropriate k_s values, agree reasonably well with the observations.

The theory underestimates ice thickness during the early part of the season and overestimates it towards the end. The use of measured snow thickness in calculating the temperature gradient in the ice on any given day and, correspondingly, the use of variable snow thickness (particularly for 1978–79) in computing ice growth might seem to give better agreement with the measurements. Calculations were therefore made using the observed snow thickness variation. These gave better agreement with observations during the early growth period, but did not provide better comparison as a whole. The overall success of calculations using constant snow cover lies in the possibility that assumed thicker snow somehow compensates for the effect of the low k_i and k_s of thinner snow cover during the early stage. The late season deviation in March or thereafter was most probably caused by increasing solar radiation.

Conclusion

The temperature distribution through a sea-ice sheet at Eclipse Sound near Pond Inlet in the High Arctic was approximately linear during most of the winters of 1977–78 and 1978–79 when observations were made. Temperature gradient, however, was dependent on existing air temperature. This dependency is now shown to be predictable with a simple theory, provided that the thickness of ice and snow cover are known and that information on their density and the salinity of the ice are also known. It is shown, further, that a simple theoretical prediction of growth rate and thickness can be reasonably reliable for first-year sea ice for growth conditions under which solar radiation is not a major component of the heat flux. Sufficient data on snow depth and density and a record of daily air temperatures are essential for these calculations.

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