**ARCTIC**
VOL. 32, NO. 2 (JUNE 1979), P. 140-147.

# Thick Sea-ice Floes

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ABSTRACT. This paper examines how sea ice floes of thickness exceeding 6 m can be formed in the Arctic. Such floes have been observed by a Soviet drifting station, by a submarine at the North Pole, and at three sites in the Canadian Arctic Archipelago. The Maykut and Untersteiner model of sea ice growth predicts an equilibrium thickness of 3m under normal conditions, but if the oceanic heat flux is set to zero and the annual snowfall is increased to 1 m growth will continue to at least 12 m thickness over tens of years. The conclusion is that thick floes grow as 'plugs' of fast ice in constricted channels of shallow water at high latitudes, and that they break out into the Arctic Ocean only after many years of growth in place. Their history in some respects resembles that of Arctic ice shelves.

RÉSUMÉ. Les contraintes de cisaillement ou de convergence sont généralement à l'origine d'une épaisseur exceptionelle de la banquise, sous la forme de rides ou de monticules de glace, auparavent écrasée. Bien que l'épaisseur normale de la glace de mer, formée par les forces thermodynamiques, soit de 3 mètres dans les régions polaires, des rapports cà et là, signalent des épaisseurs de l'ordre de 10 mètres de glace d'origine thermodynamique. L'auteur étudie ces observations.

La glace de mer se forme par congelation et perte de chaleur dans l'atmosphére — la structure cristalline de la glace favorise sa croissance dans une direction privilégée. En cas de croissance rapide, des plaques de glace san structure granulaire organisée peuvent se former. Le poids de la neige sur la plaque de glace peut favoriser l'infiltration d'eau de surface qui cristallise en glace — la glace pluriannuelle peut contenir des lentilles de glace d'eau douce formée à l'automne à partir du gel de la surface des étangs ou de glace d'origine de masses de neige insuffisament fondues en été. Les premiers observations relatives à une banquise épaisse datent de 1955 avec la station NP-6 de Cherepanov qui a derivé sur un morceau de banquise puis celles de 1972 dans le Nansen Sound (Ellesmere) et Prince Patrick. Les plaques de 10 mètres d'épaisseur se seraient formées en 40 ans. Le sousmarin nucléaire "Sovereign" a identifié une plaque d'épaisseur analanalogue sous le pôle. Les calculateurs permettent maintenant de concevoir des modèles de croissance de glace d'origine thermodynamique, faisant intervenir de nombreuses paramètres — les calculs confirment la possibilité d'épaisseur normale de 5, 5.6 ms, 6 ms, voisine de celles observées. En accroissant le paramètre "charge de neige", on peur atteindre 7 ms; avec une glace de 65 ans d'age, on peut atteindre 12 mètres. Le retour à une épaisseur d'équilibre peut être assez rapide.

DISCUSSION. Dans les conditions le plus sévères possible de climat actuel, une épaisseur de glace de 20 mètres est possible dans des baies peu profonds où le flux calorifique océanique est réduit au minimum. Cherepanov observait que ces épaisseurs anormalement élévées de glace se forment, plus en situation fixe qu'en mer ouverte. C'est le cas des plaques de glace formées entre les îles arctiques du Spitzberg, sur les côte, NE du Groenland et au nord d'Ellesmere — Les glaciers sont à l'origine de ces plaques mais des changements de climat sont un facteur important d'épaissement. Si les îles de glace sont de formation lente, leur reduction vers l'épaisseur d'equilibre dans l'océan arctique sera beaucoupe plus rapide.

Traduit par Alain de Vendegies, Aquitaine Company of Canada Ltd.

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## INTRODUCTION

Sea ice of exceptional thickness is normally formed mechanically by convergent and shear stresses in the ice cover which build ridges and hummocks out of formerly undeformed ice. Under present climatic conditions the equilbrium thickness of sea ice which grows thermodynamically is only about 3 m in north polar regions. However, there have been isolated reports of undeformed sea ice floes that have attained thicknesses of 10 m or more while retaining a crystal structure indicative of purely thermodynamic growth. It is therefore of interest to consider where and how this thick sea ice may have formed in the Arctic regions.

## SEA-ICE FORMATION

Most sea ice is formed as a result of the congelation process, whereby heat loss to the atmosphere from the sea surface creates an initial skim of ice which grows downwards by accretion. The growth of an ice crystal is easiest in a plane perpendicular to the c-axis, and so crystals with c-axis horizontal are favoured in a growth selection process. Thus below an initial transition layer of about 0.5 m thickness the ice sheet has a characteristic columnar structure of crystals with vertical basal planes.

In some conditions, especially those of rapid growth, a more granular and disorganised structure can occur due to underwater ice (Lewis and Weeks, 1971), which forms as platelets in the water column just below the ice sheet, possibly due to cold descending brine streamers. The platelets then become incorporated in the structure of the growing ice. Yet another crystal structure derives from the freezing of water which floods the surface of a sea ice sheet due to the weight of overlying snow reducing the ice freeboard to zero (infiltration ice). Multi-year ice also may have lenses of fresh-water ice

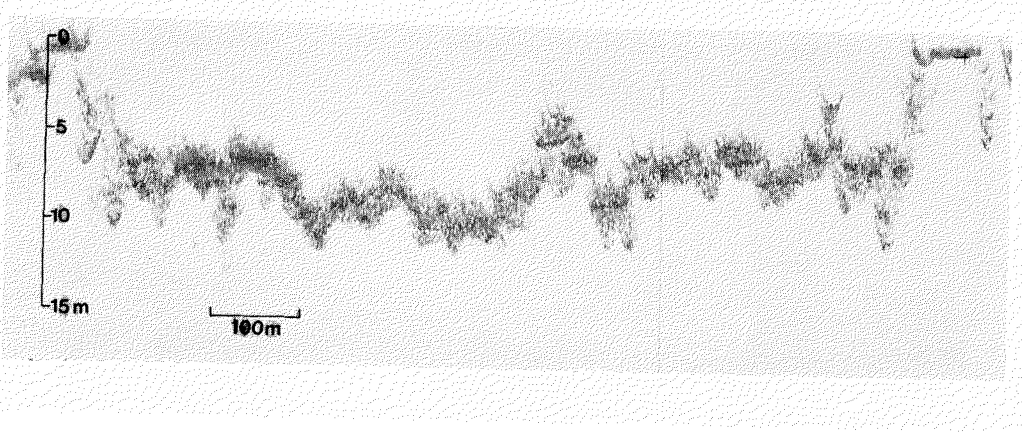

FIG. 1. Sonogram of a thick sea ice floe observed at the North Pole by H. M. submarine "Sovereign" on 23 October 1976. The upward-looking transducer had a beamwidth of 17° and profiled from 75 m depth.

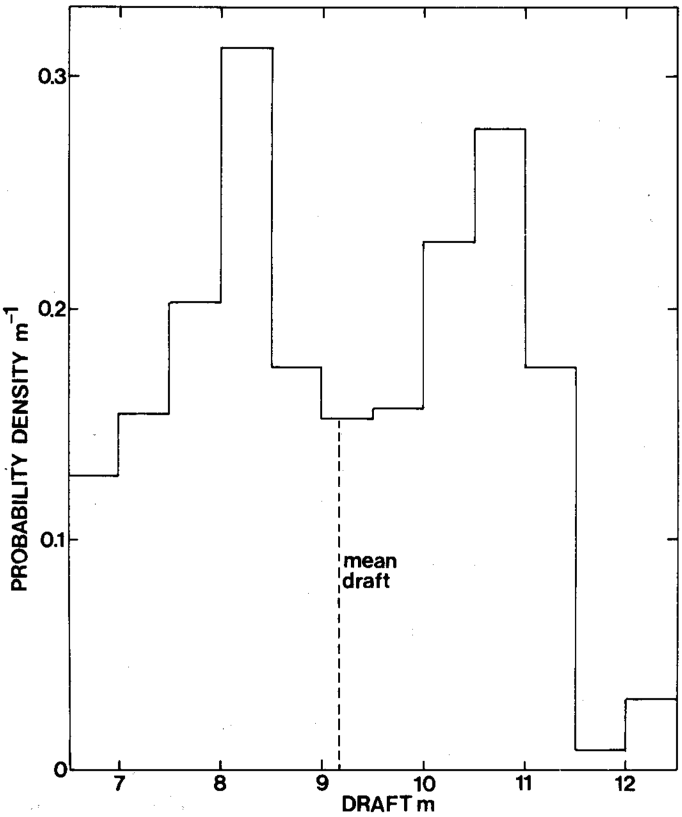

FIG. 2. Histogram of ice drafts for the thick floe of fig. 1. Bin size 0.5 m. The vertical scale is normalized to give a total area of unity under the distribution.

forming in autumn from the freezing of surface melt ponds, or of compressed firn originating from a snow load which does not completely melt in the summer. Lastly, of course, there are ice deformation structures such as hummocks, rafting and pressure ridges.

## OBSERVATIONS OF THICK SEA ICE

The first observation of exceptionally thick sea ice in the modern era was by Cherepanov (1966) in 1955. The Soviet drifting station NP-6 was situated on an 80 km$^2$, ice floe of 10-12 m thickness and of crystal structure clearly suggesting slow congelation growth. Cherepanov remarked that floes of such thickness are met with "quite often", but usually are only about 0.5-1 km across.

Later observations came from the channels of the Canadian Arctic Archipelago. Serson (1972) described a 'plug' of multi-year ice in Nansen Sound (81°N, 92°W), Ellesmere Island. some parts of this plug were 10 m thick. Using measurements of ablation and climatic data Serson estimated that the ice could have reached a thickness of 6 m over a growth period of 40 years. From historical evidence Serson believes that the plug may have been in existence since 1932, although it broke up and moved out of Nansen Sound some time after 1971, when Serson studied it. Serson's note contains no details on the crystal structure which could allow discrimination between congelation ice and ice that may have been formed mechanically. Serson (1974) has also reported a plug of sea ice in Sverdrup Channel (80°N 98°W) of about 6 m thickness. A. R. Milne (pers. comm.) encountered an ice floe 10-12 m thick on an icebreaker probe west of Prince Patrick Island in 1965.

In October 1976 the British nuclear submarine HMS "Sovereign" obtained a sonar profile of Arctic Ocean sea ice along a 3900 km track (Wadhams, 1977). Only one thick floe could be unequivocally identified in this profile, and this is shown in Figure 1. The floe is 0.98 km in length and was encountered at the North Pole on 23 October 1976 while the submarine was searching for a polynya. The draft ranges between 6.5 m and 12.5 m, with a mean of 9.18 m and a standard deviation of 1.44 m. The draft distribution (Fig. 2) is actually bimodal, with two preferred drafts in the ranges 8-8.5 m and 10.5-11 m, reflecting the roll-type roughness apparent on the ice underside. A mean draft of 9.18 m implies a mean ice thickness of about 10.2 m. Although the topography of the floe appears rough in the sonogram this is partly because of the vertical scale exaggeration; in fact it is smooth enough to be clearly differentiated by eye from pressure ridge keels which are traversed at glancing incidence by the submarine and which therefore have a long profile (Wadhams, 1978). Although the boundary between the two major Arctic Ocean surface current systems is not well delineated, it is normally supposed that the North Pole lies within the influence of the Trans Polar Drift Stream, so that this floe may well have originated as, say, a 'plug' in the channels of the New Siberian Islands or Severnaya Zemlya. The occurrence of only one such floe in 3900 km of profile implies that thick floes are rare enough to be easily missed during a single transit of the Arctic Ocean; Koerner (1973), for instance, found no floes thicker than 5.75 m during a surface crossing of the Arctic Ocean by dog sledge.

We can infer from these observations that flows over 10 m thick can be formed by the congelation process, but only under circumstances unusual enough to make such flows rare.

## THERMODYNAMIC MODELLING

Models of ice growth have been formulated for many years, but only recently has the advent of the computer allowed numerical solutions to be easily obtained. In this section we shall consider some calculations based on the Maykut and Untersteiner (1971) model of ice growth. This is a one-dimensional thermodynamic model which includes effects of snow cover, ice salinity and internal heating due to penetration of solar radiation. Surface energy balances determine rates of ablation and accretion; diffusion equations govern heat transport within ice and snow. The incoming radiative and turbulent fluxes, oceanic heat flux, ice salinity, snow accumulation and surface albedo are specified as functions of time. Starting from an arbitrary

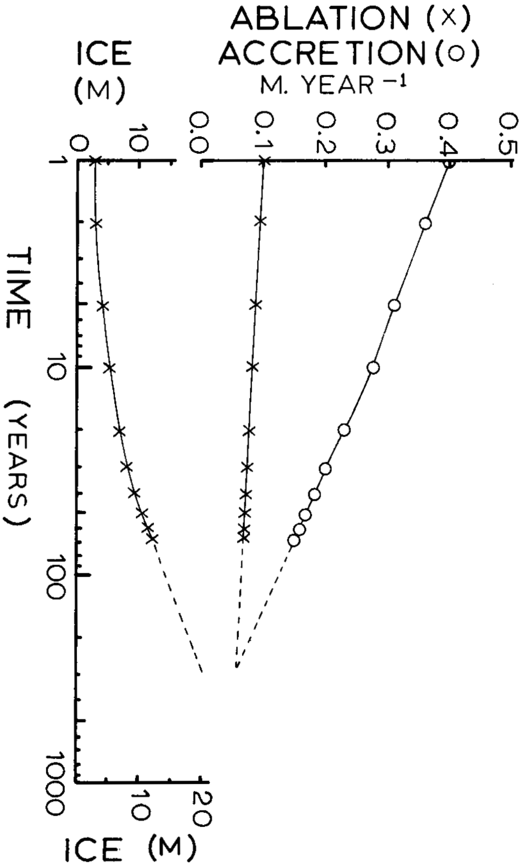

FIG. 3. Ice thickness (m) and ablation and accretion rates (m year$^{-1}$) from the model of Maykut and Untersteiner (1971) using standard parameters, an initial ice thickness of 3 m, 1 m of snowfall annually and no heat flux from the ocean. The dashed extrapolations indicate an equilibrium thickness of about 20 m with an ablation and accretion rate of about 0.05 m year $^{-1}$.

initial condition the model is integrated numerically towards annual equilibrium in ice temperature and thickness. The main limitations of the model include the necessity of specification of quantities in the surface heat budget, details of heat transport from the melting snow, and treatment of the melt ponds. Also, since it deals only with a uniform ice sheet, it cannot treat the effects of leads or of thickness redistribution by ridge building.

Maykut and Untersteiner tested their model by specifying best estimates of components of the surface heat balance. Choosing annual values of incoming shortwave radiation of 75.4 kcal cm$^{-2}$ (3.16 GJ m$^{-2}$), incoming long-wave radiation of 166.0 kcal cm$^{-2}$ (6.95 GJ m$^{-2}$), flux of sensible heat of 2.7 kcal cm$^{-2}$ (0.11 GJ m$^{-2}$), loss of latent heat of 3.2 kcal cm$^{-2}$ (0.13 GJ m$^{-2}$), flux of 1.5 kcal cm$^{-2}$ (0.06 GJ m$^{-2}$) from water to ice, annual snowfall of 0.4 m, and summer ice albedo of 0.64, the equilibrium thickness of sea ice was predicted at 3.14 m at the end of growth, 2.71 m at the end of ablation. The surface ablation was about 0.4 m, bottom ablation was 0.05 m and bottom accretion was 0.045 m in

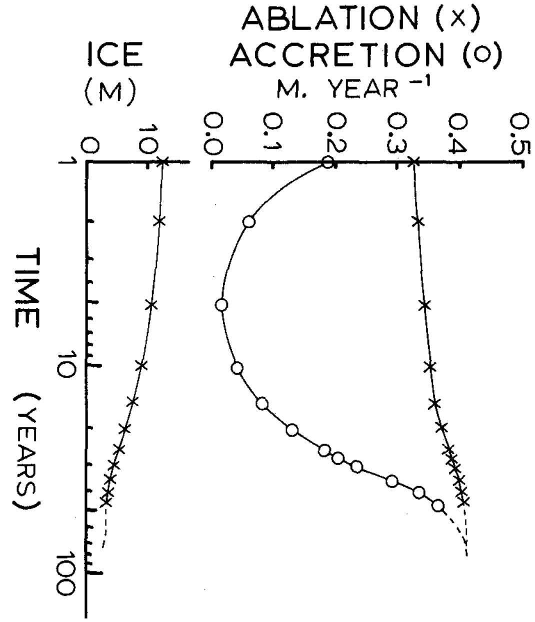

FIG. 4. Ice thickness (m) and ablation and accretion rates (m year $^{-1}$) from the model of Maykut and Untersteiner (1971) using standard parameters and an initial ice thickness of 12 m.

each year. These, and other values furnished by the model, agree fairly well with observations from the Arctic Ocean.

With specified paramaters changed only in that the heat from the ocean was set to zero Maykut and Untersteiner found the ice reached an equilibrium thickness of 5.6 m, close to that reported by Serson in very old sea ice in the northern archipelago. Annual ablation was 0.39 m at the surface, annual accretion 0.39 m on the ice bottom. With standard Maykut input but with increasing snowfall, the ice thickness increased, reaching (at a value of annual snowfall of 1.2 m) an annual equilibrium of 7.02 m with annual ablation at the top of 0.005 m, ablation at the bottom of 0.021 m and accretion at the bottom of 0.026 m. When the annual snowfall was more than 1.2 m the specified parameters did not allow complete melting of the snow which then accumulated upon the top of the ice.

To estimate ice growth and equilibrium thicknesses under conditions different from those in the Arctic Ocean the Maykut model standard input was changed, setting the oceanic heat flux to zero and the annual snowfall at 1.0 m. Other parameters were unchanged. When the model was run for 65 years sea ice of equilibrium thickness (3.0 m) increased in thickness to about 12 m (Fig. 3). Annual surface ablation fell from about 0.09 m at the beginning to about 0.06 m after 60 years, while bottom accretion fell from about 0.40 m to 0.15 m in the same time. Projecting from the curves in Figure 3, one might estimate that equilibrium will be reached in 200-300 years with an equilibrium thickness of about 20 m and annual ice top ablation and ice bottom accretion of about 0.05 m.

If ice of such thickness had formed, and then was exposed to the heat budget paramaters suggested by Maykut and Untersteiner as typical of the present-day Beaufort Gyre, reduction in the thickness might be expected to occur relatively rapidly. To indicate this, ice of initial thickness of 12 m was used in Maykut's model with standard values of the heat budget parameters. The results are shown in Figure 4. In 45 years the thickness falls to about 3 m as ice surface ablation rises to 0.41 m while ice bottom growth increases to about 0.37 m (the model taking a year or two to 'settle down' at the beginning of the run). Extrapolation from the curves indicates that Maykut's standard equilibrium values should be reached within 100 years, although the vast majority of ice wastage occurs in the first 40 years.

## DISCUSSION

It has been demonstrated that, in the present climate in locations of little or no oceanic heat flux and with annual snowfall of about one metre, congelation sea ice might reach thicknesses of about 20 m. Those parts of the world where these conditions might occur should be in high latitudes, probably in shallow bays where advection of oceanic heat is small. If annual snowfall should be less than one metre such locations may be subject to snow blown off nearby land. Strong evidence that thick sea ice grows in a fixed location rather than the open sea comes from an observation of Cherepanov (1966) that the ice of NP-6 showed strong horizontal c-axis orientation; this is a phenomenon reported by Weeks and Gow (1978) for fast ice growing in a current. The most favourable locations should be where ice 'shelves' have been reported, such as between the islands of Severnaya Zemlya, between the islands of Franz Josef Land, in Svalbard off the southern coast of Nordaustlandet and off the east coast of Edgeya, off the northeast coast of Greenland and along the north coast of Ellesmere Island.

While many of these ice shelves appear to have originated from glacier tongues the formation of some appears more complicated. The Ward Hunt Ice Shelf in northern Ellesmere Island (84°N 75°W) seems to have a core of sea ice 20 m thick with firn and brackish water ice above, and brackish water ice below to give a total shelf thickness of 50 m (Lyons *et al.*, 1971). It has been suggested that the present shelf is the result of thickening, mainly during the climatic deterioration of the last millennium, of a floating ice shelf (of thick sea ice?) which grounded in the area. At present the mass balance of these Ellesmere shelves appears to be negative and indeed parts have broken off to form ice islands (Hattersley-Smith and Serson, 1970).

Scores of ice islands or ice island pieces have been discovered in the last 30 years. If we choose an initial ice island thickness of 50 m a rough calculation shows that in the Arctic Ocean, with surface ablation of 0.2 - 0.3 m annually and little bottom accretion initially, the thickness would be reduced to 12 m in less than 200 years, after which the equilibrium thickness of 3 m would be approached as noted in Figure 4. Some of the ice islands described (such as Arlis II) are horizontally inhomogeneous so mechanical breakup may be expected to speed thermodynamic decay. So, as with thick congelation floes, the ice islands have a lifetime in the Arctic Ocean which is very brief compared to their existence in the areas in which they formed.

## CONCLUSION

It has been demonstrated that congelation sea ice can grow in the north polar region to thicknesses of at least 12 m under present climatic conditions, in localities exhibiting annual snowfall of around 1 m and little or no oceanic heat flux. The most favourable localities appear to occur in bays or channels of islands in very high latitudes. Once sea ice of thickness 12 m is released into the Arctic Ocean it should, in a few score years, be reduced to the thermodynamic equilibrium thickness of 3 m. Under the conditions postulated the equilibrium sea ice thickness is at least 20 m. A sea ice layer of this thickness forms the core of the Ward Hunt Ice Shelf, although this core (and indeed the whole shelf) may have formed under colder climatic conditions during the last millennium.

## ACKNOWLEDGEMENTS

One of us (PW) gratefully acknowledges the support of the Office of Naval Research, under contracts N00014-76-C-0660 and N00014-78-G-0003. We also wish to thank the captain and crew of HMS "Sovereign".

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