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PHYSICAL PROPERTIES OF THE ICE COVER OF THE GREENLAND
SEA(U) COLD REGIONS RESEARCH AND ENGINEERING LAB
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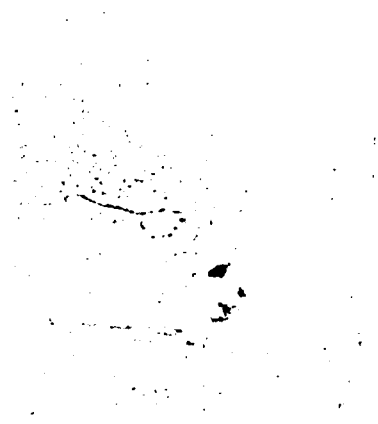
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Special Report 82-28	2. GOVT ACCESSION NO. AD-A123712	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) PHYSICAL PROPERTIES OF THE ICE COVER OF THE GREENLAND SEA		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) W.F. Weeks		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire 03755		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS ONR #N0001482MP20006
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Arlington, Virginia 22217		12. REPORT DATE November 1982
		13. NUMBER OF PAGES 30
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Greenland Ice Ice properties Sea ice		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) There is very little information available on the physical properties of the ice cover of the Greenland Sea. This paper reviews what is known about the different types of ice that are believed to occur in this area. It also discusses how the internal structure and composition of these ice masses may differ from those of the more extensively studied ice of the Beaufort Sea and identifies gaps in the present knowledge of the properties of such ice masses (regardless of place of origin). Finally a strategy is outlined for efficiently studying the properties of the ice in the Greenland Sea by combining structural and compositional characterization with limited property determinations.		

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PREFACE

This report was prepared by Dr. W.F. Weeks, Glaciologist, Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. It was funded by the Arctic Program of the Office of Naval Research under ONR #N0001482MP20006, Numerical Modeling of Arctic Ice Cover and Ocean.

CONTENTS

	Page
Abstract-----	1
Preface-----	11
Introduction-----	1
Ice types-----	2
Icefoot-----	2
Fast ice-----	2
Pack ice-----	3
Ice structure and composition-----	5
Structure-----	5
Composition-----	12
Suspected differences in the ice of the Greenland Sea----	13
Physical properties-----	17
Conclusion-----	21
Literature cited-----	22
Appendix A: Measurements of sea ice properties in the Greenland Sea-----	27

ILLUSTRATIONS

Figure

1. Major drift patterns of polar ice in the Arctic Basin---	4
2. Schematic drawing showing several aspects of the structure of first-year ice-----	8
3. Photomicrograph of a horizontal thin section of first-year sea ice showing both individual crystals and the substructure within the crystals-----	9
4. Photomicrograph of a vertical thin section of first-year ice from the columnar zone-----	9
5. Schematic drawing of representative salinity profiles from different thicknesses of first-year and multiyear ice-----	11
6. Schematic drawing of the layering and grain structure of a multiyear ice floe-----	11

TABLES

Table

1. Percentages of different ice types based on visual observations collected on the Birdseye flights-----	4
2. A general assessment of the current state of knowledge of a number of structurally sensitive physical properties of sea ice-----	18



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PHYSICAL PROPERTIES OF THE ICE COVER OF THE GREENLAND SEA

by

W.F. Weeks

INTRODUCTION

A recent paper by Wadhams (1981) thoroughly reviews our knowledge of the ice cover in the Greenland Sea. Included in it are discussions of the different ice types that have been observed in this area, the variations in the relative percentages of these types, the geometry of the ice masses, their drift and dynamics, and finally a number of physical processes, such as wave-induced breakup, that are believed to be particularly important at the ice margins. Nowhere is there a detailed discussion of either the internal structure of the ice or its physical properties. The cause of this absence is simple; there appears to be little published work on the subject (see Appendix A).

The reasons that investigators have neglected these topics are also simple. Both East Greenland and Svalbard are isolated locations with few sites that can be used as bases for field operations. In addition, even if adequate land bases were available, the ice pack in these regions is both extremely active and deformed. Therefore, movement to and from stations on the ice was nearly impossible before the advent of STOL aircraft and helicopters (one could commonly get out on the pack; whether one could also get back to land was another matter). Even today such field operations are hazardous. Finally economic or operational motivation for studying the physical properties of the ice was not present. Early work (for instance, the early sea ice bearing-capacity studies performed at Thule on the north-

western coast of Greenland [Weeks and Anderson 1958, Kingery 1962]) was invariably carried out at more convenient locations that were closer to the sites where operational problems were encountered. Until the recent discovery of oil and gas in the North American Arctic, studies of the physical properties of sea ice were limited, regardless of the location.

As observations that do not exist cannot be discussed, there are two possible options: to terminate the discussion (a choice always open to the reader by terminating reading) or to construct a "house of cards" based on speculations concerning the presumed internal structure and composition of the ice in the Greenland Sea. I chose the latter option, as I believe that it provides insights useful in estimating the range of physical property variations that would be expected and aids in planning programs to study these variations. However, as is true with all untested products, the reader is advised to heed the dictum caveat emptor.

ICE TYPES

There are a wide variety of types of sea ice that are known to occur in the Greenland Sea. Briefly these types are as follows (Koch 1945):

Icefoot

This belt of sea ice is frozen to the coast and is unaffected by tides. As this belt is extremely narrow, it covers relatively little area and it will not be discussed further. Additional descriptions of this phenomenon in Greenland and Vestspitsbergen can be found in Feyling-Hanssen (1953).

Fast ice

This ice is more or less fixed to the coast; however, it moves up and down with the tide and in some cases can move many hundreds of meters laterally. More important than its movement history is its age. Much of the fast ice is first-year ice with thicknesses of 2 m or less. In

locations where it is well protected, this ice can survive through the summer, becoming second-year and then multiyear fast ice. Fast ice that survives more than 10 years has been categorized as a separate ice type, called sikussak (Koch 1945). Sikussak can reach thicknesses in excess of 10 m (Walker and Wadhams 1979); typical multiyear ice thicknesses in the Arctic Basin are 3-4 m. Whether the sikussak regions reported by Koch in north and northeastern Greenland still exist is apparently unknown.

Pack ice

The vast majority of the ice in the Greenland Sea is pack ice, as the fast ice is usually found only in the fjord systems or along stretches of coastline heavily protected by offshore islands. The ice types include floes of sikussak that may have originated in Greenland or from locations in Severnaya Zemlya or Franz Josef Land. Evidence suggests that such extremely old ice is rare.

The dominant ice type is typical multiyear ice that has developed during a 2- to 3-year drift from the continental shelves of Siberia. This ice passes over the Pole in the Trans-Polar Drift Stream (Fig. 1) and ultimately exits from the Arctic Basin via the East Greenland Drift Stream. During this journey much of the ice becomes highly deformed. In fact, remote sensing, visual observations and modeling all suggest that the most intensely deformed ice in the Arctic, the so-called paleocrystic ice of Nares (1878), occurs in the shear zone off Northeast Greenland, where the motion of the Transpolar Drift is partially blocked. The width, length and stability of this zone are unknown. Multiyear ice also enters the Greenland Drift Stream from north of Svalbard and from the vicinity of the Soviet arctic islands, although presumably in amounts appreciably less than the ice introduced via the Trans-Polar Drift Stream. The ice from these "less-than-polar" sources is generally believed to be younger and less

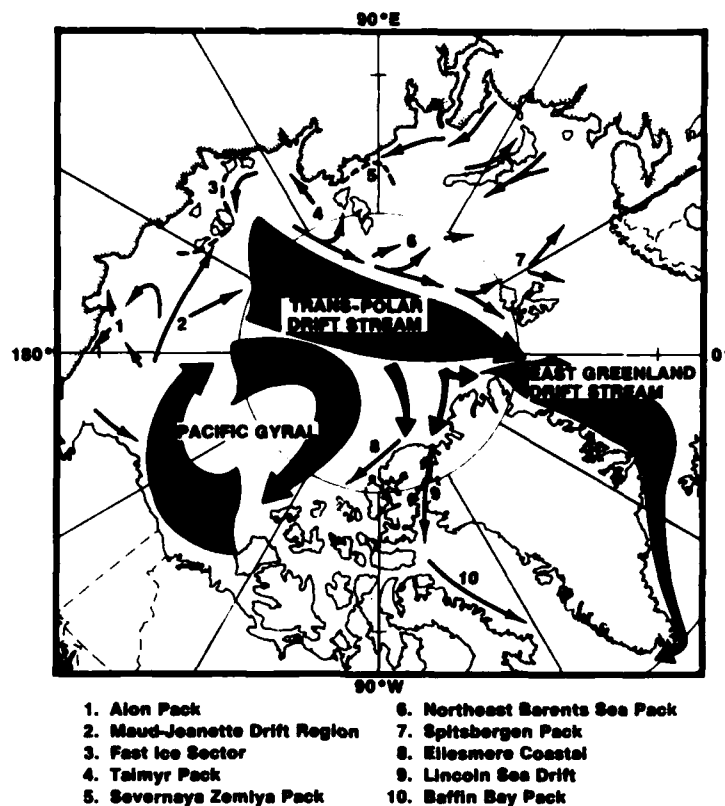


Figure 1. Major drift patterns of polar ice in the Arctic Basin. (After Dunbar and Wittmann 1963.)

Table 1. Percentages of different ice types based on visual observations collected on the Birdseye flights (Wittmann and Schule 1966).

	New ice	Thick winter ice	Second-year and multiyear ice	Number of observations
Winter (Jan-May)				
Eurasian Basin	4	10	86	168
Lincoln Sea & N. Greenland	6	24	71	175
Greenland Sea	30	47	23	128
Barents Sea	18	23	58	76
Spring (June-July)				
Eurasian Basin	Tr.	6	93	75
Lincoln Sea & N. Greenland	2	26	72	41
Greenland Sea	27	34	39	35
Barents Sea	15	26	59	12
Summer (Aug-Oct)				
Eurasian Basin	9	12	79	126
Lincoln Sea & N. Greenland	13	28	59	76
Greenland Sea	26	31	44	99
Barents Sea	38	22	40	10
Fall (Nov-Dec)				
Eurasian Basin	8	1	91	53
Lincoln Sea & N. Greenland	26	32	43	40
Greenland Sea	52	43	5	90
Barents Sea	40	31	28	25

deformed. Although it has been suggested that it might prove possible to clearly assign different parts of the ice in the Greenland Sea to different source regions, current satellite observations are not particularly encouraging, as the two-dimensional flow within the pack is rather turbulent, resulting in appreciable lateral mixing of ice types.

Incorporated in the multiyear pack is a significant amount of first-year ice with thicknesses varying from a few centimeters to 2 m. This ice characteristically forms within the pack, covering leads that form during periods of ice divergence. During subsequent periods of ice convergence, appreciable amounts of the thinner classes of first-year ice are deformed into pressure ridges and rubble fields. Table 1 gives very rough estimates, based on aerial ice reconnaissance flights (Wittmann and Schule 1966), of the amounts of different types of ice present in the areas under discussion.

As noted by Wadhams (1981) our current knowledge of the ice-thickness distribution for ice in the Greenland Sea is limited. Present sonar data suggest that at the latitude of the Denmark Strait the thickness distribution of the ice is generally similar to that of the pack of the Central Arctic, except that the maximum keel drafts of the pressure ridges off Greenland were appreciably lower, presumably due to ablation during the drift down the Greenland coast. Little appears to be known about the thickness distribution of the ice near Svalbard and farther east.

ICE STRUCTURE AND COMPOSITION

Structure

The two most important factors that control the physical properties of a specific specimen of sea ice are its internal structure and its composition. The structure determines how the sea ice crystals are shaped and how the brine and air impurities are distributed within the ice mass. The com-

position determines the relative amounts of air and brine that coexist within the ice at a given temperature. Here I will first describe the factors that control the structure and composition. Then I will speculate on how and why the nature of the ice in the vicinity of Greenland and Svalbard may prove to be different from ice at locations that have been studied more closely.

When the sea freezes, the nature of the initial ice layer depends on the state of the sea at the time of freezing. If the sea is calm, large crystals form that may have their c-axes oriented vertically, and a thin (1-2 cm) skim develops quickly on the water surface. If, on the other hand, the ocean is turbulent, free-floating crystals of ice may develop in the water column. This is called frazil ice. The grain size is typically small (<2 mm), and abrasion and rotation of crystals relative to one another results in a random c-axis orientation. At places along the Alaskan coast, frazil layers with thicknesses of up to 1.3 m have developed during initial freeze-over (Weeks and Gow 1980).

Once an initial ice layer has covered the sea surface, the crystals at the ice/seawater interface grow downward and compete with each other for domination of the interface. The favored crystals have horizontal c-axes, and their direction of easiest growth is parallel to the direction of heat flow (vertical). Associated with this growth competition between grains is a rapid increase in grain size. The portion of the ice sheet where rapid changes in crystal orientation occur is called the transition zone. The transition zone is fairly thin (5-30 cm). If conditions are calm during the formation of an ice sheet, the transition zone will start to develop essentially at the upper ice surface. If a frazil layer is present, the transition zone starts to develop at the base of the frazil layer.

Below the transition zone the ice is referred to as being in the columnar zone. This ice has a fairly uniform structure with the dominant crystals showing a horizontal c-axis orientation and a pronounced elongation parallel to the direction of heat flow. A number of illustrations showing the structure of the columnar zone, the transition zone and the initial ice skim can be found in Weeks and Assur (1967, 1969) and Weeks and Ackley (1982). Although there are grain size changes in the columnar zone, they are not striking. As the major portion of first-year ice sheets is composed of columnar ice, the majority of published property studies presumably were performed on such ice, although in many cases the structure of the ice studied was never identified.

For many years it was believed that the crystals in the columnar zone invariably showed horizontal c-axis orientations that were random in the horizontal plane. In fact, this has been documented at some locations (Weeks and Lee 1958). Such a material would be described as transversely isotropic in that its properties vary in the vertical direction, but at a given level, all directions in the horizontal plane are equivalent. However, recent studies (Cherepanov 1971, Weeks and Gow 1978, 1980) have revealed that the great majority of the ice occurring over the continental shelves of the Arctic shows strong c-axis alignments in the horizontal plane (Fig. 2). The factor apparently controlling the direction of these alignments is the direction of the current at the ice/seawater interface. Even though these crystal alignments are far from perfect, they result in orthotropic ice (the ice properties differ along three orthogonal directions).

In addition to these changes in gross crystal shape, size and alignment, there are pronounced changes in the internal structure of the individual crystals of sea ice. Within the columnar zone each crystal is

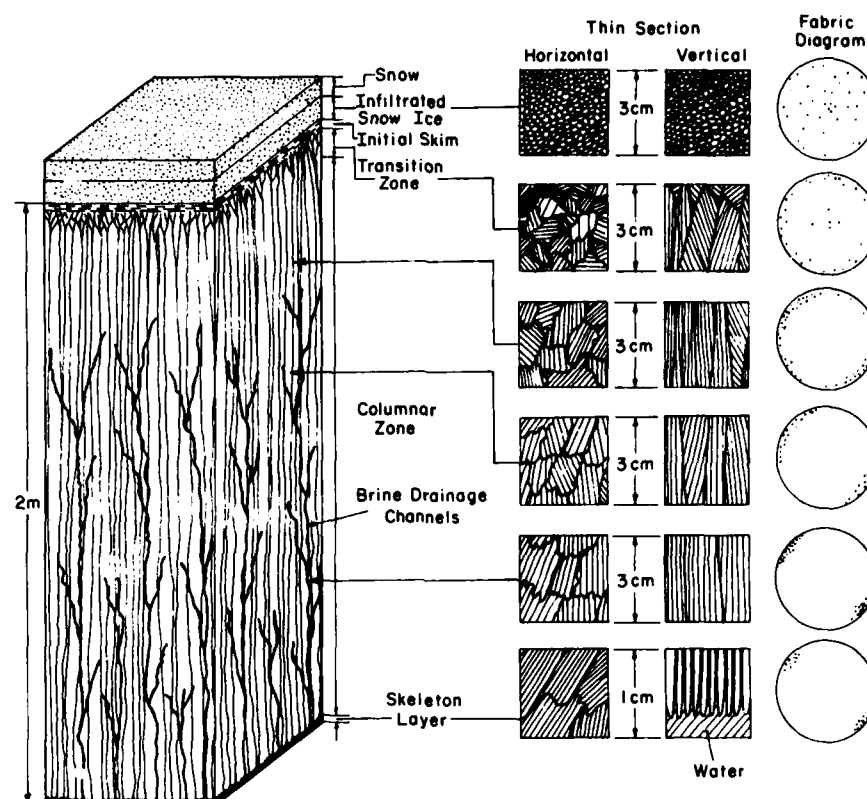


Figure 2. Schematic drawing showing several aspects of the structure of first-year ice. Note the development of a strong c-axis alignment in the horizontal plane as shown in the lower three fabric diagrams.

subdivided into a number of ice platelets that are joined to produce a quasihexagonal network when viewed in the horizontal plane. This structure can be clearly seen in Figure 3. Similar substructures are common in many materials produced by directional solidification of impure melts. As in other materials the characteristic spacing a_0 between these substructure boundaries (measured parallel to the c-axis) is a function of the growth velocity v , with the relation being of the general form

$$a_0 \sqrt{v} = \text{constant.}$$

Therefore, because thicker ice grows slower (all other things remaining equal), a_0 is commonly largest near the bottom of an ice sheet.

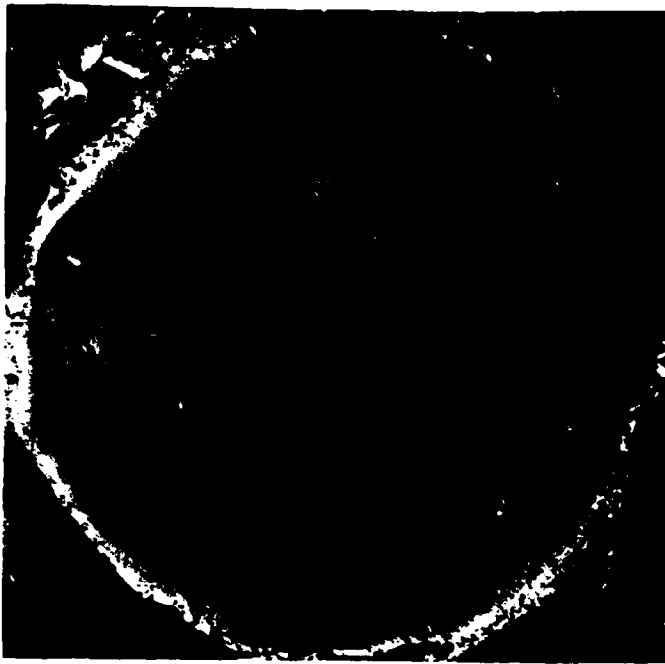


Figure 3. Photomicrograph (taken using crossed polaroids) of a horizontal thin section of first-year sea ice showing both individual crystals and the substructure within the crystals. The thin section is 7.8 cm in diameter and was made of ice from 128 cm below the ice surface.

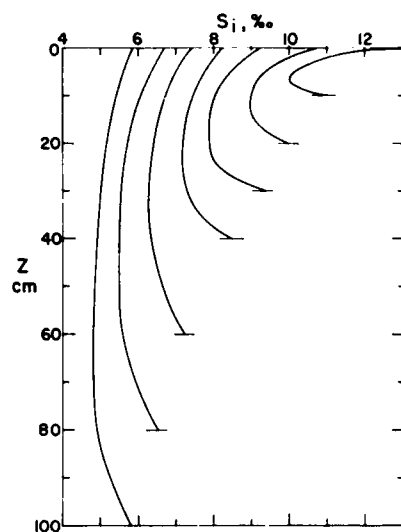


Figure 4. Photomicrograph (crossed polaroids) of a vertical thin section of first-year ice from the columnar zone. The "strings" of small crystals reveal the location of brine drainage tubes. The scale is in centimeters. This ice is from a depth of between 153 and 163 cm.

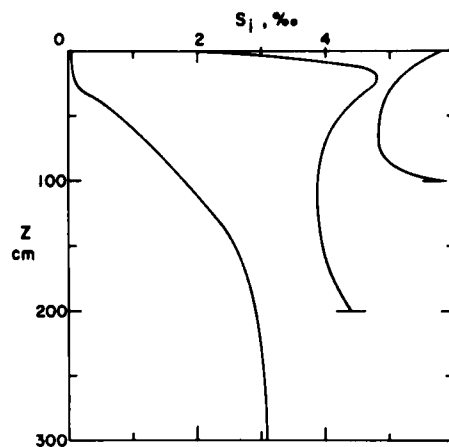
Associated with the variations in the freezing velocity of the ice are variations in the amount of salt trapped within the ice (Weeks and Lofgren 1967). The salinity of the ice is a linear function of the composition of the seawater that is being frozen, with fast growth resulting in the near-total incorporation of salt into the ice and very slow

growth resulting in near-total rejection of impurities. The trapped salt is in the form of liquid brine inclusions that are located along the substructure boundaries. Once salt has been trapped in the ice, it gradually starts to drain down and out of the ice. This is a complicated process that is only partially understood (Cox and Weeks 1974, Niedrauer and Martin 1979). Because of this brine drainage, there is a gradual decrease in the average salinity of the ice sheet at a given level as the ice thickens. Also, as the brine drains, structural features called brine drainage tubes develop within the ice (Fig. 4) (Lake and Lewis 1970). These features certainly must affect the properties of the bulk ice mass, although the subject has not been studied.

Another important event affecting the characteristics of sea ice is the summer melt season. When sea ice undergoes a period of melt, a pronounced reduction in its salinity results. This is largely caused by the percolation of relatively fresh, surface meltwater downward into the ice (Untersteiner 1967). This flushing results in salinity profiles such as that shown in Figure 5, with salinities at locations above sea level dropping to near zero and salinities at locations below sea level changing to between 2 and 4‰. Associated with high summer temperatures and the associated desalinization, there is also the possibility of recrystallization in the upper portions of ice floes. Although this speculation has not yet been verified, its possibility is suggested by the fact that recrystallization occurs when impure hexagonal metals with substructures similar to sea ice are annealed at temperatures near the melting point. Undeformed ice that survives a number of summer melt seasons ultimately becomes a layer cake of the annual growth layers that form during successive winters (Fig. 6) (Cherepanov 1957, Schwarzacher 1959). Ultimately



a. First-year ice.



b. Multiyear ice.

Figure 5. Schematic drawing of representative salinity profiles from several different thicknesses of first-year and multiyear ice (Z is the distance below the upper ice surface, and S_i is the salinity of the ice). (From Weeks and Assur 1967.)

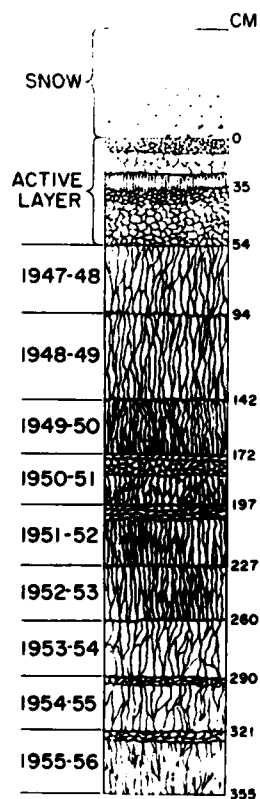


Figure 6. Schematic drawing of the layering and grain structure of a multiyear ice floe studied by Cherepanov (1957).

multiyear ice reaches a steady-state thickness, where the thickness ablated during the summer equals the thickness grown during the winter.

Composition

The other important parameter that must be known in order to specify the state of sea ice is the volume of fluid in the ice. The fluid is composed of two parts: liquid brine and gas. (If the ice is cold, there may also be solid salts present that have precipitated from the brine.) To calculate the brine volume (the percentage by volume of the specimen that is composed of liquid brine), one first determines the salinity. This is usually done by first determining the electric conductivity of the melted sample. By using tables prepared from measurements on standard seawater, the salinity of the sample is estimated. This salinity value is then combined with the temperature of the ice specimen, and the brine volume is obtained from a table (Assur 1958) that estimates brine volumes for so-called standard sea ice. The key in these procedures is the word "standard," which means that it is assumed that the ratios of the ions in the sample under study are the same as in Copenhagen seawater. This assumption is not necessarily correct for sea ice for the following reason. Once a solid salt crystallizes from the brine in sea ice ($\text{CaCO}_3 \cdot 6\text{H}_2\text{O}$ at -2.2°C , $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ at -8.7°C , $\text{NaCl} \cdot 2\text{H}_2\text{O}$ at -22.7°C , etc.), the solid salt crystals presumably become relatively immobile, being trapped in the tortuosities of the brine pockets and brine drainage tubes (see Sinha [1977] for observations on the solid salts). However, the remaining brine can presumably still drain slowly out of the ice. This differential drainage of the different components of seawater would change the ratios of the ions in sea ice. For instance, if ice were to remain at -10°C for a long period, $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ would presumably remain in the ice while chloride-rich brine drained out. The result would be an increase in

the $\text{SO}_4^{2-}/\text{Cl}^-$ ratio. These effects has never been adequately studied. If they do occur, they would be most pronounced in ice that has been subjected to temperatures below -8.8°C for long periods of time, that is, in the upper portions of thick first-year ice and particularly in multiyear ice. This ice makes up much of the ice in the Greenland Sea.

Suspected differences in the ice of the Greenland Sea.

There are reasons for suspecting that the ice, particularly that in the Greenland Sea, may be appreciably different from ice in regions that have been studied more closely. First, as just mentioned, if there are changes in the ratios of the ions in the salt in sea ice, these changes would be expected to be at a maximum in the multiyear ice that is continuously moving through the Fram Strait into the East Greenland Drift Stream.

Second, there may be structural differences in the ice. These differences would presumably not be caused by new sea ice types (although such types are certainly possible); instead they would result from differences in the relative amounts of ice types that are now known to occur. As mentioned earlier, until recently the generally accepted concept of sea ice structure was one of a transversely isotropic material (c-axes randomly oriented in the horizontal plane). The recent discovery that sea ice along the coast of Alaska and Siberia has strong c-axis alignments, resulting in an orthotropic material, would lead one to anticipate that the great majority of the coastal ice of Greenland and Svalbard would show a similar structure. The one piece of sikussak that has been studied showed strong c-axis alignments in the horizontal plane (Cherepanov 1964).

Not only are such alignments expected in the coastal ice, it is also possible that they will occur in the pack ice. For instance, radar observations (Kovacs and Morey 1979) of first-year pack ice located well off the coast of the Beaufort Sea (Weeks and Gow 1980) suggest strong crystal

alignments. At first glance these observations appear to contradict the suggestion that the controlling factor in determining crystal alignments is the direction of the current relative to the ice (pack ice floes are generally thought of as being free to rotate during drift). In fact, observations such as those made at AIDJEX show, at least in the Beaufort Sea, that the ice is so tight during winter and early spring that little rotation occurs. Therefore, even if the ice is moving, as long as the current direction relative to the ice is fairly constant, crystal alignments should develop. Whatever the reasons, such alignments do occur. Therefore, they should also be expected in much of the ice exiting the Polar Basin via the Trans-Polar Drift Stream. It is possible that multi-year floes will show different alignment directions in the different annual growth layers, as the free rotation of floes relative to the current is easy during the summer when ice concentrations decrease and difficult during the winter when ice concentrations are high. The resulting floe would be structurally orthotropic on a small scale (in individual layers) and transversely isotropic on a large scale. The fact that the structure and composition of typical multiyear ice are largely unknown, even in the Beaufort Sea, may surprise people. However, this is definitely the case. Principal papers on the subject are Cherepanov (1957, 1964), Schwarzacher (1959) and Cox and Weeks (1974). The state of the subject is similar to attempting to describe the geology of the United States based on an examination of four random outcrops.

Other general characteristics of the multiyear ice exiting the Arctic Basin are that it is thicker, has grown more slowly, and is generally more highly deformed than most ice at near-coastal sites. The slow growth results in larger a_0 values (characteristic spacings between the brine layers in the ice). For instance, typical a_0 values for first-year sea

ice average about 0.5 mm (Anderson and Weeks 1958). A similar average for 3.5-m multiyear ice is 0.9 mm (Schwarzacher 1959), while the 10- to 12-m-thick sikussak investigated by Cherepanov (1964) averaged between 1.3 and 1.5 mm. The latter values are similar to a_0 values (1.5 mm) determined on 14-m-thick sea ice located near McMurdo Sound, Antarctica.¹ It is known from studies of NaCl ice that larger a_0 values cause lower strengths (Weeks and Assur 1963). These effects would certainly have to be considered in studying the properties of ice in the Greenland Sea.

It is not known what structural differences will be observed in the large amounts of highly deformed ice that are expected in the Greenland Sea. The random piling of ice blocks that compose most ridges should produce a material that is isotropic on a scale of greater than about ten block sizes. It is also possible that the upper, low-salinity portions of multiyear ice may recrystallize. Certainly all the components necessary for recrystallization are present: a thermodynamically unstable substructure, large local strains associated with the ridging process, and near-melting temperatures. There is no information on whether or not recrystallization actually occurs. If it does, it will presumably cause major changes in the ice structure.

The last "difference" that may occur in the ice of the Greenland Sea is the possible presence of large amounts of frazil ice. It has commonly been believed that the formation of significant amounts of frazil ice in the sea was limited to the period of initial freeze-over. However, examples are now known when this definitely is not the case. For instance, large quantities of frazil ice have been observed in the ice pack of the Weddell Sea (Gow et al. 1982, Weeks and Ackley 1982). In some cases 70% of

¹ Personal communication with A.J. Gow of CRREL.

4-m-thick multiyear floes located well within the pack were composed of frazil.

How does marine frazil form and why should one expect large quantities of it to occur in the Greenland Sea? Although there are a number of possible ways in which frazil can form and there is still considerable disagreement about such matters (Martin 1981), the most important processes appear to be 1) the formation of cold, saline water in large leads and polynyas and 2) the drainage of this dense brine downward into the underlying water column, causing ice crystals to develop. As brine drains most rapidly in thin, fast-growing sea ice, these processes require a similar physical setting: significant regions of open water or very thin ice during periods of low air temperatures. Are there reasons to believe that this physical setting occurs in the Greenland Sea? The answer is, of course, yes. Winter and spring polynyas are well known along the coast of East Greenland (Koch 1945, Wadhams 1981) and may persist for days or even weeks. Also, a recent film prepared from NASA microwave imagery suggests the development of a large polynya or thin ice area within the Arctic pack north of Franz Josef Land. Frazil generated in this polynya would presumably exit the Arctic Basin via the East Greenland Drift Stream. In addition, although the ice north of Fram Strait is generally quite tight, south of the strait the ice diverges rapidly, with each lead and thin ice area serving as a potential site for frazil generation. Also, the marginal ice zone of the Greenland Sea is a major frazil generator as the result of pronounced wave action associated with the strong cyclonic atmospheric disturbances that track along the ice edge.

In summary, it is reasonable to expect that one could find large amounts of frazil in the ice of the Greenland Sea, perhaps amounts similar to that observed in the Weddell Sea, where there was as much frazil ice as congelation ice.

PHYSICAL PROPERTIES

It is beyond the scope of this report to provide a detailed review of the status of knowledge about the physical properties of sea ice; a number of reviews are already available (Weeks and Assur 1967, 1969, Schwarz and Weeks 1977, Weeks and Cox, in press). Here I will describe what is missing rather than what has been done.

There are a large number of physical properties that could be discussed. Here I will only consider mechanical, thermal, friction and adhesion, and electromagnetic properties. Furthermore, I will separate specific properties into two classes: structure-independent properties, such as the specific and latent heats and the density, and structure-dependent properties, such as the mechanical and electromagnetic properties, the friction and adhesion characteristics, and the thermal conductivity and diffusivity.

It should always be remembered that sea ice is a complex geometric mixture of four components: pure ice, brine, gas and solid salts (listed in approximate order of decreasing importance). Fortunately a great deal is known about the physical properties of the main component, pure ice (Hobbs 1974, Glen et al. 1978). There is, however, a need for improved data on the properties of seawater brines existing in equilibrium with ice. Also, the data on which the current sea ice phase diagram is based (Assur 1958) are either very old or were collected for quite different purposes, and questions concerning the possible formation of metastable phases were never adequately addressed (Ringer 1906, 1928, Nelson 1953, Nelson and Thompson 1954). Data on the properties of the solid salts that crystallize from seawater brines are also very spotty. I am not aware that the presence of $\text{CaCO}_3 \cdot 6\text{H}_2\text{O}$ and $\text{MgCl} \cdot 8\text{H}_2\text{O}$ has ever been directly confirmed in sea ice or that the bulk properties of fine-grained aggregates of $\text{NaCl} \cdot 2\text{H}_2\text{O}$

Table 2. A general assessment of the current state of knowledge of a number of structurally sensitive physical properties of sea ice. A discussion of the meaning of the terms nil, poor, fair, good and excellent as used here can be found in the text.

Ice Property	First Year				Multiyear				Sikussak (>10 years)
	Congelation		Frazil		Congelation		Frazil		
	Transverse	Isotropic	Orthotropic	Isotropic	Transverse	Orthotropic	Isotropic	Isotropic	
	isotropic				isotropic	tropic			
MECHANICAL									
Compressive strength	Fair (Saeki et al. 1978)	Fair (Wang 1979)	Fair (Wang 1979)	Fair (Wang 1979)	Poor		Nil	Nil	Nil
Tensile strength	Fair (Dykens 1970)	Fair (Peyton 1966)	Nil	Nil	Poor (Gladwell 1977)		Nil	Nil	Nil
Flexural strength	Good (Weeks and Anderson 1958)	Poor	Nil	Nil	Poor (Gladwell 1977)		Nil	Nil	Nil
Shear strength	Poor (Paige and Lee 1967)	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Elastic modulus	Good (Dykens 1971)	Fair (Peyton 1966)	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Poisson's ratio	Poor	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
THERMAL									
Thermal conductivity	Good (Schwerdtfeger 1963)	Good (Schwerdtfeger 1963)	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Thermal diffusivity	Good (Ono 1968)	Good (Ono 1968)	Nil	Nil	Nil	Nil	Nil	Nil	Nil
FRICTION AND ADHESION									
Friction	Poor	Fair (Tusima and Tabata 1978)	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Adhesion	Poor (Sackinger and Sackinger 1977)	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
ELECTROMAGNETIC									
Resistivity	Fair	Fair (Timco 1979)	Fair	Fair	Poor		Nil	Nil	Nil
Dielectric constant		Good at some freq. (Vant et al. 1978)	Nil	Nil	Good at some freq. (Vant et al. 1978)		Nil	Nil	Nil
GENERAL QUALITY OF STRUCTURAL CHARACTERIZATION OF ICE TYPE									
	Good (Weeks and Assur 1967)	Good (Weeks and Gow 1980)	Poor	Poor (Schwarzacher 1959)	Poor		Nil	Poor (Cherepanov 1964)	Nil

or $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ have ever been determined. Finally, very little is known about the composition of the gas in sea ice (data presented by Tsurikov [1979] indicate that its composition can be very different from that of air). Also, the amount of gas actually present in the ice is rarely determined; it is commonly assumed that the value is sufficiently low to have a negligible effect on sea ice properties. For the upper, low-salinity portions of the multiyear floes and pressure ridges that are so common in the Greenland Sea, it is difficult to believe that this assumption would withstand critical inspection. However, even considering these problems, if we are concerned with a bulk property of sea ice that is not sensitive to changes in the structure of the ice masses, such as density or latent heat, then our general knowledge of the property is good.

On the other hand, if we examine the current status of the knowledge of the structure-sensitive physical properties of the different types of ice that either are known to occur or have been assumed to occur in the Greenland Sea, a very different picture is obtained. This situation is assessed in Table 2. In all cases the observations that are used in these assessments are from ice from other locations that is presumed to be similar to the ice of interest in the Greenland Sea. "Transversely isotropic" refers to columnar zone ice that has a random c-axis orientation in the horizontal plane. "Orthotropic" refers to columnar zone ice with a strong c-axis alignment in the horizontal plane. Specific meanings of the terms used in the assessment are as follows:

Nil - effectively no observations are available

Poor - observations are very limited in quantity and/or of poor
quality

Fair - observations are of reasonable quality and number

Good - test procedures are of good quality and a large number of observations are available

Excellent - high quality experimental procedures were used and a large number of observations in which the nature of the ice being tested was carefully documented are available. (Note that the term "excellent" does not appear in Table 2.)

The fact that the state of knowledge of a given property may be listed as poor does not necessarily mean that the quality of the measurements is poor, only that there are few of them. In many cases good quality observations have been performed on ice whose structure is unknown. A descriptor centered midway between two ice types means that measurements are available but that the exact ice type is unknown. The references given were selected because of their usefulness (and in some cases because of their obscurity). For additional references see the review papers mentioned earlier. In making these judgments it is quite probable that I have overlooked a few papers (so that nil should be changed to poor or fair changed to good). It is, however, doubtful that a major paper would go unnoticed (so that there would be major changes in the table, such as nil changed to good).

The table is quite revealing. It shows that the most information is available on transversely isotropic, first-year congelation ice. Even there the general quality of the data set leaves much to be desired. The amount of information on orthotropic first-year congelation ice is less, but there are still some observations. On the other hand, almost nothing is known about the properties of first-year marine frazil, even less is available on multiyear ice, regardless of the structural type, and nothing is available on sikussak. It should again be stressed that these judgments

are concerned with measurements on ice properties that were made at any location and that none of the above information comes from the Greenland Sea.

In short, even if we knew the exact structural characteristics of the ice in the Greenland Sea, we would still not be able to specify its properties adequately, as the properties of sea ice in general and of multiyear ice in particular are inadequately known.

CONCLUSION

When I started to write this report I knew that there was little known about the properties of the ice in the Greenland Sea. However, the state of knowledge appears to be even lower than I had anticipated. The situation does not appear to be improving, even though the physical properties of sea ice are invariably identified as important to almost every aspect of arctic oceanography (Andersen et al. 1980). For instance, recent field operations in the ice of the Greenland Sea have utilized small stations with programs primarily focused on conventional oceanography. The ice simply serves as a platform, even though it is the material that makes the environment unique. Such monodisciplinary approaches and programs strike me as extremely shortsighted. The essential ingredient for advancing one's understanding of the physical properties of sea ice is to get small groups of investigators experienced in studies of sea ice structure and properties into the field.

The first programs that should be undertaken should focus on characterizing the structure of the ice in the region, particularly the multiyear ice. This should be combined with a limited amount of property measurements made using standard techniques that have been applied to sea ice from other regions. This study should give a rough but factual

impression of the nature of the ice off East Greenland and how its properties differ from those of ice from other regions. Only when such a survey has been completed can more focused efforts be profitably designed.

The majority of the ice exiting the Arctic Basin via the East Greenland Drift Stream is the product of the multiyear exposure of this ice to the grist mill produced by ice-ocean-air interactions in the Pacific Gyre and the Trans-Polar Drift Stream. To understand all these interactions in detail will take a very long time. It would seem that a wise first move toward developing such an understanding would be to characterize the nature of the ice that is the product of this mill. If this paper can assist in making this task clearer and a little closer in time, it will have been worthwhile.

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APPENDIX A. MEASUREMENTS OF SEA ICE PROPERTIES IN THE GREENLAND SEA

In the course of the writing of this report a few studies were noted in which measurements were made of the properties of the sea ice in the Greenland-Svalbard region. These are as follows:

1. Frederking, R. and F.-U. Häusler (1978) The flexural behavior of ice from in situ cantilever beam tests. IAHR Symposium on Ice Problems, Proceedings Lulea, Sweden, part 1, p. 197-215. [11 cantilever beam tests on sea ice in Isfjorden, Svalbard].
2. Overgaard, S. (1979) Electrical losses in multi-year ice in the East Greenland current. Draft manuscript, Electromagnetics Institute, Technical Univ. Denmark, Lyngby. [Temperature and salinity determinations on five multiyear ice cores collected near Mestersvik, Greenland.]
3. Wadhams P. and V.A. Squire (1980) Field experiments on wave-ice interaction in the Bering Sea and Greenland waters, 1979. Polar Record, vol. 20, no. 125, p. 147-153. [Determination of the properties of ice by studying its flexing during the passage of ocean waves (see also references given by Wadhams 1981).]