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ICE THICKNESS CALCULATION FROM PARTIAL CONCENTRATION VALUES

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ABSTRACT

Thickness and concentration are the most fundamental and important parameters to describe the state of ice at sea. While remote sensing from satellites has enabled ice concentration observation for wide areas, there have been no such methods established to evaluate ice thickness. This paper presents a method to calculate ice thickness from partial ice concentration values. Calculation results are compared with field data measured by moored Upward-Looking Sonars in the Beaufort Sea and Fram Strait.

INTRODUCTION

Thickness and concentration are the most fundamental and important parameters to describe the state of sea ice for both engineering and scientific purposes. Recent developments in remote sensing technique from satellites have enabled ice concentration observation over wide areas on a daily basis. Sea ice retreat in the Arctic in recent years, which is the most notable sign of global warming, would have not been fully recognized without observations from space.

Drilling ice is a traditional and still widely used method for ice thickness measurement. Although direct and reliable, this method only gives localized information on ice thickness. Measuring ice thickness over a wide area by drilling is very time- and labour-consuming. Electro-magnetic (EM) sensors are being applied to ice thickness measurement recently. The sensor enables non-destructive and real-time measurement of ice thickness. However, ice thickness data by way of this method is limited to areas along the track of ship or aircraft on which the sensor is installed. Although attempts including ICESat and CryoSat were made, there have been no methods established to evaluate ice thickness over a wide area.

Ice covers found at sea is composed of different types of ice. The World Meteorological Organization (WMO) defines these ice types and their thickness. This paper presents a method to calculate average ice thickness from partial concentration and thickness of ice types present at a location considered. Partial concentration is concentration of each ice type. Calculation results are compared with field data measured by moored Upward-Looking Sonars (ULSs) in the Beaufort Sea and Fram Strait.

CALCULATION METHOD AND DATA

Ice Types

Under low temperatures sea water freezes to form ice. Ice develops with time. WMO categorized sea ice into types under different stages of development and defines thickness for each type (World Meteorological Organization, 2004). Table 1 shows sea ice types and thickness defined by WMO. There are four main types of Nilas, Young Ice, First-Year Ice and

Old Ice in the order of development. Each main type is subdivided into two or three ice types with different values of thickness. Ice thickens as it develops. Ice covers found at sea are in general composed of not a single type but several different types of ice.

Table 1 Sea Ice Categories and Thickness defined by WMO

Ice Types		Thickness
Nilas	Dark Nilas	- 5 cm
	Light Nilas	5 - 10 cm
Young Ice	Grey Ice	10 - 15 cm
	Grey-white Ice	15 - 30 cm
First-year Ice	Thin First-year Ice	30 - 70 cm
	Medium First-year Ice	70 - 120 cm
	Thick First-year Ice	120 - 200 cm
Old Ice	Second-year Ice	up to 2.5 m or more
	Multi-year Ice	up to 3 m or more

Ice Thickness Calculation

In this study, we calculated ice thickness based on definitions given in Table 1. The following equation was used to calculate the average value of ice thickness, h_{AV}, in an area at sea.

$$h_{AV} = \sum_{i=1}^{N} C_i \overline{h}_i \ , \qquad (1)$$

where N is the number of ice types, C_i and $\overline{h}_i$ are partial concentration and average thickness of the i-th ice type, respectively. Total ice concentration, C, in the area is given as the sum of partial ice concentration of each ice type.

$$C = \sum_{i=1}^{N} C_i \ . \qquad (2)$$

It should be noted that open water (0 ice thickness) is implicitly included in the calculation of the average ice thickness by equation (1).

Equation (1) gives average ice thickness in an area when partial concentration and average thickness of ice types present are given. In the present study, they were obtained and defined as described below.

Partial Ice Concentration

Partial ice concentration values obtained from ICE06 were used for the present study. ICE06 is a sea-ice statistics software commercially available from Canatec Associates International Ltd. The software includes data from Canadian Ice Service and US National Ice Center, and covers waters north of 35°N and Antarctic waters (Canatec Associates International Ltd. (a)). Figure 1 is a sample display of ICE06 showing distribution of (total) ice concentration in Davis Strait between Greenland and Baffin Island, Canada.

Sea ice data included in ICE06 is ice concentration in the above-mentioned waters. Not only values of total ice concentration but also those of partial concentration for ice types defined by WMO (see Table 1), except the thinnest ice types, are included in ICE06. No discrimination between dark and light nilas is made in ICE06, and they are collectively treated as Nilas (Canatec Associates International Ltd. (b)).

Beside displaying ice condition as shown in Figure 1, ICE06 has a function to output data table in the ASCII format. Those ICE06 data tables were used for the present calculation. An ICE06 data table contains codes with (maximum) nine characters. The first character of a code indicates total concentration. Following characters indicate partial concentration values in the descending order of thickness. As an example, a code "T013402" means 10/10 total concentration, 1/10 Second-year Ice, 3/10 Thick First-year Ice, 4/10 Medium First-year Ice, and 2/10 Grey-white Ice.

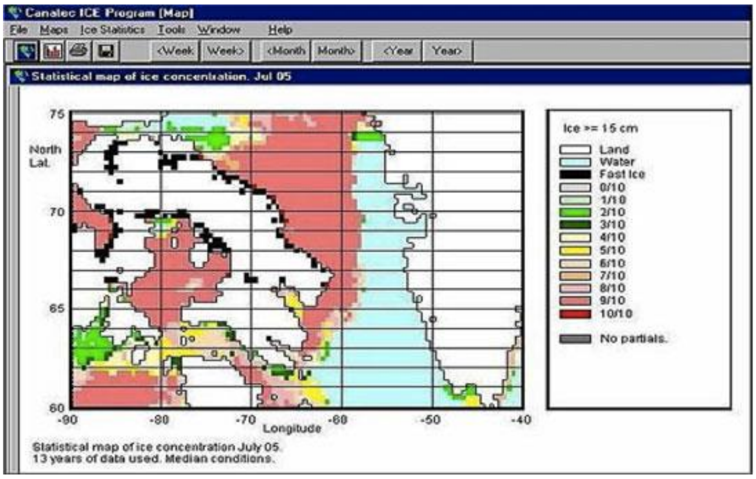
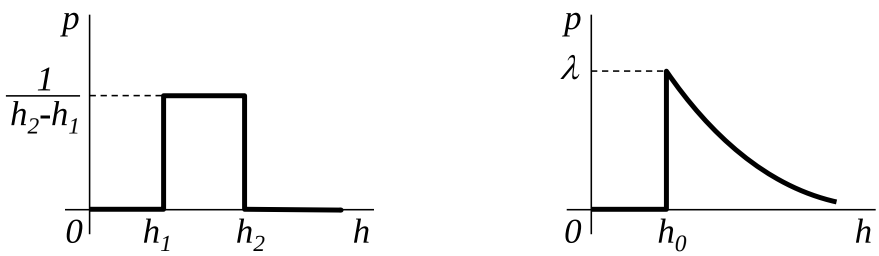


Figure 1 A Sample Display of ICE06 (Canatec Associates International Ltd.)

Average Ice Thickness for Ice Types

Probability distribution functions (PDFs) were considered to define the average thickness values for each ice type to be used in equation (1). Figure 2 schematically shows PDFs assumed in this study.



(a) Nilas, Young Ice and First-Year Ice (b) Old Ice

Figure 2 Schematics of Probability Distribution Functions assumed in this Study

WMO defines ranges of ice thickness for ice types from Dark Nilas to Thick First-year Ice as shown in Table 1. For these ice types, it is assumed that thickness, h, distributes uniformly over the range given in the table. PDF, $p(h)$, for these ice types is given as;

$$p(h) = \begin{cases} \dfrac{1}{h_2 - h_1} & for\ h_1 \le h \le h_2 \\ 0 & for\ h < h_1\ or\ h_2 < h \end{cases} , \qquad (3)$$

where h_1 and h_2 are the lower and upper values of ice thickness range for the ice type concerned. Figure 2 (a) schematically shows this PDF. The average ice thickness to be used in equation (1) is given by the central value of the thickness range for each ice type. Those values are 5, 12.5, 22.5, 50, 95 and 160 cm for Nilas, Grey Ice, Grey-White Ice, Thin First-Year Ice, Medium First-Year Ice and Thick First-Year Ice, respectively.

For old ice, which is the thickest ice type and composed of second-year and multi-year ice, WMO doesn't give definite thickness values as those for other ice types. (see Table 1). In this study, it was defined that old ice has thickness lager than 2.0 m. Discussion will be made of this assumption later in this paper.

Results of field measurements were considered to determine PDF for old ice. Wadhams (1972) analysed upward-looking sonar profile of ice underside measured in a submarine cruise in the Arctic Ocean and Greenland Sea. Figure 3 shows a re-plot of a figure included in Wadham (1972). The figure shows PDFs of ice draft in two zones in the Arctic Ocean. It is a semi-logarithmic plot. In the region with ice draft deeper than 2 m, plots decrease linearly with draft. This indicates that PDFs fit well to a negative exponential distribution.

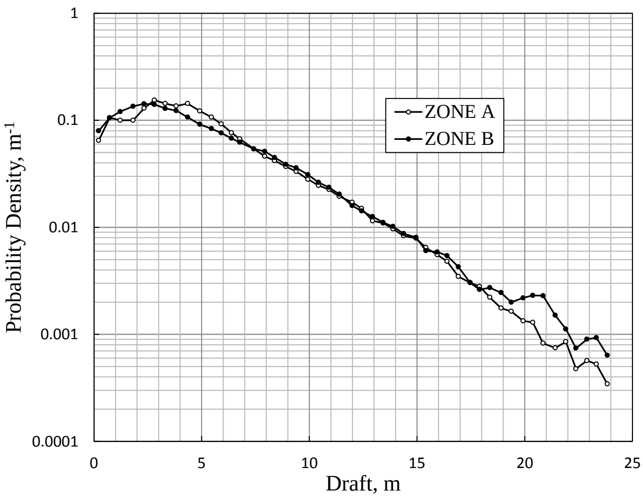


Figure 3 PDFs of Ice Draft (re-plotted from Fig. 6 of Wadhams, 1992)

In this study PDF for old ice thickness was given by a negative exponential distribution as;

$$p(h) = \lambda \exp\{-\lambda(h - h_0)\} \quad for\ h \geq h_0, \tag{4}$$

where λ is a rate parameter and h_0 is a lower threshold value for old ice thickness, which is 2.0 m. Regression line for the plots in Figure 3 gives $\lambda = 0.3\,m^{-1}$. Mean value of this PDF is given as $h_0 + 1/\lambda$. With $h_0 = 2.0\,m$ and $\lambda = 0.3\,m^{-1}$, average thickness for old ice to be used in equation (1) is 5.33 m.

COMPARISON WITH FIELD MEASUREMENTS

In this section, ice thickness calculated by the method described in the previous section is compared with results of field measurements. Field data used for the comparison are ice draft measured by moored ULSs. Data available in the public domain including those in the Beaufort Sea (Melling and Riedel, 2008), Fram Strait (Vinje et al, 1998), and Fram Strait (Witte and Fahrbach, 2005) were used for the comparison.

Ice thickness, h, is calculated from ice draft, d, with a factor, k, as

$$h = k\,d\,. \tag{5}$$

In this study $k = 1.136$ is used after Vinje (1998).

ICE06 includes data for fixed geographical coordinates (Canatech Associates International Ltd (b)). Spacing between neighbouring data points is 15' in latitude and 1° in longitude in the north of 76˚ north. For the comparison below, ice draft data measured at or in the vicinity (within 5' in latitude and 12' in longitude from the point concerned) of ICE06 coordinates were used to minimize the error due to difference in local ice conditions.

It should be also noted that some ICE06 data were judged to be inappropriate for the ice thickness calculation by equation (1). Such data include data that only include total ice concentration without values for partial concentration. In other data, although both total and partial concentration values are given, they don't satisfy equation (2). These data were not used for the comparison.

Beaufort Sea (Melling and Riedel, 2008)

A series of ice draft measurements were carried out over the continental shelf of the Eastern Beaufort Sea (Melling and Riedel, 2004). Ice draft data can be downloaded from a website of US National Snow and Ice Data Center (NSIDC) at http://nsidc.org/data/g02177.html. Over a period from April 1990 to September 2003 measurements were made at ten different sites as shown in Figure 4. Monthly mean ice thickness measured at these sites is compared with those calculated.

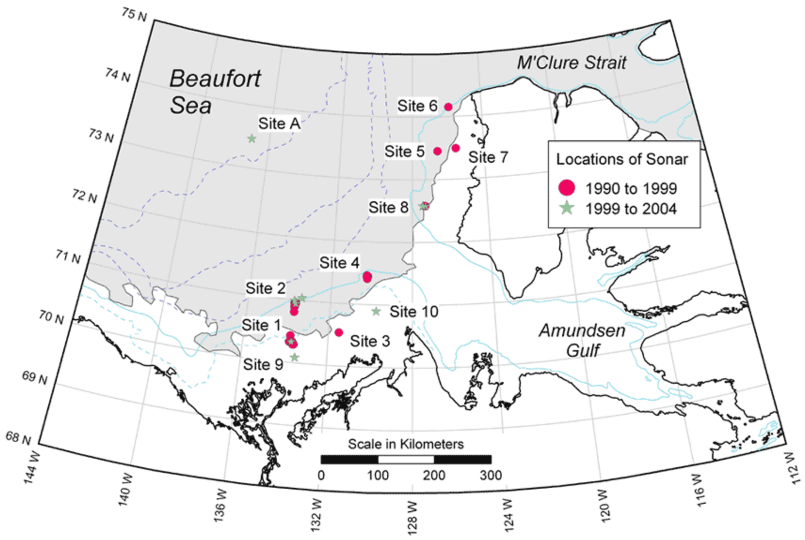


Figure 4 ULS Sites in the Eastern Beaufort Sea (Melling and Riedel, 2004)

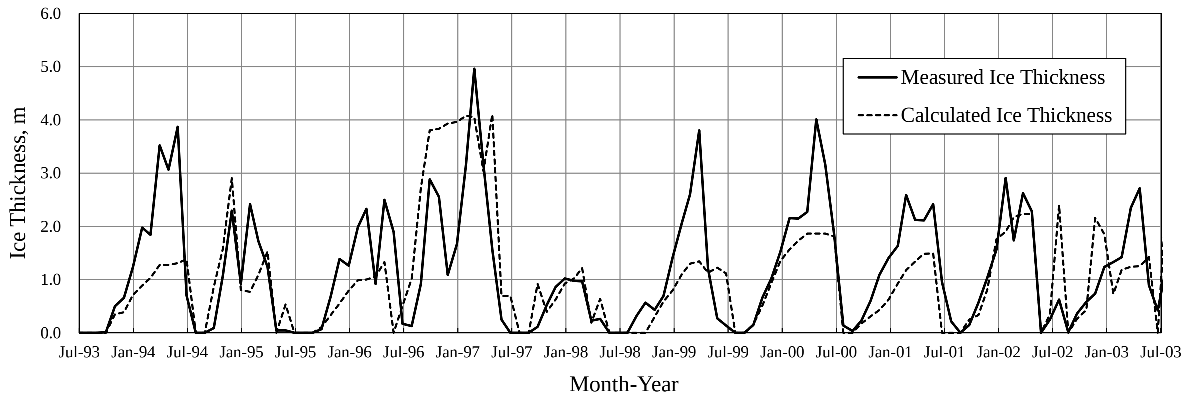


Figure 5 Time Curves of Measured and Calculated Ice Thickness at Site 1 in Beaufort Sea

Figure 5 shows time curves of measured and calculated ice thickness at Site 1, where the longest continuous measurement was made, for a ten-year period from July 1993 to July 2003. Measured ice thickness shows annual cycles with an increase from autumn to winter followed by a rapid decrease in spring. In summer ice is very thin indicating that little ice is left at the site. There is considerable inter-annual variability in ice thickness. In 1997 ice thickness reaches the maximum of 5 m, while it is only 1 m in 1998.

Figure 6 compares calculated and measured ice thickness in winter (January, February and March) and summer (July, August and September) months. Data from Sites 1, 2, 4 and 8 are included in the figure. Although calculation tends to underestimate and overestimate winter and summer ice thickness respectively, calculated results generally correspond well with measured ice thickness. It is interesting to note that unusually thick ice was observed in a winter and even in a summer. Calculation is successful to replicate such thick ice.

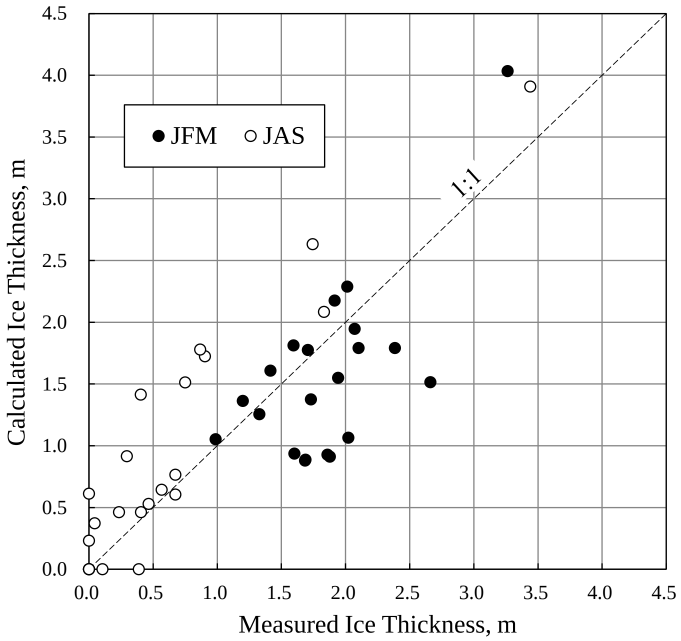


Figure 6 Comparison of Measured and Calculated Ice Thickness for Winter (January, February and March: JFM) and Summer (July, August and September: JAS) Months

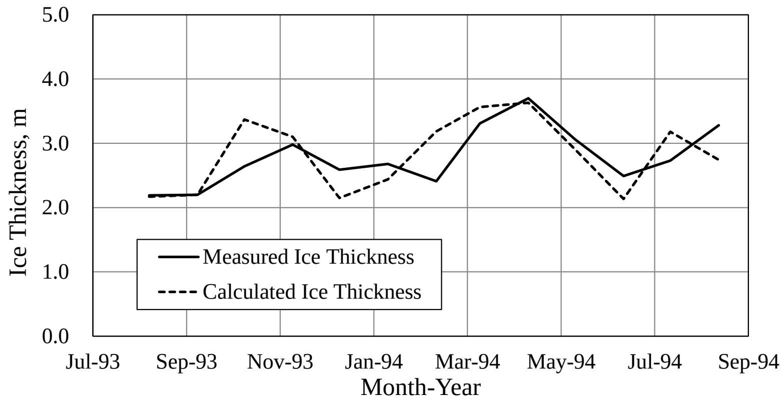
Fram Strait (Vinje et al, 1998)

Vinje et al (1998) analysed time series of ice draft data measured by ULSs moored in Fram Strait in the period from August 1990 to July 1996. Most of the ULSs were deployed on and in the vicinity of 79˚ north parallel and one was deployed on 77.5˚ north. The period of deployment of each ULS at a position was 7 to 19 months. Monthly mean values of measured ice thickness are presented in Vinje et al (1998). These values were compared with calculation. Table 2 summarize ULSs used for the comparison.

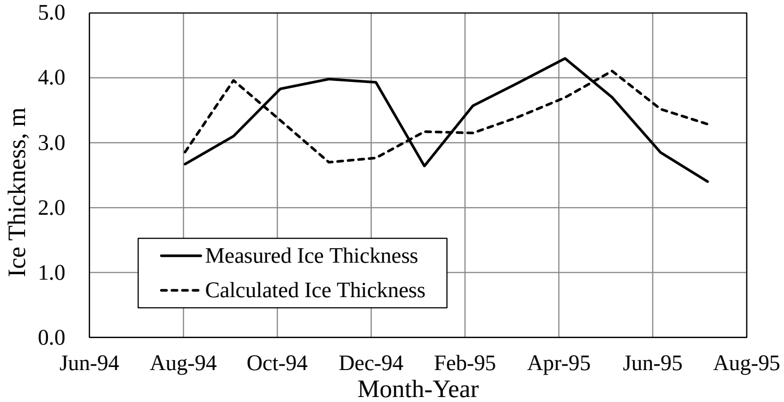
Table 2 ULSs used for Comparison

ULS No.	Position		Deployed Period		
	ºN	ºW			
5	78.9	4.9	Sep-91	-	Mar-93
12	79.0	7.0	Aug-94	-	Jul-95
13	78.9	5.0	Aug-94	-	Feb-95
16	79.0	6.0	Aug-93	-	Aug-94
19	77.5	6.3	Sep-95	-	Jul-96
20	78.4	6.0	Sep-92	-	Mar-93

Figure 7 shows time histories of measured and calculated ice thickness. Data from two ULSs, located both on 79° north parallel but differ in latitude by one degree, are shown. Fram Strait is a passage for sea ice that originates various regions in the Arctic to outflow into the Greenland Sea (Kwok, 2009). Unlike the Eastern Beaufort Sea data, ice thickness doesn't show distinct annual cycles but maintains values higher than 2 m. This indicates continuous presence of sea ice in these sites.



(a) ULS No. 16 (79.0˚N, 6.0˚W)



(b) ULS No. 12 (79.0˚N, 7.0˚W)

Figure 7 Time Curves of Measured and Calculated Ice Thickness in Fram Strait

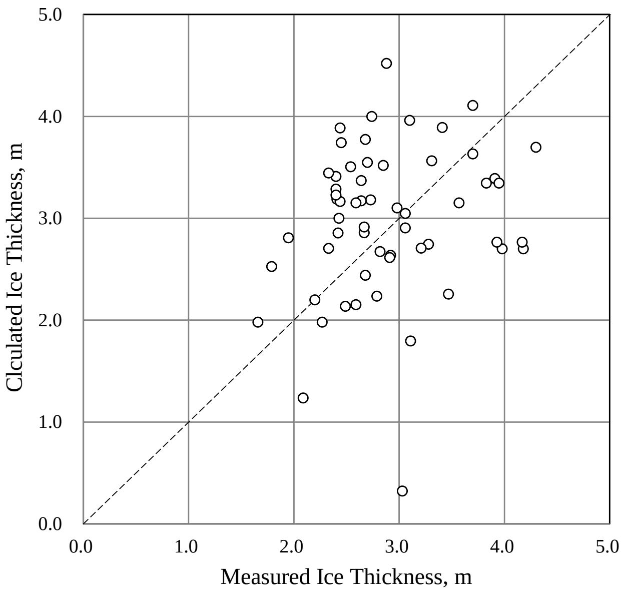


Figure 8 Comparison of Measured and Calculated Ice Thickness in Fram Strait

Figure 7 (a) shows very good agreement between the calculation and field measurement. They agree in terms of seasonal variation as well as in magnitude. In Figure 7 (b), although the agreement is not as good as Figure 7 (a), the range of fluctuation of calculated ice thickness is equivalent to that of measured ice thickness. Figure 8 shows a comparison of calculated and measured ice thickness for all data combinations available. Some scatter is seen in the plot, but there is overall correspondence between the two. Mean and standard deviation of ratio of calculated and measured ice thickness are 1.03 and 0.29, respectively.

Fram Strait (Witte and Fahrbac, 2005)
The Alfred Wegener Institute for Polar and Marine Research (AWI) deployed a series of ULSs in Fram Strait and Greenland Sea (Witte and Fahrbac, 2005). Results of the measurements are available also from the above-mentioned website of NSIDC. Data from Fram Strait were compared with calculation. For the Greenland Sea, no data were found in the vicinity of ICE06 coordinates.

Figure 8 shows time histories of measured and calculated ice thickness at 79.0˚ north and 2.0˚ west. Ice is thinner than those measured in western region of Fram Strait shown in Figure 7. Ice thickness varies from 0 to 2.5 m. Calculation qualitatively replicates such fluctuations. However, calculated ice thickness is about two times larger than the measured one.

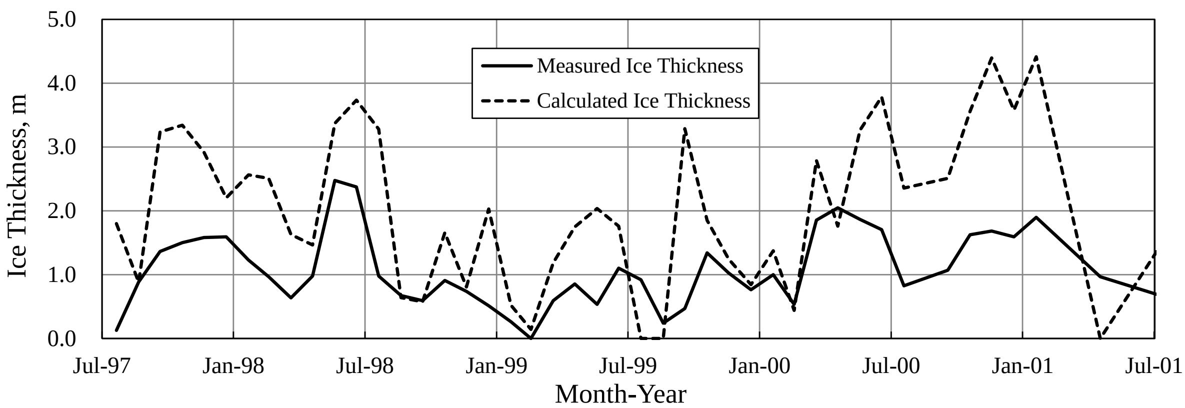


Figure 9 Time Curves of Measured and Calculated Ice Thickness in Fram Strait at 79.0˚N, 2.0˚W

DISCUSSION

Old Ice Thickness
As WMO defines, sea ice develops and thickens from Nilas to Old Ice (Table 1). This is a thermodynamic process. The present calculation uses this WMO definition to calculate average thickness of sea ice covers composed different types of ice.

Besides the thermodynamic development, sea ice can also be thickened through mechanical deformation including ridging and hummocking. Wadhams (2000) describes that sea ice thicker than can be attained by the thermodynamic thickening of about 5 m is mechanically thickened ice. In Figure 3, such thick ice (> 5 m) accounts for about 40 % of the whole ice thicknesses. This portion of ice can certainly include not only old ice but also first-year ice (mostly pressure ridges).

However, there is no reliable data for the contribution of first-year ice to this thick ice portion. It was defined in this study therefore that ice thicker than 2 m, which is the upper bound for thick first-year ice, is all old ice, and that its thickness follows a negative exponential distribution as given by equation (4).

Rate Parameter

Equation (4) include a rate parameter, λ. The value for this parameter determines average thickness for old ice to be used equation (1). In the calculation described in the previous section a value of $\lambda = 0.3\,m^{-1}$ is assumed based on PDFs obtained from ice draft measurements in the Arctic Ocean shown in Figure 3. This gives average thickness for old ice of 5.33 m. Calculated thickness with this value of λ agrees with field measurements in the Beaufort Sea (Melling and Riedel, 2004) and Fram Strait (Vinje et al, 1998) as shown in Figure 6 and Figure 8, respectively.

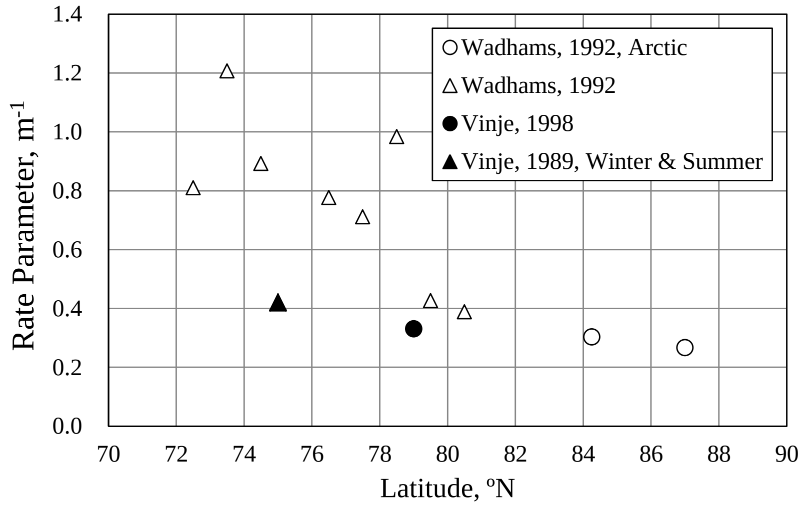


Figure 10 Rate Parameter

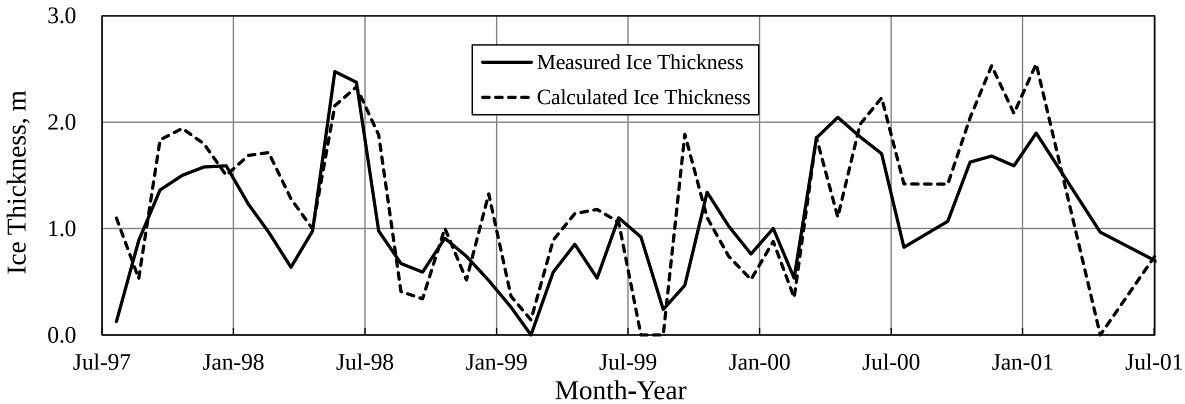


Figure 11 Time Curves of Measured and Calculated Ice Thickness in Fram Strait at 79.0˚N, 2.0˚W ($\lambda = 1.0$)

To the contrary, calculated ice thickness considerably overestimates results of field measurement by Witte and Fahrbac (2005) in Figure 8. Although the reason for this requires more detailed study, this might be due to that the value of rate parameter ($\lambda = 0.3\,m^{-1}$) is not appropriate for this case. Figure 10 shows the value of rate parameter obtained from ULS ice draft measurements in the Arctic Ocean and Greenland Sea (Wadhams, 1992), Fram Strait (Vinje, 1998) and Greenland Sea (Vinje, 1989) as a function of latitude. Rate parameter is its minimum of about $0.3\,m^{-1}$ in the Arctic Ocean and increases southward as ice condition becomes more moderate. In Fram Strait sea ice is dominant in the west and ice concentration lessens toward the east. ULSs in Witte and Fahrbac (2005) were deployed in Fram Strait at

79.0˚ north as was in Vinje et al (1998) but more to the east at 2.0˚ west near the ice edge. A higher rate parameter might be relevant for this area. An attempt was made to calculate ice thickness for a value of $\lambda = 1.0$. Figure 11 shows time curves of measured and calculated ice thickness. Calculation agrees well with measurement for this value of rate parameter.

SUMMARY

In this paper a method to calculate sea ice thickness from partial concentration values is presented. Ice types and thickness defined by WMO were used in the calculation. Probability distribution functions (PDFs) were considered to define the average thickness values for each ice type. PDFs assumed were a uniform distribution for ice types from Nilas to Thick First-Year Ice and a negative exponential distribution for old ice. Calculated ice thickness was compared with results of a field measurement in the Beaufort Sea (Melling and Riedel, 2008) and two different measurements in Fram Strait (Vinje et al, 1998; and Witte and Fahrbac, 2005). Calculation results agreed with and Melling and Riedel (2008) and Vinje et al (1998), but overestimated Witte and Fahrbac (2005).

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