Study on Thin Sea Ice Thickness using Passive Microwave Brightness Temperature

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ABSTRACT The use of passive microwave data for estimating sea-ice thickness is limited by strong dependence of emissivity on near-surface brine. However, this particular characteristic becomes a basis for an algorithm to estimate thickness of thin sea-ice if a thickness-salinity-emissivity relationship is established. This study aims at developing an algorithm to estimate sea ice thickness on the basis of this relationship. In order to establish a thickness-salinity-emissivity relationship, we have conducted multi-platform synchronous observations in the Sea of Okhotsk. We note a positive relationship between thickness and brightness temperature. From observations, we also establish an empirical relationship between salinity and emissivity, thus between thickness and brightness temperature. The derived relationship is qualitatively similar to the one based on Hoekstra and Cappillino's formulation. Our results suggest that for thin sea-ice in the winter period there is potential to develop an algorithm to estimate sea-ice thickness.

KEY WORD: sea ice, emissivity, thickness, microwave

1. Introduction

Sea ice is an essential component of the global climate system, as it influences and is influenced by changes and variations in the global energy balance and water cycle. It is also argued that sea ice is a sensitive indicator of climate changes based on the ice-albedo feedback mechanism that may amplify climatic responses to global changes in high latitudes. The brightness temperature measurements from the microwave radiometer show that the sea ice area/extent in the Northern Hemisphere has significantly decreased over the last two decades (Comiso, 2002). Despite the significance of satellite observations on the sea-ice area and extent such as this, information on changes in the sea ice thickness distribution is still needed for the assessment of possible changes in the sea-ice mass balance.

Maykut (1978) reported that the heat flux over sea-ice less than 0.4 m thick is 10 to 100 times more than that over thicker ice. Thin sea-ice, especially newly formed, has higher salinity compared with older sea ice, and it becomes less saline as it grows. This implies that the sea ice thickness is crucial not only for the heat flux but also for the salt flux, an important parameter when we consider the air-sea-ice interaction. It is thus highly desirable to extract information on sea-ice thickness from remotely sensed data.

Our study is an attempt to develop an algorithm to estimate sea ice thickness for thin category using in situ measurements on sea-ice thickness, brightness temperatures, and salinity. In comparison, most of previous studies examine the relationship between sea-ice thickness and brightness temperatures with laboratory and pool experiments (e.g. Grenfell and Comiso, 1986; Germain et al., 1993). Although thin, this class of sea ice may play an important role in the global climate system, as large parts of sea-ice in marginal and seasonal sea-ice zones fall in this category, over which particularly strong air-sea-ice coupling takes place.

A common thought is that strong dependence of the emissivity on near-surface brine makes the brightness temperature highly independent of thickness once sea ice reaches certain thickness. On the other hand, *if a thickness-salinity-emissivity relationship were to hold* and successfully modeled within the thin sea-ice category, we could estimate thickness within this category. In this presentation we show the results from our investigation on this potential.

2. Sea ice observation

In order to establish a thickness-salinity-emissivity relationship from *in situ* observations, we first made multi-platform synchronous observations in the Sea of Okhotsk using satellites, an aircraft, and a ship (the study area shown in Figure 1). Figure 2 is an image from PSR onboard the NASA

P3-B plane with the solid line indicating the ship's track (shown here is the image using the horizontal polarization at 39GHz).

An important step in this study is accurate and representative estimation of sea-ice thickness from the ship, which provides us with the information on how thickness, salinity, and emissivity are related. For this purpose, we have developed a method using vide-recorded scenes taken from the ship, which enables us to evaluate the extent of the spatial homogeneity in ice conditions (Naoki et al., 2006). Based upon this method, we have identified six sections during the cruise. Each of these sections is at least 250m of the length with relatively homogeneous ice conditions. The averaged thickness over each of these sections ranges from approximately 2 to 30cm.

For those six sites (A to F in Figure 2), Figure 3 presents the relationship between sea-ice thickness and brightness temperatures measured at different frequencies (10.7 to 89GHz indicated by different symbols) and for horizontal and vertical polarizations, (A) and (B) respectively. The brightness temperature tends to increase with sea-ice thickness to approximately 20cm. Beyond this range, brightness temperatures either reach a ceiling or start decreasing, which is more pronounced for higher frequencies (e.g. at 89GHz). Also noted is that the positive relationship between thickness and brightness temperature is more pronounced (steeper slope) for horizontal polarization than vertical polarization and at lower frequencies (e.g. 10.7GHz).

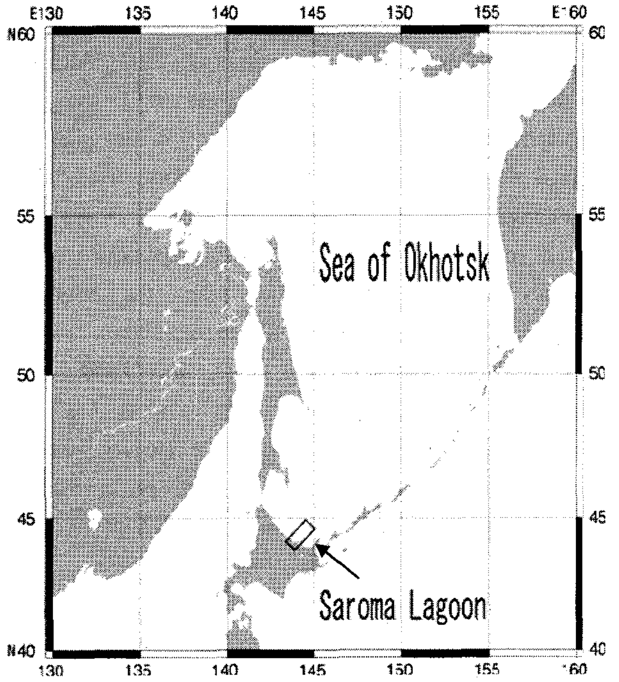

Fig. 1 The location of the study area. The area enclosed with the square indicates the location of the synchronous observations. The samples for the relation between thickness and the surface salinity were taken from Saroma Lagoon shown by the arrow.

3. Stimulation of sea ice emissivity

3.1 Thickness-salinity relationship

When sea-ice is newly formed its surface becomes saline, which tends to remain to be so. This makes the microwave radiometer measurements less sensitive to differences in sea-ice thicknesses, as this saline layer dominates the emission. However, the results from our observations rather clearly suggest the dependence of the brightness temperature on sea-ice thickness (Figure 3). The observed relationship may be explained by the fact that the surface brightness temperature is controlled by the salinity of the near-surface layer but not just at the top. If so, this near surface saline layer affects the way in which the microwave is absorbed, scattered and emitted. In order to test this idea, we measured the bulk salinity of the near-surface layer and compared it with thickness. Figure 4 plots sea-ice thickness against corresponding near-surface salinity for samples taken from Saroma Lagoon, which is located adjacent to the Sea of Okhotsk (see Figure 1). All samples were from the uppermost parts of the sea-ice columns (3cm) before measuring the thickness of the entire columns. It is confirmed here that the bulk salinity in the uppermost part of the sea-ice column decreases with increasing thickness (Figure 4). Although we do not have measurements thinner than 4.2cm (the thinnest sample), we would expect that salinity increases as sea-ice gets further thin. Now assuming 35ppt of salinity at the intercept, we obtain an empirical relationship (e.g. exponential) between thickness and salinity, indicated by the solid line.

3.2Salinity-emissivity relationship

The next step is to convert the relationship between

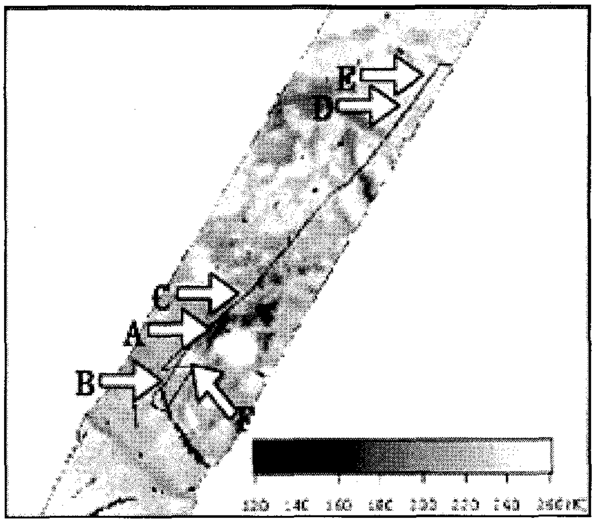

Fig. 2 An image from the PSR observation (brightness temperature of 37.0GHz horizontal polarization data). The solid line indicates the track of the P/V Souya.

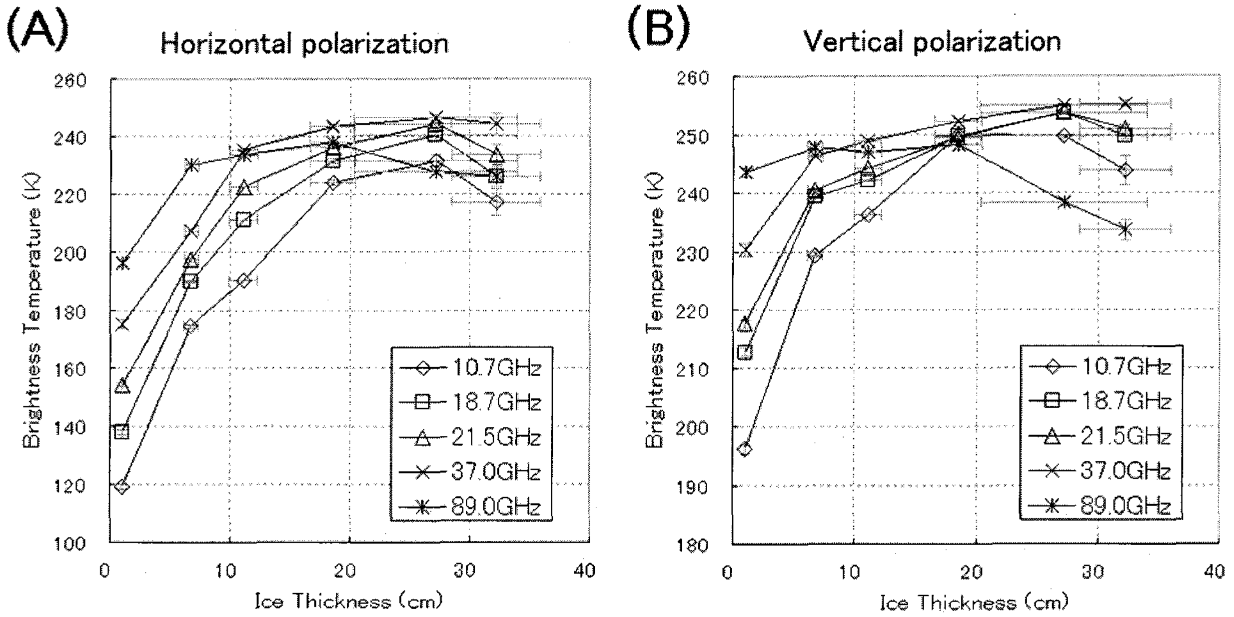

Fig. 3 Sea ice thickness vs. Brightness temperature.

thickness and brightness temperature derived from the observations in the Sea of Okhotsk (Figure 3) into another relationship between salinity and emissivity. Here thickness is converted to salinity using an estimated relationship between thickness and salinity (Figure 4). We then compute emissivity by diving the observed brightness temperature by observed sea-ice surface temperature (-7℃). Figure 5 shows a derived relationship between salinity and emissivity for six different sites.

For thin ice (approximately <30cm of thickness), the above results suggest a monotonically decreasing relationship of emissivity with salinity. When combined with another monotonic relationship between thickness and salinity (see Figure 4), we are able to invert a product of two monotonic functions from brightness temperature to thickness, which provides a basis for our algorithm.

4. Discussions

Figure 6 provides a schematic picture of our algorithm. First, brightness temperature is converted to emissivity using air temperature. We have already confirmed that the air temperature can be used as a proxy for the temperature of the near surface layer. Then two empirical relationships, one between emissivity and salinity (Figure 5) and the other between salinity and thickness (Figure 4), are combined to give an estimate of thickness from emissivity.

In order to understand underlying physical processes, let us compare our algorithm with another model. Given a frequency, emissivity depends on the dielectric constant, which is a function of temperature and salinity, or more precisely brine volume. The formulation of Hoekstra and Cappillino (1971) combined with the temperature of -7℃ would lead to a salinity-emissivity relationship (a solid line in Figure 5). The curve and our empirically derived relationship are in reasonable agreement when salinity is high, say above 20ppt. Our empirical relationship gives higher emissivity, and the difference becomes wider when salinity becomes low. For example, at 15ppt our interpolated value for emissary is 0.74, which is compared with 0.59 from Hoekstra and Cappillino's formula.

Hoekstra and Chaplin's formulation is based on the notion that the absorption is most dominant in controlling the emissivity, and the amount of absorption depends on the brine volume within a thin layer near the surface. It is interesting to note that two estimates in Figure 5 are rather close for the high

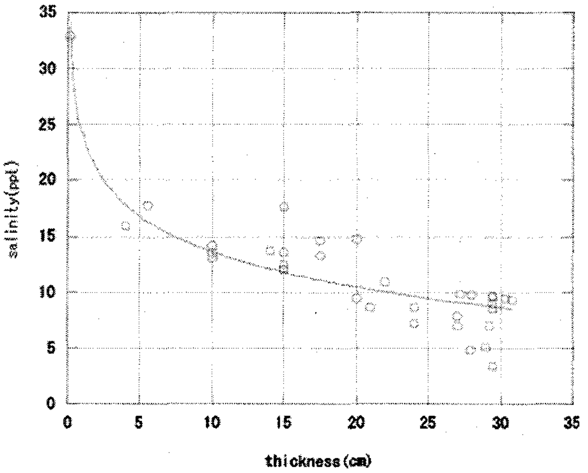

Fig. 4 Sea ice thickness vs. surface salinity of the uppermost layer of 3cm thickness.

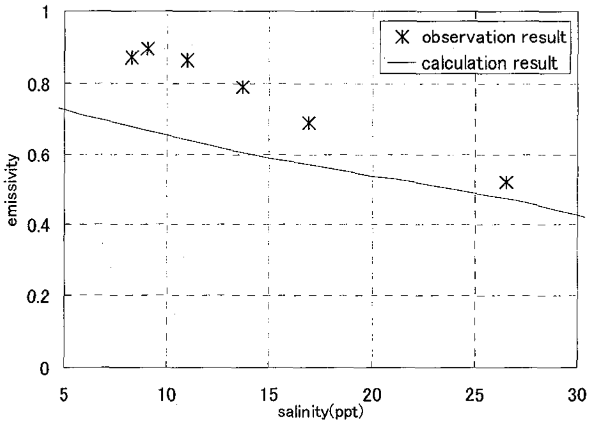

Fig. 5 Comparison of emissivity-salinity relationships, one based on our observations (cross) and the other based on the dielectric constant model of Hoekstra and Capplliano (solid line).

salinity range. This may be taken as an indication that the absorption model though the dielectric constant put forward by Hoekstra and Cappillino is likely at work. For the sake of argument, suppose that our empirical relationship were real. Then, different explanations account for the discrepancy over the lower salinity range. One is that the brine volume used in their calculation is overestimated, which results in lower emissivity. An alternative explanation is that volume scattering becomes a source of higher emissivity. To assess relative contributions from these two processes and to further improve our estimation model, it is needed to measure brine characteristics and the dielectric constant of sea-ice with the thickness in the rage of approximately 5 – 30cm. Nonetheless, we believe that our results show potential of successfully constructing an algorithm for sea-ice thickness targeted at the thin category.

5. Conclusions

From observations, we establish an empirical relationship between salinity and emissivity for a thin class of sea-ice. The derived relationship is qualitatively similar to the one based on Hoekstra and Cappillino's formulation. Our results suggest that for thin sea-ice in the winter period there is potential to develop an algorithm to estimate sea-ice thickness. For future, we plan (i) to apply the derived relationship to AMSR-E data to estimate sea-ice thickness and/or identify thin sea-ice over a large domain and (ii) to make *in situ* measurements on the electromagnetic properties and physical characteristics of sea-ice to improve our algorithm.

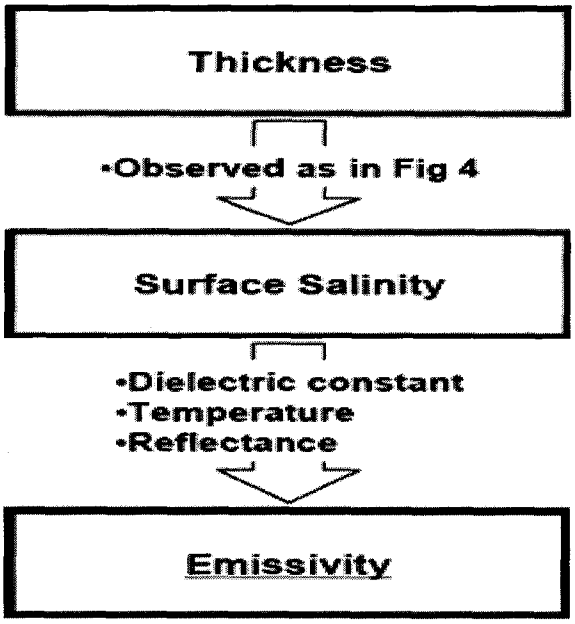

Fig.6 Schematic diagram of estimation of emissivity/thickness from brightness teperture.

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