

1. Introduction

The Arctic is recognized to be an important environment in the global climate system. Observational evidence of atmospheric and climate-sensitive variables such as sea ice, ocean water masses, river discharge, snow cover, glaciers and permafrost indicates that a reasonably coherent portrait of late 20th century change in the Arctic and sub-Arctic is apparent (e.g., Bobylev et al., 2003).

In the context of the International Arctic Science Committee (IASC)’s research priorities, the First and Second Chinese National Arctic Research Expeditions were organized in 1999 and 2003, respectively, to conduct a variety of scientific programs in the Bering Sea, the Chukchi Sea and the Canadian Basin of Arctic Ocean. One of the research programs was to understand the process of the Arctic sea ice change and its influence on the air/sea/sea ice exchange.
The objective of the present study was to measure the thickness of sea ice by the ship-borne electromagnetic induction instrument (hereafter denoted as SEM) mounted on the R/V Xuelong during the Second Chinese National Arctic Research Expedition (CHINARE-2003). SEM observations were conducted during the period from 19 August to 9 September 2003. Figure 1 indicates the tracks of the R/V Xuelong during SEM observations in the Chukchi Sea, together with the ice edge derived from DMSP SSM/I data at the end of August 2003.

2. Measurements

Combining an electromagnetic induction (EM) instrument with a laser altimeter is a widely used technique for measuring sea ice thickness from icebreakers (e.g., Kovacs and Morey, 1991; Haas et al., 1997; Worby et al., 1999; Uto et al., 2002). The ship-borne EM (SEM) utilized in the present study was a single frequency EM sensor (EM-31/ICE, Geonics Ltd., Canada), having two coils; a transmitter (Tx) and a receiver (Rx) at both ends. It can measure the distance from the sensor to the bottom of sea ice; namely the ice-water interface, in other words the surface of sea water. A laser altimeter (LD90-3100HS, Riegl Japan Ltd., Japan) detects the distance from the sensor to the top surface of snow or ice. Figure 2a is a schematic of ice thickness measurements by the SEM. The operating frequency is 9.8 kHz, and the distance between Tx and Rx is 3.66 m. The Tx generates an alternating primary magnetic field $H_p$ and induces small eddy currents in the underlying seawater. These currents generate a secondary magnetic field $H_s$, which is sensed along with $H_p$ by Rx. The EM instrument automatically transforms the measured quadrature response of $H_s$ to the apparent conductivity $\sigma_a$ in mS/m (McNeill, 1980). $\sigma_a$ is defined as
\[ \sigma_a = \frac{4}{\omega \mu_0 r^2} Q \left( \frac{H_s}{H_p} \right), \]  

where \( \mu_0, \omega, r, \) and \( Q(H_s/H_p) \) denote the magnetic permeability of free space (4\( \pi \times 10^{-7} \) H/m), angular frequency \( (\omega = 2\pi f) \), transmitter-receiver coil separation (3.66 m) and the quadrature component of the ratio of \( H_s \) to \( H_p \) at Rx, respectively. The frequency \( (f) \) is 9.8 kHz.

Since the difference in conductivity between snow and ice is very small, the EM instrument cannot distinguish snow from ice. Therefore, we discuss the relationship between
σ, derived from SEM measurements and the observed total thickness of snow and ice (Z$_S$ + Z$_I$, where Z$_S$ is the snow depth and Z$_I$ is the ice thickness). The total thickness can be calculated by subtracting the distance between the EM sensor and the snow/ice surface (Z$_L$) measured by a laser altimeter from the distance between the EM sensor and the seawater surface (Z$_E$).

σ can be measured in either the horizontal coplanar (HCP) mode or the vertical coplanar (VCP) mode of the EM instrument. In the present study we used the latter mode, since it has a finer lateral resolution than the HCP mode and possesses a high capability of distinguishing thin ice (Reid et al., 2003). According to Reid and Vrbancich (2004), the footprint size for the VCP geometry is 1.4–1.5 times larger than Z$_E$; i.e. when sounding a 6-m-thick ice ridge at an instrument height of 4 m (Z$_E$ = 10 m), the apparent footprint size for the VCP mode is 14–15 m. Therefore, the instrument should be placed 5.6–6.0 m away from the ship hull for the VCP mode at an operating height of 4 m (Fig. 2b), so that the effect of the ship hull can be prevented from affecting the observed data.

2.1. Calibration and core sampling

The output of the EM instrument was calibrated by measuring stepwise changes of sensor height over a 2.39-m-thick multi-year ice floe covered with a 0.26-m-deep snow layer on 29 August. The relation between the apparent conductivity (σ$_a$) and the distance between the EM instrument and the seawater surface (Z$_E$) is shown in Fig. 3a.

Snow, ice and seawater samples were collected from the site where the EM instrument was calibrated. The ice temperature was measured in-situ using a thermistor stick inserted into holes drilled at 5 or 10-cm intervals in the sample cores. These ice cores were cut into 5 to 10-cm sections and melted out on the ship. Sea-ice conductivity (σ$_I$) was measured from the melted ice water. The snow density and temperature were measured at 1–3 cm vertical intervals, and snow conductivity (σ$_S$) was measured from the melted samples. Ship-based CTD profile data were used for seawater conductivity (σ$_W$). Finally, the values of Z$_S$, Z$_I$, σ$_S$, σ$_I$, and σ$_W$ were derived as 0.26 m, 2.39 m, 0 mS/m, 15 mS/m, 2270 mS/m, respectively. The conductivity values of ice and seawater obtained in the present study were smaller than those previously obtained in spring and summer in the Arctic and sub-Arctic (Tateyama et al., 2006). In the present study, significant desalination might have occurred as the ice core samples were obtained from the second-/multi-year ice floes and less saline waters were found just below the ice prior to the onset of freezing.

2.2. Data reduction

A method to calculate Z$_S$ + Z$_I$ from σ$_a$ by using a 1-D multi-layer model was proposed by Haas et al. (1997) and Haas (1998). In the present study, we used a theoretical calculation program, PCLOOP developed by Geonics Ltd. (McNeill, 1980) to calculate σ$_a$ using the 1-D multi-layer model, which consists of three layers, snow (Z$_S$, σ$_{SBULK}$), ice (Z$_I$, σ$_{IBULK}$) and seawater (infinite depth, σ$_W$). The instrument height (Z$_L$) was also included in this model.

The σ$_a$–Z$_E$ transform equation is based on an empirical approximation of the analytical equation for the measured electromagnetic field. An approximation for the inversion model, which calculates Z$_E$ from σ$_a$, is commonly used and gives stable results (Pfaffling et al., 2004).
where \( a_n \) are coefficients. The \( \sigma_a - Z_E \) relationship was derived from calibrations done by varying the SEM instrument height over the 2.39-m-thick multi-year ice floe covered with a 0.26-m-deep snow layer, as shown in Fig. 3a. From the 1-D multi-layer model, \( a_0, a_1 \) and \( a_2 \) were derived as 13.47, 5.19 and 0.48, respectively.

The comparison between \( Z_E \) values measured in-situ and those estimated from eq. (2) is shown in Fig. 3b. Estimated \( Z_E \) values agree well with the measured ones within 8% error.

### 3. Results and discussion

SEM ice thickness data were obtained for 24–29 August and 4–7 September 2003. First, the time series of \( \sigma_a \) records obtained at the sampling rate of 10 Hz were processed with a 1001st low-pass digital filter, which cuts off the signal higher than 0.5 Hz, in order to reduce the noise level from 0 db to –80 db. Those noises might be induced from the signal/power cable. After removing the noises, the total ice thickness was then calculated by subtracting \( Z_L \) from \( Z_E \) estimated by eq. (2).

The time series of total thickness was combined with the time series of GPS (Global Positioning System) position of the EM instrument obtained at the sampling interval of 0.5 Hz. The total thickness is shown as a function of time for 24–29 August and from 4–7 September, in Figs. 4 and 5, respectively. Thickness values were obtained every 2 s in Figs. 4 and 5 from time 0 (00h00m00s) to 43199 (23h59m58s). The hatched area shows no data. SEM measurements during the first period in Fig. 4 were carried out in regions farther from the ice edge (see Fig. 1), which were compact ice fields mainly filled with deformed and second-/multi-year ice floes. In the beginning of the first period from 24 to 26 August in Fig. 4, the ship proceeded northward, where approximately 0.3-m-thick ice, 1.5 to 2.0-m-
thick second-year ice and 4-m-thick multi-year ice were dominant. At the end of the first period from 27 to 29 August in Fig. 4, the ship headed towards the south through a rather loose ice area. After ramming into a thicker multi-year ice field, the ship anchored in large multi-year ice for establishing the ice station until 4 September. The probability density function (PDF) of total thickness in the 0.1 m bin size obtained from all data during the first period is shown in Fig. 6a. All ice over 6.1-m-thick was classified as 6.1-m-thick ice. The primary peak appeared at around 1.5 m, presumably corresponding to second-year ice; a peak at around 0.3 m was also found.

During the second period in Fig. 5 the ship sailed along the ice edge (see Fig. 1), where ice floes less than 1.5-m-thick were dominant in open pack ice. The PDF in Fig. 6b

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**Fig. 4.** Time series of total ice thickness by SEM measurements from 24 to 29 August 2003. The x-axis shows time from 0 (00h00m00s) to 43199 (23h59m58s). The hatched area shows no data.
shows three peaks at around 0.3 m, 1.3 m, and 3 to 4 m thickness, apparently corresponding to level ice, deformed or second-year ice, and multi-year ice, respectively. Although 3 to 4-m-thick multi-year ice floes were observed at around 80°N, they do not appear to be significant in the PDF.
4. Concluding remarks

Measurements of the ice thickness were carried out using a ship-borne electromagnetic induction instrument (SEM) mounted on the R/V Xuelong during the Second Chinese National Arctic Research Expedition (CHINARE-2003). SEM observations were conducted during the period from 19 August to 9 September 2003 in the Chukchi Sea. The SEM data were reduced to a 1-D multi-layer model, consisting of the three layers snow, ice and seawater.

The time series of total (snow plus sea ice) thickness obtained during SEM observations indicate that deformed and second-/multi-year ice floes appeared frequently in very close pack ice farther from the ice edge, while thinner ice floes less than 1.5 m were frequently found in open pack ice along the ice edge. The PDFs show that peaks appear at around 0.3 m, 1.3 to 1.5 m and 3 to 4 m thickness, presumably corresponding to level ice, deformed or second-year ice, and multi-year ice, respectively.

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References

