Comparison of seasonal sea-ice thickness change in the Transpolar Drift observed by local ice mass-balance observations and floe-scale EM surveys

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ABSTRACT. Local and transect ice-thickness measurements were performed between May and November 2007 on an ice floe in the Transpolar Drift of the Arctic Ocean using an ice mass-balance buoy and electromagnetic induction (EM) sounding. Repeated EM surveys along an originally 2160 m long profile including level and deformed ice showed that between June and September modal and mean thicknesses decreased by 0.6 and 0.86 m respectively. The modal thickness decrease is in good agreement with the thinning of 0.6 m observed by the ice mass-balance buoy at one location on unponded ice during the same period, although the local observations do not capture the different melt rates on level and rough ice. The paper discusses methodological and operational challenges in sustaining both measurements over periods of several months, and concludes that more work needs to be done to better understand their representativeness.

INTRODUCTION

Satellite observations show that the areal coverage of sea ice in the Arctic Ocean decreases rapidly, and much faster than predicted by climate models (Stroeve and others, 2007). Recent satellite data also indicate widespread thinning (Kwok and others, 2009), in agreement with sporadic ground-based measurements in the region of the Transpolar Drift (Haas and others, 2008a). Those measurements also show large seasonal thickness differences primarily related to cycles of winter freezing and summer melt. The seasonal thickness cycle has to be considered when comparing observations performed at different times of the year. This is often the case with submarine or airborne surveys due to logistical constraints (Haas and others, 2008a; Rothrock and others, 2008; Kwok and Rothrock, 2009).

Seasonal thickness changes can most easily be observed with continuous measurements by moored upward-looking sonars (ULS; e.g. Melling and others, 1995; Strass and Fahrbach, 1998) or with so-called ice mass-balance buoys (IMB; Richter-Menge and others, 2006). ULS provide information on ice-thickness changes in an Eulerian reference system as the ice drifts over a mooring location. Interpretation may be complicated if there is a combination of thermodynamic thickness changes and advection of ice of different age and origin. IMBs are usually deployed on ice floes and measure snow- and ice-thickness changes by means of acoustic rangefinders above the snow and below the ice. They provide data of an individual location in a Lagrangian reference system as the ice floe drifts about. IMBs have been used to distinguish between bottom and surface accumulation or ablation, and to compare summer ablation rates in various regions of the Arctic. During the summer of 2007 when the Arctic ice cover assumed a record minimum areal coverage, Perovich and others (2008) used IMBs to observe ~2.70 m of melt in the Beaufort Sea and only 0.60 m in the region of the North Pole. This large difference was due to different ice concentrations in the two regions and, together with feedback processes of solar radiation input into the mixed layer, contributed to the strong ice retreat in the Beaufort Sea. However, the representativeness of IMB results is unclear, as their measurements only provide local observations at the buoy deployment sites (Perovich and Richter-Menge, 2006). By means of repeat surveys along the same profiles during a period of one summer melt cycle, Eicken and others (2001) and Perovich and others (2003) showed that ablation rates are strongly dependent on the local ice type and the morphology of the surrounding area.

Here we compare local results from an IMB with profile measurements of ice- and snow-thickness change on the same ice floe to provide further insights into the local variability of seasonal thickness changes and representativeness of local measurements. Ice-thickness profiles were obtained by means of electromagnetic induction (EM) sounding. This method is well suited for repeat, non-destructive surveys along the same profiles for longer periods of time (Eicken and others, 2001; Haas and others, 2008b). Measurements were performed between May and November 2007 and therefore cover a period from maximum end-of-winter ice thickness through the summer melt season and into the fall freeze-up. They were obtained on an ice floe drifting from the Siberian Arctic almost across the North Pole and into Fram Strait, thus providing additional information on ice conditions during the remarkable summer of 2007 (Fig. 1).

MEASUREMENTS

Data presented here were obtained during the drift of the French schooner *Tara* with the support of its crew, who

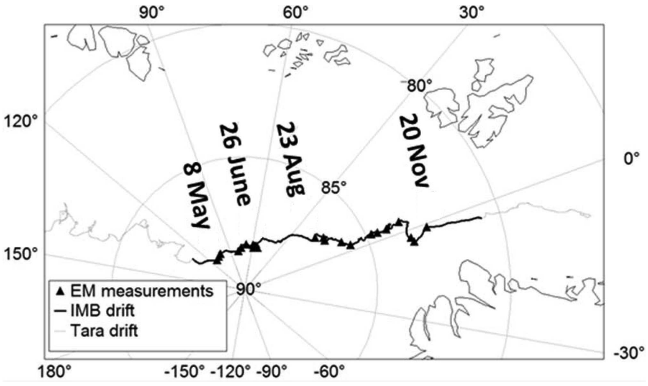

Fig. 1. Map of the drift track of *Tara* and the ice mass-balance buoy (IMB), and of the locations of EM thickness surveys.

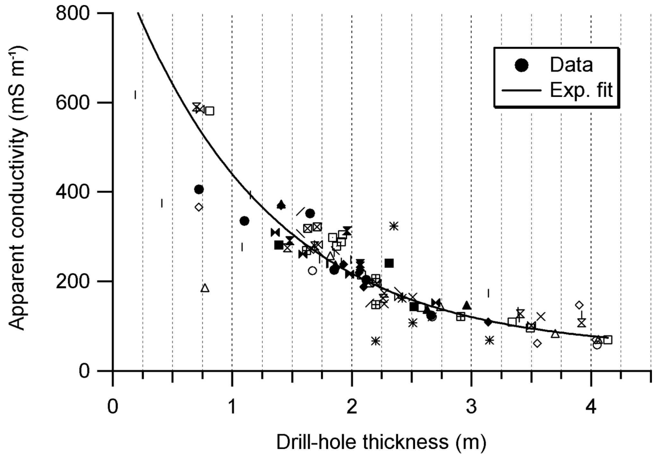

Fig. 2. Comparison of coincident measurements of apparent conductivity and drillhole thickness used to calibrate the EM measurements. Different symbols show measurements on different days. Line shows exponential fit (Equation (1)) used in this study to convert measured conductivity into thickness.

drifted with the Transpolar Drift between September 2006 and January 2008 (Gascard and others, 2008). The boat served as a logistic platform for various atmospheric (Vihma and others, 2008), oceanographic and sea-ice measurements (Sankelo and others, in press; M. Nicolaus and others, ~~unpublished information~~). When first entering the ice in autumn 2006, the boat sailed into loose fields of small ice floes of surviving first-year ice formed in the previous winter. By definition, this ice became second-year ice when freezing began. Consequently, during the study period discussed here, the ship was embedded in predominantly second-year ice with a few patches of newly forming first-year ice.

In April 2007, a group of six scientists visited the boat by aircraft and performed extensive drillhole measurements of ice and snow thickness with 5 m point spacing along an 870 m long profile including level ice and ridges. They also deployed an IMB on second-year ice 250 m away from the ship but close to the drill profile. IMB data were transmitted 2 hourly by a satellite communication system. Snow- and ice-thickness changes can be observed with an accuracy of a few centimetres (Richter-Menge and others, 2006). Results of the IMB at *Tara* are presented by Nicolaus and others (in press).

Two weeks after completion of the drillhole profile, EM surveys commenced along the same and a perpendicular profile, 2160 m long in total. The drillhole data served as initial validation for the EM measurements, which were repeated 20 times by the ship's crew in the following months, approximately once every 1–2 weeks.

With EM measurements, the electrical conductivity of the underground can be determined ~~by EM in the sea water under the ice~~. As sea ice is highly resistive and sea water is a good conductor, the measured average or 'apparent' conductivity decreases with increasing ice thickness. Measurements represent total thickness, i.e. the sum of snow and ice thickness (referred to as 'thickness' from here on), because both snow and ice are highly resistive and cannot be distinguished. The accuracy of the method is ±0.1 m over level ice under typical summer and winter conditions (Kovacs and Morey, 1991; Haas and others, 1997), and only little affected by melt ponds (Eicken and others, 2001). Due to the lateral extent of induced eddy currents, results represent average conditions over a footprint area a few metres in diameter, which leads to the underestimation of maximum ridge keel depths. The magnitude of this underestimation is still being debated, but new insights were obtained during this study by comparisons with drillhole data (see below). Note that despite the underestimation of maximum ridge thickness, relative changes of ridge thickness can be observed if exactly the same measurement locations were occupied.

In this study, all EM measurements were performed with a Geonics EM31-MK2 instrument, which operates with a frequency of 9.8 kHz and a coil spacing of 3.66 m. The same instrument was used in similar studies, where drilling of holes was to be avoided to prevent changes of the hydraulic drainage network during the melt season (Eicken and others, 2001; Haas and others, 2008b).

Accurate conversion of measured conductivity to ice thickness depends on careful calibration of the EM instrument, which changes with the conductivities of the water and ice, with prevailing level-ice thickness, and may vary with ambient temperature and time due to drift of some electronic components. Therefore, on most survey days, 2–15 (average 5) coincident drillhole measurements were performed to verify the calibration of the instrument. Figure 2 shows that unfortunately there was quite large scatter in the obtained conductivity/thickness ratio, which indicates that the drillhole locations were not always on sufficiently level ice. An exponential fit to the data of the form

$$\sigma_a = k_0 + k_1 \exp(-k_2 Z_{tt}), \qquad (1)$$

with apparent conductivity σ_a and (total) thickness Z_{tt}, resulted in coefficients of $k_0 = 45$ and $k_1 = 900$, where $k_2 = 0.826$ was derived by Haas and Eicken (2001) for ice of comparable modal thickness. This preserved the dynamic behaviour (curvature) of the conductivity/thickness relation, but corrections were allowed for possible differences of bias and gain of the instrument used in this study. All calibration and EM measurements were performed by the crew of *Tara*, non-experts who, however, were carefully trained before the campaign. The instrument was operated on a sled at a height of 0.4 m above the surface, which proved challenging when traversing rough ice. As laying ruler tapes or maintaining markers along the profiles was very difficult due to repeated floe breakages and melt-related surface changes, the point

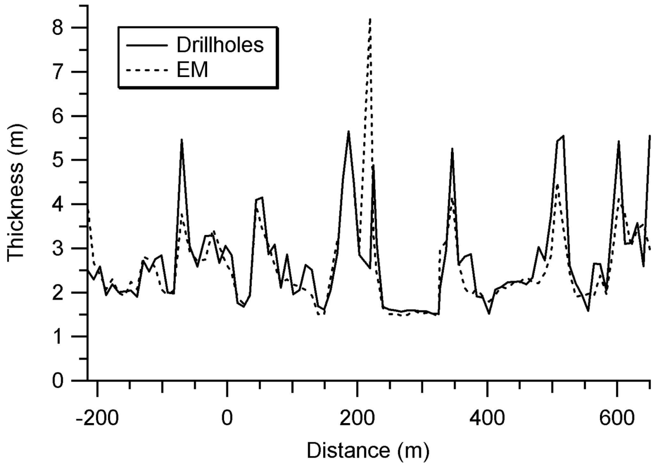

Fig. 3. Comparison of drillhole and EM thickness along the validation line, 8 May 2007.

spacing between individual measurements was measured by footsteps, and amounted to ~9.5 m. However, a few flags were maintained at characteristic points and served to co-align each profile measurement as well as possible with the others.

Unfortunately, the calibration of the EM instrument deteriorated towards the end of June due to a faulty electronics component, and the instrument could not be used in July and most of August. It was replaced during a Twin Otter aircraft resupply flight on 23 August. Therefore, no EM data are available during the period of maximum thinning, but the data can still be used to compare ice thicknesses before and after the melt.

RESULTS

Validation

Figure 3 compares 92 drillhole and EM ice-thickness measurements along the 870 m long validation line, showing level sections and many ridges. The deformed state of the sea-ice cover was probably due to its origin from small second-year floes embedded in newly forming first-year ice, typical for sea ice originating from the marginal ice zone. A point-to-point comparison between drillhole and EM measurements was difficult as, due to their temporal separation of 2 weeks, their locations were not always exactly coincident and had to be reconstructed by interpolation. Thickness histograms of both datasets (not shown) were bimodal, with thicknesses of 1.55 and 2.05 m representing the predominant first- and second-year ice types. They agreed exactly within the bin width of 0.1 m, although their areal fractions differed slightly. Mean drillhole and EM thicknesses were 2.70 and 2.53 m, respectively. Despite the general underestimation of maximum ridge thicknesses by EM data, this good agreement may be due to poor drillhole data over some of the thickest ridges (e.g. at 430 m where the drilling must have missed a deep keel). However, the close agreement may also be due to the compensating effects of EM overestimations of true thicknesses over ridge flanks and narrow troughs (Haas and others, 1997).

A linear regression of EM data onto drillhole data from Figure 3 resulted in a correlation coefficient of $r = 0.63$ and a slope of the regression line of 0.59 (not shown). As the level-ice data agree well (Fig. 3) and lie on the 1 : 1 line, the scatter and slope are largely controlled by the measurements over deformed, rough ice. The slope of 0.59 indicates that EM data underestimate deformed ice thickness by 41%. This value is less than the 60% underestimation found by Haas and Jochmann (2003) for thin, unconsolidated ice in the Baltic Sea.

Seasonal changes

Figure 4 shows four examples of thickness profiles representing typical stages of ice development in 2007. Comparison of the 8 May and 26 June surveys shows close agreement between measurements, but also some differences, particularly in sections of deformed ice which result from slight variations in the actual measurement locations. Mean and modal thicknesses were 2.75 ± 1.11 m (1 std dev.) and 2.1 m on 8 May (number of measurements $N = 218$; modes calculated for bin width of 0.1 m), and 2.69 ± 1.15 m and 2.1 m on 26 June ($N = 184$), respectively. In contrast, they were 2.25 ± 0.90 m and 1.7 m on 23 August ($N = 164$), and 2.11 ± 1.05 m and 1.5 m on 17 September ($N = 160$), respectively. Differences between profiles are not only due to seasonal thinning, but also due to the different number of measurements on each date, and to slightly different

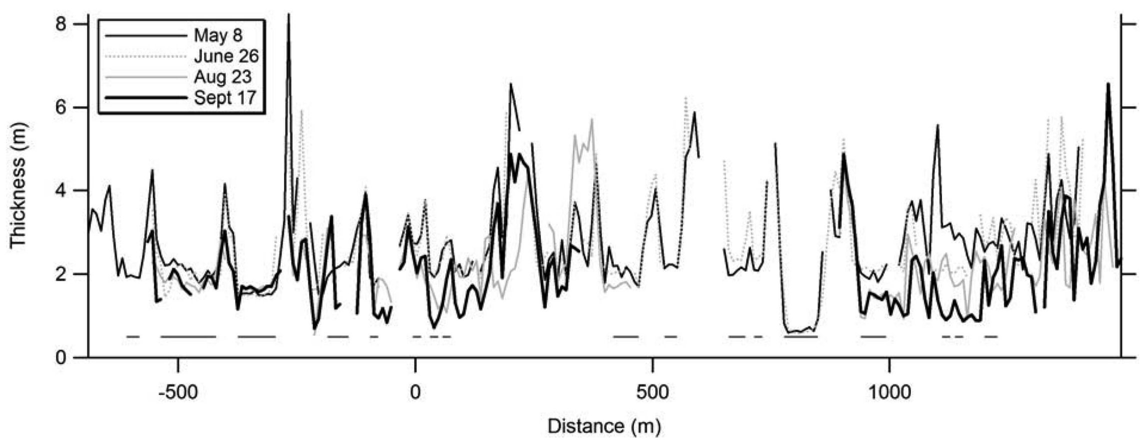

Fig. 4. Four ice-thickness profiles obtained at different, characteristic times during the summer of 2007. Note that later profiles are discontinuous, and some ice has disappeared, as for example between 400 and 900 m along the profile, where only May and June data were available. Horizontal bars at 0.5 m thickness denote level ice identified on 8 May (see text).

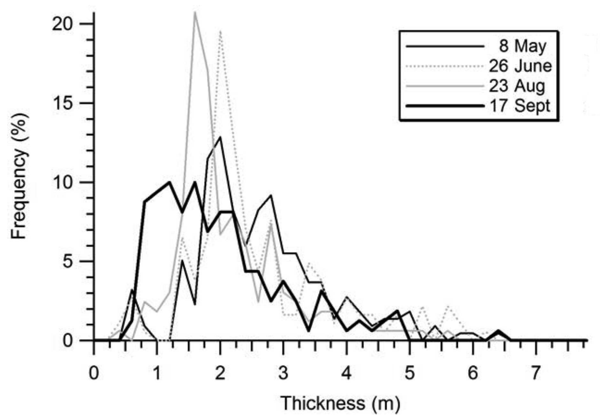

Fig. 5. Thickness distributions of the four profiles from Figure 4, calculated with a bin width of 0.2 m. Mean and modal thicknesses are discussed in the text.

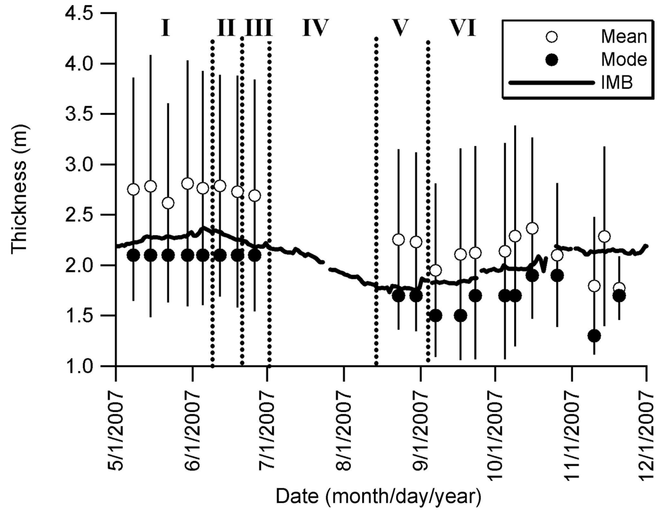

Fig. 6. Time series of modal and mean (±1 std dev.) EM and IMB total thickness. *N* is the number of EM measurements on each day. Stippled vertical lines and roman numbers indicate different phases of melt season development according to Nicolaus and others (in press): I. dry snow; II. melting snow; III. ponded surface; IV. surface drainage; V. autumn freeze-up; VI. dry snow.

measurement points. For example, the section between 1100 and 1600 m in Figure 4 could not be remeasured in August and September because the ice had fragmented and disintegrated. Nevertheless we consider the number of samples large enough to provide statistically reliable information on thickness changes along the profile, as the variation of the mean before melt onset is only 0.06 m, less than the uncertainty of individual measurements. Modal thickness is not much affected by the varying numbers of samples.

Unfortunately, records did not include information about the locations of melt ponds or other descriptions of surface types. Therefore, it is difficult to interpret the different amounts of melt visible along the profile (Eicken and others, 2001; Perovich and others, 2003). However, we performed a rough classification of ice types into level and rough ice. Identification of level ice required that ice thickness at adjacent points differed by <0.3 m. Accordingly, the original thickness profile comprised 23% level ice on 8 May (Fig. 4). Note that rough ice can be thin or thick, and is not necessarily associated with prominent pressure ridges. Mean level- and rough-ice thicknesses of points surveyed both in May and September were 2.07 and 3.11 m on 8 May, respectively. On 17 September, mean level- and rough-ice thicknesses had decreased to 1.61 and 2.24 m, respectively, i.e. mean level-ice thickness decreased by 0.46 m, while rough ice thinned by 0.87 m. The mean level-ice thicknesses, derived from only a small number of points, are in close agreement with modal thicknesses. However, the data indicate that melting was strongest on rough ice. Interpretation of this observation is hampered by the limited accuracy of EM measurements over rough ice, and by slightly varying measurement locations between profiles (see below).

The histograms in Figure 5 show the thickness distributions of the four profiles in Figure 4. Most changes are visible with decreases of modal thickness. In contrast, the amount and thickness of ridges does not seem to change very much. Therefore the observed thinning of rough ice described above is rather due to the thinner rough ice sections like those between 1700 and 1900 in Figure 4, and may be related to the preferred flow and collection of meltwater in these zones. Unfortunately, a more detailed investigation of the different behaviour of different ice types is hampered by the fact that individual measurement locations were not always exactly revisited (see below).

Comparison of EM profiles and IMB

The results of all 20 EM profiles are summarized in Figure 6 and compared with total thickness changes observed with the IMB. Between 8 May and 26 June, modal EM thicknesses were constantly 2.1 m, although IMB thickness first increased from 2.2 to 2.4 m, due to the accumulation of 0.2 m of new snow, and then decreased to 2.2 m due to the onset of melt (Nicolaus and others, in press). Mean EM thicknesses ranged between 2.6 and 2.8 m during the same time. Differences between methods may be due to different snow accumulation at different locations, but also due to the disturbance of the new snow by the EM sledge. Differences in mean EM thickness may represent snow accumulation, but are rather a result of slightly different measurement locations as discussed above. Between 27 June and 22 August, no EM measurements were possible due to technical difficulties. This was the period of surface drainage and most rapid thinning, as documented by the IMB. The ice at the IMB remained unponded throughout the summer. On 23 and 30 August, modal EM thickness had reduced to 1.7 m and was only 1.5 m on 7 and 17 September, i.e. 0.6 m less than in June. The minimum IMB thickness of 1.7 m was observed on 19 August, i.e. 0.5–0.7 m less than total thickness during May and June. This is in good agreement with the EM measurements, although snow accumulation was already observed at the IMB when the EM data reached their minimum. Minimum mean EM thicknesses ranged between 1.9 and 2.1 m on 7 and 17 September. The mean standard deviation of EM thickness decreased from 1.15 m in May and June to 0.99 m in August and September. In October and November, IMB thickness increased to values up to 2.2 m due to new snow accumulation. The latter has contributed to similar and locally variable changes in the EM data, but in November results are highly biased by small sample numbers of only five measurements per profile.

DISCUSSION AND CONCLUSION

The presented data are extensive enough to provide a reliable estimate of second-year (snow-plus-ice) thickness in April and May 2007. The observed modal thickness of 2.1 m was slightly less than the 2.3 m at the North Pole at the same time (Haas and others, 2008a). This may be due to less thermodynamic growth at the more southerly location of *Tara*, or due to thinner ice at the onset of fall freeze-up. The observed thinning of 0.6 m is not sufficient to explain the significantly lower thicknesses of only 0.9 m found in the same region in August 2007 (Haas and others, 2008a). This adds further evidence to the fact that the second-year ice in the region of the North Pole had been replaced by first-year ice during summer.

The obtained dataset is one of a few where sufficient coincident drillhole and EM measurements were obtained including level and rough ice. The slope of 0.59 of the regression of EM-derived thickness onto drillhole thickness can be compared to a similar comparison from the Baltic Sea, which resulted in a slope of only 0.4 (Haas and Jochmann, 2003). This result indicates that the underestimation of deformed first- and second-year ice thickness in the Arctic is 41% on average, less than the 60% obtained in the Baltic. The better performance of the EM soundings in the Arctic may be due to a larger conductivity contrast between the ice and water, due to larger keel block sizes, and due to the higher degree of consolidation of Arctic ridge keels. Still, more extensive and improved drillhole data including information on void sizes and fractions as well as on the three-dimensional character of the profiled ridges would be required to better address the performance of EM soundings. Our main results are little affected by these uncertainties as we mostly focus on level ice which is primarily represented by modal thicknesses.

The main purpose of this study was to compare the amount of summer melt observed by EM profiling and local ice mass-balance measurements. In general, the modal EM thickness decrease of 0.6 m agreed well with the thinning observed by the IMB. However, the observed times of maximum and minimum ice thickness were different, and the two methods reacted differently to the accumulation of snow. It has to be noted that with the stated accuracy of EM measurements of ± 0.1 m, the total observed seasonal change of 0.6 m can only just be resolved. Short-term, small amplitude changes of EM thickness may therefore rather represent noise than be due to real temporal change. Similarly, with the stated EM accuracy, different ablation rates at different locations were hard to resolve. Additional problems arose from the fact that exactly the same measurement points could not always be revisited. Therefore, ice thicknesses obtained at these locations at later times were sometimes larger than before (e.g. when the EM instrument was accidentally located closer to a ridge or block of ice than before). For example, over rough ice the resulting thickness uncertainties could be as large as the local freeboard variability times $\sim$10, the thickness-to-freeboard ratio. This is a problem of repeat measurements on rough ice with any method and could only be resolved by using very small and accurate spatial sampling intervals.

Despite the good agreement between local and floe-scale measurements, it remains unclear whether the results are more than fortuitous, as other results would have been obtained for a different IMB location. This demonstrates the importance of careful selection of a deployment site for the IMB that is unponded and undeformed (Perovich and Richter-Menge, 2006). A judgment is very difficult in the presence of a thick, wind-blown snow cover, and it is almost impossible to exclude the possibility of later melt-pond formation, which would dramatically change the results. In our study, the thickness at the IMB site was close to the modal thickness of the ice floe from the outset. Single IMBs obviously cannot provide information on floe-scale changes. However, they could be equipped with differential (total minus sea-level pressure) underwater pressure sensors to measure changes in submergence, which could be related to integral mass changes in an area $\sim$10 m in diameter around the IMB, depending on the flexural strength of the ice. The IMB data showed that the 0.6 m of thinning was partitioned into 0.5 m of surface melt and only 0.1 m of bottom melt (Nicolaus and others, in press). In this regard, the summer of 2007 was quite normal compared with other years in the region of the Transpolar Drift (Perovich and others, 2008). Analyses of causes of these melt rates are beyond the scope of this paper, but are complicated by the fact that the thickness changes represent both varying seasonal and regional conditions as the floe drifted from the interior of the Arctic Basin south towards Fram Strait.

The study proved that IMBs are robust instruments well designed for long-term, automatic observations of local conditions. In contrast, maintenance of the EM profiles under changing surface conditions and floe break-up stages proved very challenging, both for technical and for manpower and accessibility reasons. A little boat like the *Tara* and its small crew are barely able to support demanding kilometre-scale measurements over such a long time, although their achievements were quite remarkable. The experience gathered here clearly points to the lasting requirement for more committed campaigns, including research vessels and the continuous presence of scientists and technicians, to address the comparability of local and floe-scale changes.

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