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COMPARISON OF ALONG TRACK EM ICE THICKNESS PROFILES WITH SHIP PERFORMANCE DATA

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ABSTRACT

During the Arctic Demonstration and Exploratory Voyage (ARCDEV) in April/May 1998 to the Kara Sea extensive continuous electromagnetic (EM) ice thickness measurements were performed along the route on board the icebreaker KAPITAN DRANITSYN. The measurements were compared with ship speed and power data.

The ice thickness distribution along the ships track correlates well with the overall convoy speed, regardless of the actual delivered power. There is less correlation when DRANITSYN made her way as a leading ship at constant power. Linear equations are given to predict the convoy speed for a given ice thickness. The variance of these relations can be explained as the result of highly variable ice conditions and properties, in contrast to the homogenous level ice normally chosen for full-scale ice trials. Thus, our data can be taken to principally evaluate the usefulness of along track EM ice thickness measurements for the improvement of ship performance models.

1. INTRODUCTION

A common practise to judge icebreaker performance is to find relations between maximum achievable ship speed and the thickness of the broken ice (*Varges*, 1990; *Klinge & Hellmann*, 1991; *Tsoy*, 1993). To be comparable with other measurements, normally homogenous, level ice is chosen for such trials. Nevertheless, in any routine icebreaker operation, it can also be expected that there is some relation between ships progress and overall ice thickness. However, as the physical ice properties as well as the general ice conditions are highly variable along relevant distances, clear relations will be difficult to derive.

The EU-funded Arctic Demonstration and Exploratory Voyage (ARCDEV) in April/May 1998 to the Kara Sea (Fig. 1) provided a rare opportunity to gather continuous along track ice thickness data along with measurements of ship speed and power from a convoy operation. The convoy consisted of the nuclear icebreaker ROSSIYA, the conventional icebreaker DRANITSYN, and the tanker UIKKU which was escorted to load gas condensate at Sabeta, a station in the Ob estuary. The convoy sailed around the islands of Novaja Zemlja to reach the Kara Sea, where mainly coastal flaw leads were chosen for rapid progress towards the Ob mouth. On the way back, the ships passed through the Kara Gate (Fig. 1).

2. MEASUREMENTS

All measurements presented here were performed during six days on board DRANITSYN, along the outlined sections of the cruise track in Figure 1. Ships speed was obtained from standard GPS/GLONASS satellite navigation data averaged for 1 minute intervals. The propulsion power was measured with a sampling frequency of 5 Hz from each shaftline through the analog power indicator terminals in the engine room. Ice thickness profiling was performed by means of electromagnetic-inductive (EM) sounding. The technique is shortly described below. The EM/laser system was suspended below a self-constructed scaffold boom sidewards of the foreship, approximately 5 m above the water level and 6 m away from the ship (Fig. 2).

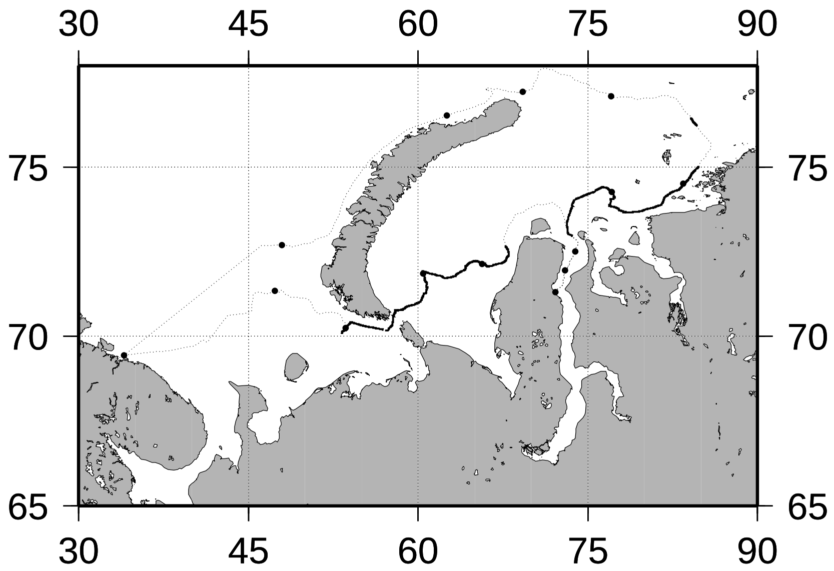

Figure 1: Map of the ARCDEV cruise track through the Barents and Kara Seas (stippled line). Circles indicate the position at 0:00 GMT every day. Ship-based ice thickness measurements have been performed along the sections indicated by a solid line.

2.1. EM measurements

EM sounding is a well established geophysical technique to measure sea-ice thickness (for detailed descriptions of the method, see *Kovacs et al.*, 1987; *Kovacs & Morey*, 1991; *Haas et al.*, 1997; *Haas*, 1998). Generally, the integral electrical underground conductivity is derived from measurements of the strength of a secondary EM field which results from eddy currents induced in the ice and water by means of a primary low frequency EM field generated by the instrument. As there is a large conductivity contrast between the resistive ice (conductivities < 50 mS/m) and conductive sea water (conductivities around 2500 mS/m), the measured integral underground conductivity will decrease with increasing ice plus snow thickness. Relations between measured conductivity and total ice thickness can be found either by numerical modelling or by comparisons between EM measurements and drill-hole determined thicknesses (*Haas et al*., 1997).

During ARCDEV, we used the same instruments, procedures and data processing as described by *Haas* (1998) for earlier surveys from board the German RV POLARSTERN. In short, a Geonics EM-31 instrument is used for the conductivity measurements. The instrument consists of two coplanar coils with a spacing of 3.66 m for the generation and receival of a 9.8 kHz EM field. It was operated in vertical dipole mode. With the conductivity measurement described above, determining the ice thickness is analogous to measuring the distance between instrument and the ice underside, which is identical with the water surface. Thus, if the height of the instrument above the ice surface is known, simple subtraction of the distance to the ice underside and to the ice surface yields ice thickness (Fig. 3). Here, the latter distance is measured by means of a downward looking laser altimeter, which was mounted along with the EM instrument (Fig. 2, 3). As was shown by *Haas* (1998), the laser measurements provide independent information of pressure ridge distributions.

From Figure 3 it is obvious, that the resulting ice thicknesses might also take on negative values over open water or very thin ice, e.g. if the laser is not pointing vertically downwards in case of a swaying instrument. This is commonly observed, and provides a rough estimate of the measurement accuracy. For the ARCDEV measurements, accuracy is probably not better than ±0.2 m.

As basic products for an ARCDEV data CD-ROM, mean ice thicknesses for one-minute intervals were calculated, as well as histograms for ten-minute intervals of the original data measured with a sampling rate of 20 Hz. To avoid statistical bias and data from ramming, only measurements were processed where the average speed was higher than 2 kts.

Figure 2: Photograph of typical conditions during our ship-based EM/laser measurements, taken from the bridge of DRANITSYN. ROSSIYA is leading (upper right), leaving behind a channel with broken ice. The EM system (lower left) is profiling only broken and disturbed ice. Note the scaffold boom construction which had to be built on the ship to suspend the instruments.

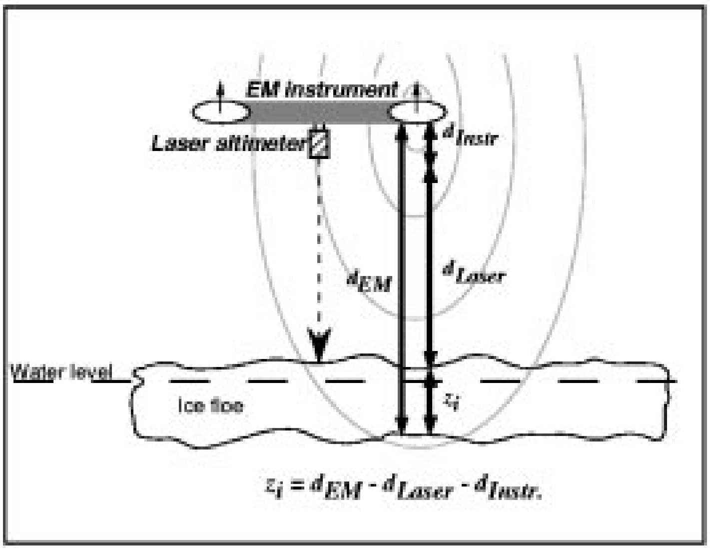

Figure 3: Sketch of principle of ice thickness calculation from combined EM and laser profiling, as applied for the ship-based measurements (from *Haas*, 1998).

An important caveat of EM measurements is their extended lateral footprint of several meters, over which the ice thickness is averaged. Therefore, the accuracy of thickness estimates can decrease dramatically once the ice structure deviates from being level, as e.g. at pressure ridges and floe edges. At ridges, the maximum thickness is always underestimated, while at the ridge flanks too great values may be measured. In EM data floe edges use to appear as smooth transitions from a certain finite ice thickness towards water with thickness zero. During ARCDEV, particularly the latter was a big problem, as DRANITSYN mostly followed in the channel broken by ROSSIYA. Thus, even with the instruments suspended sidewards, often the edges of fragmented floes, brash ice, or open water patches extended underneath the footprint of the instruments (Fig. 2), making accurate thickness measurements almost impossible. Mostly, the given values will be underestimates of the true thickness. This should be kept in mind when considering the results of this study.

Another challenge during ARCDEV was the partially low seawater conductivity at the mouths of the Yenissey and Ob rivers. As with the EM-31 the conductivity of ice covered water cannot easily be measured, we performed salinity measurements on water which was

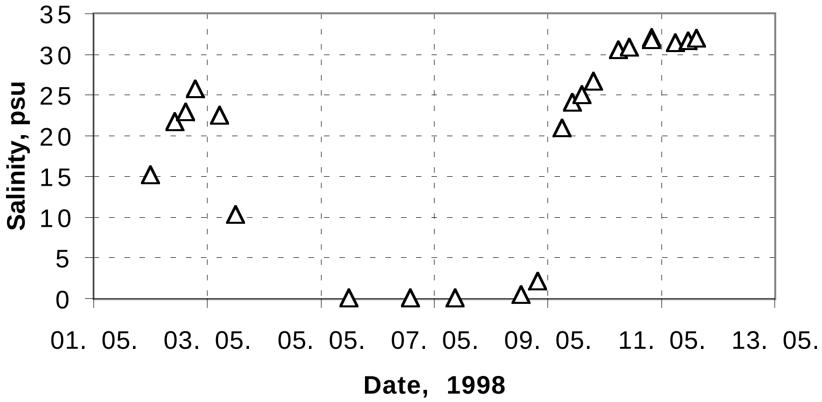

Figure 4: Sea water salinities along the cruise track, showing highly reduced salinities in front of the mouths of Yenissey and Ob rivers

obtained from the ships seawater supply (Fig. 4). For the relevant periods (May 01-05, 09-12), they ranged between 10 and 33 psu, corresponding to conductivities of 900 and 2600 mS/m. With increments of 100 mS/m, for the range of these conductivities different transformation equations to convert the EM signal into a distance to the ice underside were developed from numerical modelling, and applied to the data from respective sections of the cruise track.

Accompanying the ship-based profiles, EM thickness measurements were performed also directly on a few floes. Figure 5 gives an example for such a floe profile, and a comparison with a thickness distribution derived from the ship in the same region. As can be seen, the second mode of the thickness distribution derived from the ship-based measurements agrees reasonably well with the histogram from the single floe. As expectable, the peak at 0 m thickness (i.e. open water) as well as the tertiary mode at about 0.5 m thickness are missing in the floe data. It should be noted that these peaks are caused mainly by the operational problems stated above, and that they contribute significantly to reduce the measured mean ice thickness.

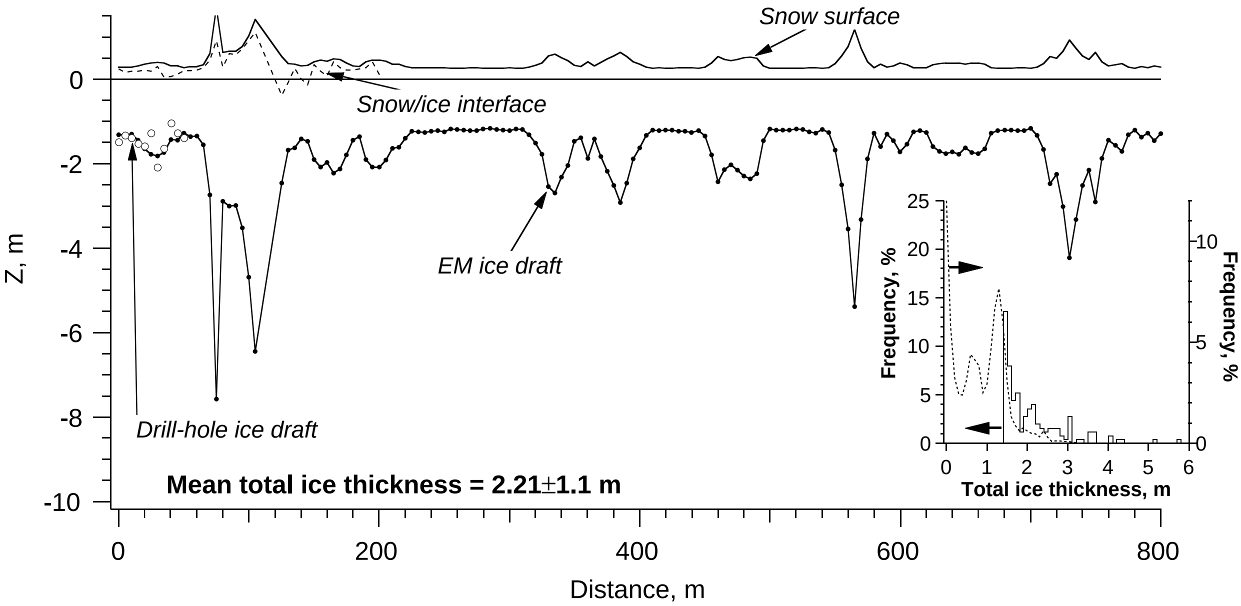

Figure 5: Thickness profile of an ice floe ('Station 5') as measured by carrying the EM instrument across the floe. Some drill-hole data are also presented for comparison. Along the first 200 m of the profile, also snow thickness was determined. The inset shows a comparison of the thickness histograms from the floe (solid line, left axis) and from the ship-based measurements in the same area (stippled line, right axis).

3. RESULTS

3.1. Ice thickness distribution along the cruise track

Due to concealment restrictions, we cannot show the mean ice thicknesses distribution along the cruise track. However, although the true mean thicknesses are probably underestimated as noted above, there is good agreement with visual observations performed from the ships bridge. In particular, the main ice regimes passed are well represented in the data, like coastal flaw leads with almost no or very thin ice; convergent young ice fields with modal thicknesses of about 0.8 m and a long tail of thicker deformed ice; fast ice with uniformly distributed thicknesses around 2 m; and first-year pack ice fields in the southern Kara Sea with typical thicknesses ranging from 1 to 1.5 m. Figure 6 shows some exemplary thickness histograms.

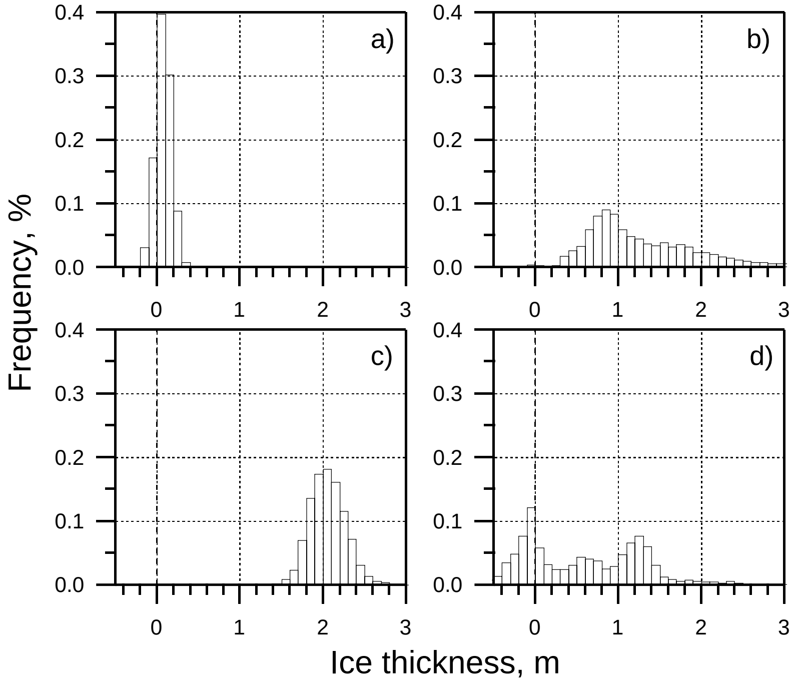

Figure 6: Typical ice thickness histograms for the main ice regimes encountered: a) flaw leads; b) deformed young ice; c) fast ice; d) first-year pack ice.

3.2. Comparison with ship performance data

Figure 7 presents ice thickness and ships speed along a 33 hours long section of the cruise track. As it is difficult to see any correlations from the original one-minute data, a 30 minute running average is plotted as well. From 0 to about 500 minutes, a coastal flaw lead was passed, with pancake and young ice concentrations of less than 7/10. Then, convergent fields of deformed grey and thin to medium first year ice were crossed until about 1500 minutes. With ice concentrations of 10/10, typical floe sizes ranged from 50 to 1000 m, and the ice was usually covered by less than 0.05 m of snow. Finally, fields with concentrations of 7 to 9/10 of medium (<500 m) size floes of young and first year ice were traversed, until the first broken off fast ice floes were reached towards the end of the transect.

Principally, ships speed decreases with increasing ice thickness. Note that for much of the time DRANITSYN was not the leading ship, but followed in the channel of ROSSIYA. As the data have been plotted irrespective of the actual delivered power of DRANITSYN (Fig. 7b), the plot might rather show the relation between ice thickness and the speed of the whole convoy.

The correlation in Figure 7 can be better evaluated from Figure 8 where speed and thickness have been plotted against each other. While there is a good correlation for the one-

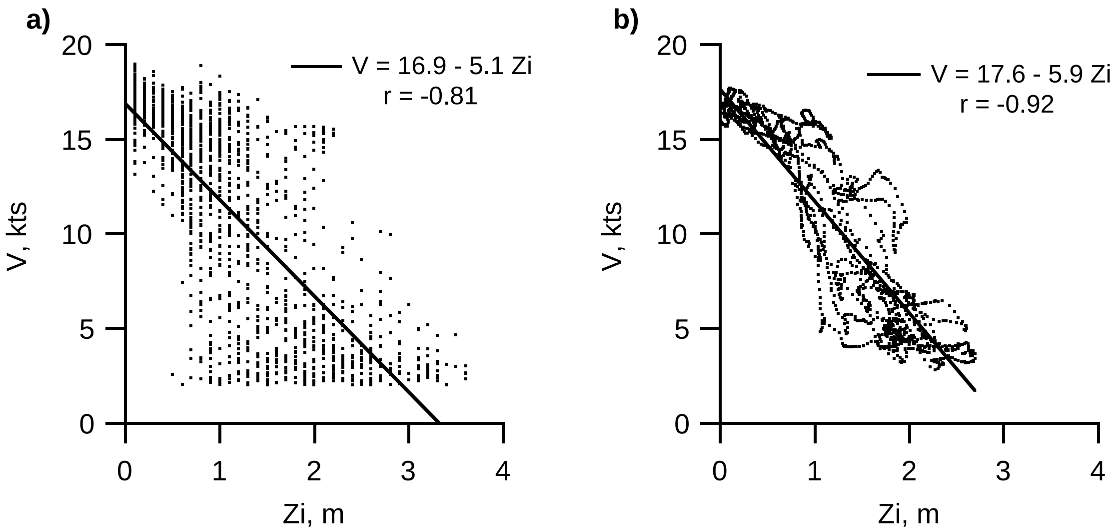

Figure 7: Ice thickness, ships speed (a) and power (b) along a 33 hours long section of the cruise track. Shown are 1 minute data as well as 30 minute running averages.

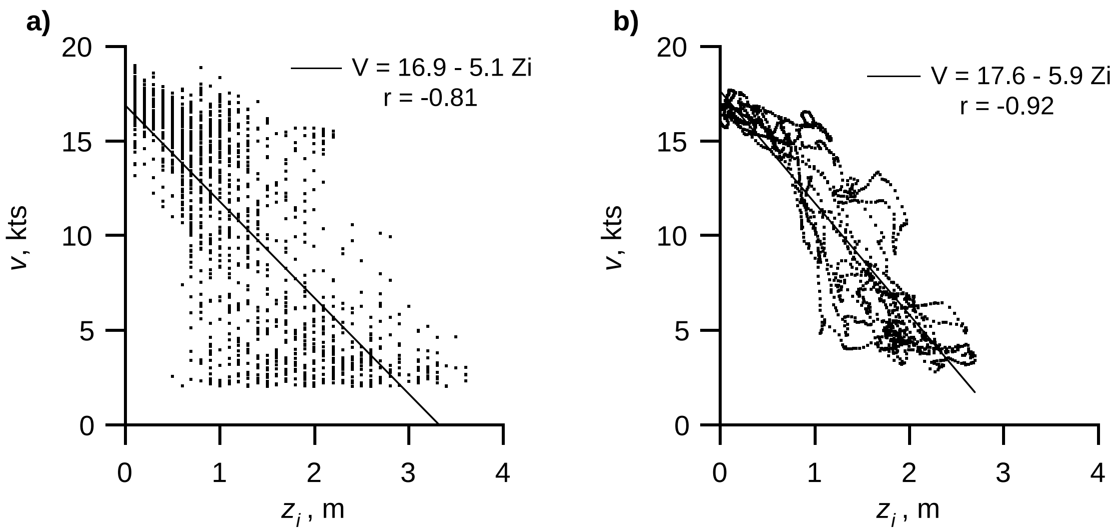

Figure 8: Mean speed *v* versus mean ice thickness z_i from Figure 7 for 1 minute intervals (a) and 30 minute running averages (b). The lines show a linear regression, and the resulting equations are given as well as the correlation coefficient *r*.

minute data already (r = -0.81; Fig. 8a), the correlation is even better if 30 minute running averages are considered (r = -0.92; Fig. 8b).

In Figure 9 speed and thickness are presented for a 80 minutes section when DRANITSYN steamed as a leading ship at constant maximum power of approximately 16.2 MW (Fig. 9b). This section corresponds to the interval around 600 minutes in Figure 7, and the convergent ice conditions are described above. Curves for one minute data as well as for 10 minute running averages are shown. Figure 10 shows the respective plots of speed versus thickness. Compared with the results for the whole convoy as shown in Figures 7 and 8, the correlations are worse. However, averaging improves r from -0.57 to -0.85. Probably, the considered time interval is too short to be comparable with the results from Figures 7 and 8. Additionally, there was some ramming during this time period, when the speed becomes more unstable and unpredictable.

4. DISCUSSION

Despite all operational difficulties encountered with the ship-based EM measurements, including instrument suspension to the ships side and that DRANITSYN followed only in the channel of ROSSIYA (Fig. 2), the derived thicknesses agree surprisingly well with thickness information from other sources. Thus, in general the goal of profiling thicknesses continuously along the cruise track was realised. However, this statement is only true on a statistical basis, i.e. for longer time periods, while these ARCDEV measurements are probably very unrepresentative for the 'real' conditions on a local meter to hundreds-of-meter scale.

Also with respect to the ship performance data, we observed that the correlations between thickness and speed improve if averages over longer time intervals are considered. As no correction for the highly variable delivered power of DRANITSYN was applied, the averaged thicknesses and speed data may be interpreted as relevant values for the performance of the whole convoy. Thus, the equation given in Figures 8b might be taken to predict the speed of a convoy over longer distances. However, it should be noted that the speed and performance through a multi-floe pack ice field is not only dependent on a certain ice thickness distribution, but also on other conditions like ice concentration and physical properties. Thus, different equations might result under different general ice conditions, although the mean ice thickness along the ships route could be similar. Maybe most important here is the ice dynamics, i.e. whether an ice field is convergent or divergent. In the former, a convoy might get stuck even in quite thin ice, while in the latter even very thick ice might be passed with considerable speed. On the other hand, this would be indirectly indicated by the ship-based measurements, because a certain finite ice thickness would be derived in a convergent ice field, as the footprint underneath the instrument will completely be composed of ice. Contrary, in a divergent but thick pack, the measured ice thickness can be zero, as the ship passes through open water leads only. Therefore, the ship-based measurements really show the relevant thickness distribution immediately on a scale where ship-ice interaction takes place.

In Figure 10b it is interesting to compare the regression equation with that in Fig 8b and with speed versus thickness relations derived for DRANITSYN in full-scale trials in level ice, as given e.g. by *Klinge & Hellmann* (1991) and *Tsoy* (1993). The highest speeds for a constant

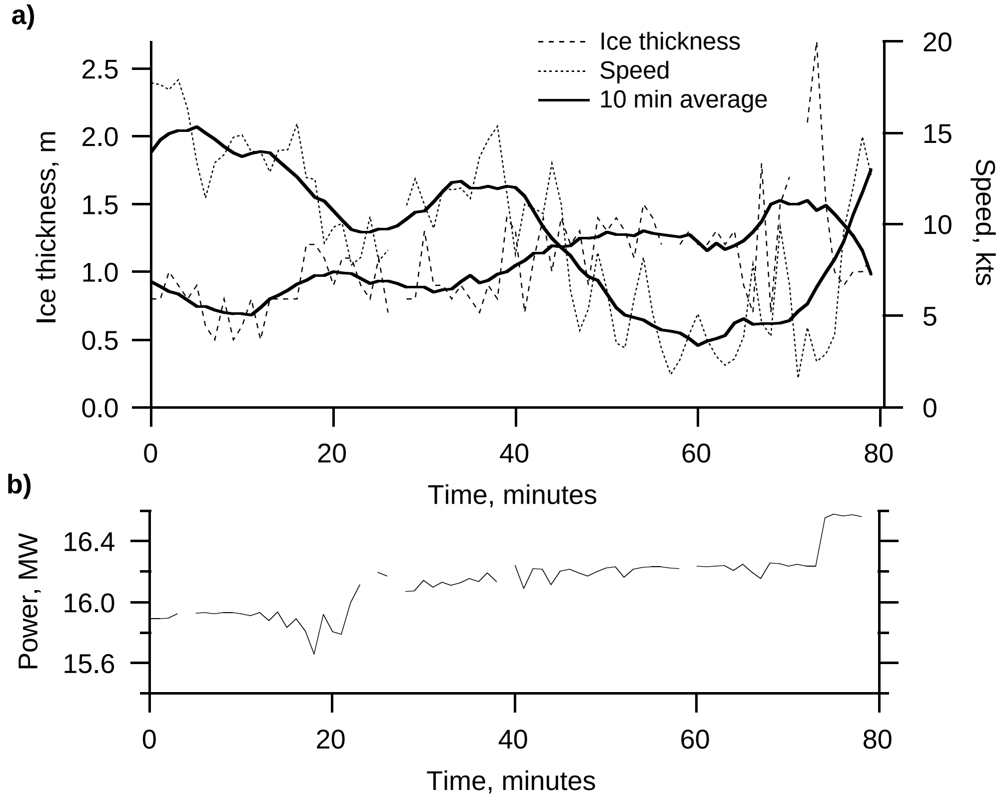

Figure 9: Ice thickness, ships speed (a), and power (b) for a short section when DRANITSYN steamed as a leading ship. Shown are 1 minute data as well as 10 minute running averages.

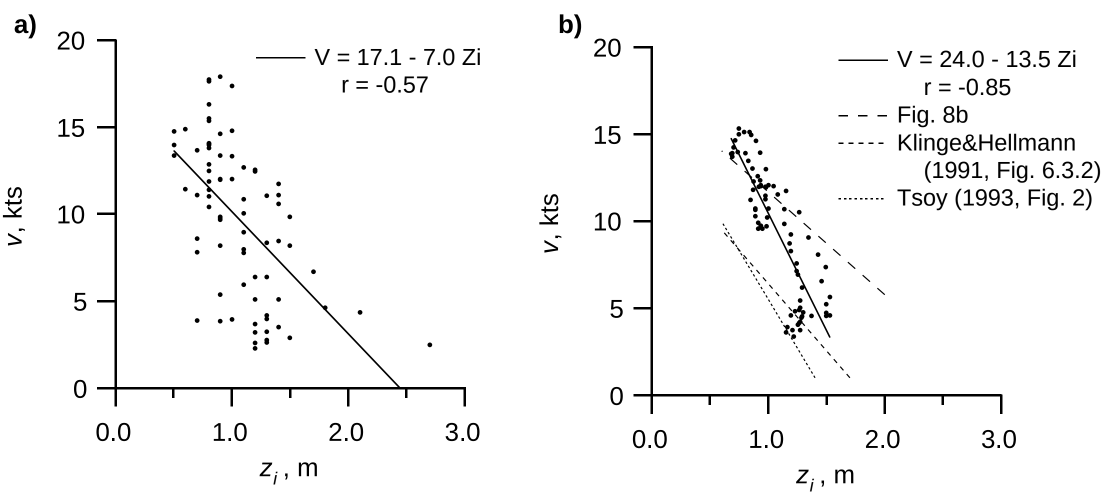

Figure 10: Mean speed v versus mean ice thickness z_i from Figure 9 for 1 minute intervals (a) and 10 minute running averages (b). Solid lines show a linear regression, and the resulting equations are given as well as the correlation coefficient r. Dashed lines in (b) have been taken from *Klinge & Hellmann* (1991), *Tsoy* (1993), and from Fig. 8b.

ice thickness can be reached according to the equation in Figure 8b for a long transect of 33 hours. The regression indicates that even at thicknesses of about 3 m some progress could be made, although the very low speeds less than 2 kts were excluded from our analysis. For the same constant thickness as above, the equation derived when DRANITSYN was shortly sailing alone (Fig. 10b) yields slightly smaller achievable speeds. The lowest speeds, however, result from the full-scale tests, where only a single floe is crossed. Thus, the measurements indicate some kind of scaling effect, where the mean speed through an ice field of a certain thickness increases with increasing track length. Clearly, this is an integrating effect over a range of other ice conditions as mentioned above, which all contribute to a bulk trafficability. It shows that even in thick ice the ships are able to choose routes which are easier to pass.

5. CONCLUSION

We have shown that ship-based measurements of ice thickness are well suited to explain the performance of a single ship or a convoy. Some relations between ice thickness and ship speed have been derived, which however should yet be checked for their representativeness on other comparable cruises. Once these or similar equations have been confirmed, they may be combined with thickness climatologies derived from regular ice thickness monitoring, or with the results of numerical ice forecast models to develop accurate ship performance prediction models. These are the ultimate goal of economic operational shipping in ice covered waters.

Our study encourages further measurements, particularly as the results are expected to improve significantly if the EM/laser system is operated in front of the bow of a leading ship.

6. ACKNOWLEDGEMENTS

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