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MEASUREMENTS OF ANTARCTIC SEA ICE THICKNESS DURING THE ICE TRANSIT OF S.A. AGULHAS II

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ABSTRACT
The South African polar supply icebreaker S.A. Agulhas II was permanently instrumented for ice load measurements when built in Finland in 2012. The ship is used as a research platform during her annual relief voyages to Antarctica. The performance data is complemented with ice observations and ice thickness measurements using both electromagnetic (EM) method and stereocamera system. The thickness measurements are described and results from the first full campaign 2013-2014 are presented. The first period of ice transit extends from early December to early January while the latter covers late January and early February. Both include meridional transits between the ice margin and ice shelf, and zonal transits along the shelf. Six hour ice thickness averages grow gradually from 0.5 m of ice margin to 1 m at about 200 km from the shelf. This is followed by a transition to extremely deformed and 1.5-2 m thick near shelf ice types. The two types have different thickness distribution characteristics which is also reflected by the very large amount of ramming during the zonal transits. The EM results are in a good agreement with observations which also demonstrates that reliable thickness data can be obtained by careful observational methods. The reliability of shipborne thickness data to represent regional thickness variation is discussed and different ways to define the thickness distribution are compared.

INTRODUCTION
Although the ship traffic in the Arctic is increasing the number of ship transits across the Antarctic ice cover is still comparable. This is due to the logistic needs of research stations operated by 30 countries and housing a population of over 4000 during the summer season. The logistic vessels must also reach their coastal destinations also in difficult ice conditions. This sets high requirements for the ice iceworthiness of the vessels and for the navigational tactics. The Antarctic ice transits provide a good opportunity to study both in relationship to the ice thickness characteristics. Shipboard thickness measurements and observations also provide basic data on Antarctic ice thickness variation which is important for the developing and validations of ice modelling and satellite based thickness retrieval methods.

Apart from dedicated sea ice research cruises the Antarctic logistic fleet has been little used for systematic ice performance and sea ice studies. To establish a sustained platform for such research the new South African polar supply vessel S.A. Agulhas II was instrumented for ice load measurements. This was in 2011-2012 when the ship was under construction at Rauma Shipyard (STX Finland). The length and breadth of the 5000 DWT ship are 122 and 22 m respectively and it has ice classifications +1A1, Ice Class IACS PC5 and DNV ICE-10. The load instrumentation consists of optical strain gauges in the bow, bow shoulder and stern shoulder. The shaftline deformations are also monitored, and all load data is logged together with propulsion, navigation and basic environmental data. This can be done without further surveillance whenever the ship is in operation.

The Agulhas vision is to collect datasets that cover several Antarctic ice seasons and combine ice thickness and other ice characteristics with ice load and ice performance data. These can be then be further combined with ice climatology from satellite data and ice models, enabling the assessing of ice loads and navigability for the whole expected lifetime of the ship. There are no permanent systems for sea ice measurements however, but these are conducted by researchers participating the relief voyages. Three mutually supporting methods to quantify ice thickness are used. An electromagnetic (EM) thickness sounding system is hanged in front of the bow shoulder during ice transit. Second, a stereocamera system is mounted to the ship side to monitor ice pieces turned into an upright position by the ship. The thickness is also estimated from the upturning pieces as a part of ice observations, which include also other ice parameters. The observations are supported by the recordings by the regular onboard video system.

This paper focuses on variation of ice thickness measured by the EM system and also compares the EM with the other methods. The emphasis is on the Antarctic variations of ice thickness and the reliability of the results when interpreted to represent regional thickness characteristics. It uses the results from the 2013-2014 relief voyage which was the second Antarctic ice transit for the ship and first with EM measurements. The first relief voyage 2012-2013 included only stereocamera system and ice observations (Suominen et al. 2015) but was preceded by Baltic ice trials in March 2012 with EM measurements included (Suominen et al. 2013, 2014). The EM method has become one of the standard methods to collect shipborne ice thickness data during Antarctic ice transits (Haas 1998, Uto et al. 2002, Reid 2003,Tateyama 2006) and more specifically during campaigns targeting ship ice performance (Haas et al. 1999, Suythi et al. 2012). Most ship installations have been similar to the present one and employed the same device, Geonics EM-31, which has been standard instrument since late 1980's (Kovacs and Morey 1991).

During the voyage S.A. Agulhas II departed Cape Town on November 28th 2013 and proceeded to the Queen Maud Land ice shelf by the zero meridian. It conducted logistic operations at Akta Bukta and Penguin Bukta between 22-30 December to cater Neumayer III and SANAE IV research stations. After a visit to South Sandwhich Islands and South Georgia the logistic operations by Akta and Penguin Bukta were completed between 25th and 31st January 2014. The ship then returned back to Cape Town. The ship was navigating in ice from 7th December to 4th January and second time from 23rd January to 1st February. The passage trough ice infested waters is described in more detail below

MEASUREMENTS AND METHODS

EM thickness measurements system

The EM thickness measurement system consists of a Geonics EM-31 electromagnetic conductivity sounder and a laser distance meter in a protective cover. The two instruments measure distance to the ice underside and to the ice or snow surface respectively. The difference yields then combined thickness of ice and snow layers (Figure 1). A collapsible instrument beam erected about half way between bow and bow shoulder was used to suspend the instrument over ice. The instrument location aligns with the ship perpendicular so that the ice thickness becomes measured before it becomes into contact with the bow shoulder instrumented with strain gauges. The horizontal distance from the hull was about 6 m, sufficient to avoid its influence, and the safe distance to sea surface was varied between 2-4 m, depending on the height of ridges. The cabling was led trough a workhole to the forecastle storage room where the Linux based data logging system was located.

The EM -31 instrument consists of transmission and receiving coils separated by 3.7 meters. The sounding principle is to transmit an electromagnetic pulse to a conductive medium and determine the strength of the secondary field generated in the medium and received by the opposing coil. This depends on the spatial distribution of the conductivity in the medium. The simplest assumption is a semi-infinite conductive homogenous medium, for example sea water, below the device. The strength depends then on the distance from the device to sea surface, which constitutes a method of distance measurement. In a straightforward ice application it is assumed that this distance is to the ice underside instead. As the distance to the ice or snow surface is obtained from the laser, the difference gives combined ice and snow thickness. The get the ice thickness measurements or observations of snow thickness are required. The EM-31 footprint over which the thickness variation affects the results has no exact definition but can be taken to be 3.7 times device height above ice (Reid et al 2003), or typically 10 m. The nominal penetration depth is about 6 m (McNeill 1980) so that from the operating height the ice thickness can be reliably resolved to no more than 4 m. This is the main shortcoming of the instrument. However, larger thicknesses, especially ridge keels, can be estimated from the freeboard profile obtainable from the laser record.

The data from the thickness measurement system includes GPS data, laser distance to ice or snow surface, laser signal amplitude measuring the relative strength of the returning laser signal, apparent conductivity (AC) recorded by the EM device. The AC quantifies secondary field strength. For example, if the device hangs above sea surface, AC is the conductivity of such sea water that would give the same response when EM-31 is at the surface. The nominal measurement frequencies of the GPS is 1Hz while the frequencies of laser and EM show variation, being for laser above 20 Hz and for the EM around 11 Hz.

The distance to sea surface or ice underside is derived from AC using conversion diagrams. These may be generated from the calibration exercises conducted during the voyage, best estimates based on accumulated experience, and theoretical calculations. Although for the sea water the conversion can be based on theory if the salinity is known, the EM-31 readings are sensitive to external influences, poising of the instrument, etc., and calibration exercises are due. In a basic calibration the device is lowered close to sea surface and raised with small increments and with a pause after each increment. This provides a conversion valid for sea ice thickness determination under two idealising assumptions: the ice is non-conducting and has uniform thickness over the device footprint. Similar procedure above ice surface, accompanied by ice thickness drilling, provides information on how well the idealising assumptions apply. A basic calibration was made during the voyage whenever possible, as well as several calibrations over ice.

Ice observations and stereocamera system

Ice thickness and other ice parameters were estimated by observers during all icegoing. The regular practice on board research vessels has been to estimate the ice parameters once an hour. However, as the thickness data are compared with ice loads and ship performance a more meticulous ice observations are due. With the same this provides a better quantification of thickness variation. The observers were present on the bridge during all icegoing, doing three hour shifts. The ice parameters were written every ten minutes, or about for every 1-3 km of transit. The estimated parameters refer to the variable ice conditions encountered by the ship during the 10 minute period.

Ice thickness was estimated from ice pieces turning into an upright position by the ship movement. A scale with 10 cm division and visible from the bridge was attached to the bulwark for the purpose. The scale was located between the ice and the observer but the estimates were done by comparing to the scale and the parallax error was corrected by multiplying by 1.25. The relative abundance of ice in thickness categories was estimated during the 10 minute period. The categories were defined at 20 cm intervals up to 2 m and then at 50 cm intervals. What was obtained hereby was a coarse estimate of the whole thickness distribution during the 10 minute period.

The concentration was estimated in a similar manner. The concentration variation was included by estimating the relative abundance of ice in concentration categories during the ten minute period. The categories were defined in 10% steps. Thus the concentration was resolved actually in a finer scale than the distance covered during the period. The same practice was applied to floe size, which was quantified using category limits 20, 100, 500, 2000 , and 5000 meters. Brash ice was taken to be open water and its relative coverage from brash covered plus brash free open water was estimated. The observers also estimated minimum and maximum snow thickness, counted rammings, estimated vibration state of the ship, and provided comments on ship-ice interaction events and navigational status.

The ship was also equipped with a stereocamera system for ice thickness determination (Kulovesi and Lehtiranta 2014). It seeks to determine the thickness from upturning floes as well but replaces the observers' estimates by computer vision algorithms to detect ice block edges and calculate the thickness. Presently the method is semi-automatic and human input is needed to select feasible input data and also to verify the results, and development towards higher level of automation is ongoing. The preliminary datasets are not used here.

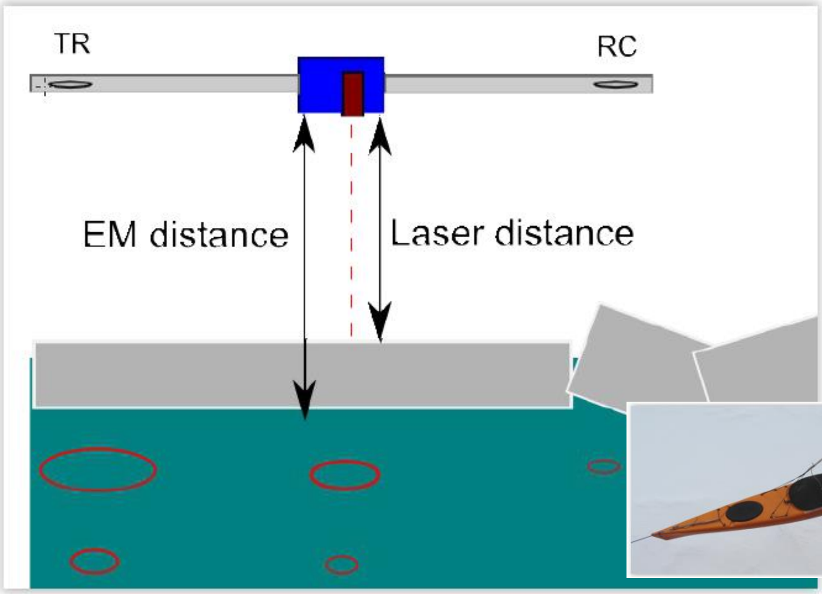

Figure 1. a) The principle of the EM thickness measurements. b) The EM device suspended from a collapsible beam mounted on the forecastle of S.A. Agulhas II. The 5 m long kayak servers as a protective cover for the instrument.

PROCESSING AND ANALYSIS OF DATA

Ship track, ship speed and ice drift.

For the ship track GPS position every five seconds was used. Shorter intervals generate cumulating GPS position errors and five seconds is also sufficient to resolve the ship movements and speed changes during rammings. For thickness analysis the track was interpolated to match the EM data frequency. The ship speed was calculated for five second intervals from the track steps.

Ice drift speed was then calculated for those sections of the speed record that contained sufficiently periods when the ship was stationary with respect to the ice field. The stationary periods were identified from 100 second intervals by requiring that the average speed and speed standard deviation for the interval are below v_0 and $v_0/10$ respectively. The threshold v_0 depends on ice drift conditions but was typically 0.3 m/s. This can be supported by propulsion data which is not alone sufficient for the purpose as full power is often on during periods of being stuck. The ice drift speed components were first obtained for the stationary periods and interpolated to the whole speed record part.The ice drift was then compensated from the speed record to obtain ship speed relative to the moving ice field. The track relative to the moving ice field was finally calculated from the relative speed components. For days with large numbers of rammings, slow advance, and periods of being beset the drift compensation is essential for proper data and can also be done. On the other hand, for continuous steaming the drift is not easily available from the speed record only but is also insignificant.

Ice transit modes.
The ice transit can be divided into three modes, continuous steaming, ramming, and being stuck or otherwise having a longer speed zero period notwithstanding attempted progress. The ramming sequences were identified from their tell-tale signatures in speed and track records. Each ramming sequence was further broken down to ramming cycles described by their backing and forward thrust phases. The periods of speed zero between the reversals are not considered as being stuck if not excessively long. Being stuck can be told apart from voluntary stationary periods with propulsion data and observation records, but unlike ramming this distinction is not relevant for the present ice thickness analyses.

During continuous steaming shipborne ice thickness measurements generate representative records from the transited ice cover, and the periods of being stationary are left outside the analyses. On the other hand, during a ramming sequence the ship may repeat the same ramming cycle several tens of times. This shows as increase of track length while the true advance relative to the ice field can be close to nil. At the same time the shipborne measurements span repeatedly the same ice masses which are also deformed to a new arrangement during each ramming cycle. The including of such thickness data to the statistics so that the end result can be assumed to represent regional thickness distribution requires careful considerations.

Ice thickness data.
The raw EM system data consists of logged GPS, laser and EM. All data is equipped with the measurement computer timestamp for the ongoing second. The variable frequency laser and EM data were interpolate to constant 20Hz. The basic data consists of packets of 20 readings of both instruments per one second and one GPS reading. The EM apparent conductivity was converted to vertical distance using geographically closest calibration made over open water. The conversion thus assumes nonconducting ice and small thickness variation in the instrument footprint. The thickness of the combined snow and ice layer was obtained by subtracting the laser distance value. Data for ice thickness analyses was chosen by deleting non-measurement values, outliers, calibration periods and bad sections.

The EM data has several error sources that affect especially the relative accuracy for thinner ice categories. The data set contains readings from open water and brash ice. For the latter the EM conversion is not reliable. Moreover, the in spite of the stayropes the instrument may swing and wobble rather erratically in windy conditions. This generates oblique measurements resulting into both negative and positive thickness values over open water. The same error source can be assumed to persist for all data, to which adds the conversion errors from suboptimal calibration data. To add, the bow wave and spray during open water steaming generates spurious high thickness values. Thus a condition based on thickness threshold is not sufficient to choose a proper ice thickness subset. Instead, the laser signal amplitude of the Noptel CM3-30 laser was used. This parameter shows for all data the same statistical characteristics where the high amplitudes have normal distribution with mean around 1215 and the 99.7% quantile (3 standard deviations) around 1170. The high amplitudes are interpreted to present snow surface and exclude water surface and all intermediate cases like wet brash. Thus it was required that the signal amplitude is at least 1170. Finally, only positive thickness values were accepted. The data still refers to the combined ice and snow layer, and the estimation of the snow layer thickness has not been attempted here. In general the relative error magnitude decreases with thickness.

The ice thickness statistics can be studied either in time or space domain. The first considers ice encountered per unit time. It is meaningful in comparison with ice load statistics which usually refers to time interval maxima. The space domain description considers ice encountered per unit track length. As thicker ice reduces ship speed the thick ice types get more weight in the time domain description. It does not conserve ice volume unlike the space domain description, for which the average thickness can be understood as the thickness of a uniform ice layer with the same total volume as the encountered ice. This is often called equivalent thickness in ice navigation contexts. For space domain analyses 5 meter track segment averages of the selected EM data were calculated. Shorter segments are not meaningful, considering the 10 m footprint. The track distance is relative to the ice cover, that is, excluding ice drift.

THE VOYAGE AND GENERAL ICE CHARACTERISTICS

The ice transit of S.A. Agulhas II is shown in Figure 2. The transit is divided to regimes R1-7 in reference to different time periods or ice and performance conditions (Table 1). The regimes R1-4 cover the ice transit to the end of the year 2013 while R5-7 were transited about one month later at the end of January 2014. *Regime R1* begins as the ship enters the ice cover at 63S on 7th December 2013 and continues steaming south along the zero meridian. At about 66S it took a more SW course towards Akta Bay trough increasingly difficult ice conditions. *Regime R2* begins on 10th December at about 100 km from shelf when the ship could not stay the course to Akta Bay but was forced to a more westward course. It reached the shelf about 100 km west from Akta Bay and continued along the shelf eastwards to the destination. *Regime R3* is along shelf zonal transit from Akta Bay to Penguin Bukta. *Regime R4* is the ice transit after leaving towards South Georgia and exiting ice cover on 4th February. Agulhas then re-enters ice on 23th January, and *Regime R5* is the return ice transit back to Penguin Bukta. *Regime R6* is zonal shelf transit to Akta Bukta, and *Regime R7* is the northbound transit to ice edge which is reached on 2nd January 2014.

The increasing difficulty during the southbound transit is seen in the exceedingly high percentage of time used to ramming in R2, for which the total number of ramming cycles exceeded 1000. The average speed includes both forward thrusting and backing during ramming cycles so the true speed of advancing to the destination is much lower still. Agulhas still encounters difficult conditions at R6 at the end of January. However, the rammings for R6 include also bay ice breaking when Agulhas was attempting to get into suitable position for loading operations. Only part of R& rammings occurred during the actual ice transit.

Table 1. The regimes of the ice transit of S.A. Agulhas II

	Start time	End time	Track length relative to ice [km]	Ramming time % from all icegoing	Speed relative to ice [m/s]
R1	12/07 11:00	12/10 0:00	887	21	3.25
R2	12/10 0:00	12/22 15:00	762	63.3	0.81
R3	12/24 5:00	12/25 04:00	225	0	2.53
R4	12/30 22:00	01/04 18:00	2082	0	6.03
R5	01/23 12:00	01/24 23:00	313	0	2.57
R6	01/24 23:00	01/29 15:00	589	39.8	1.47
R7	01/31 15:00	02/01 04:00	318	0	3.94

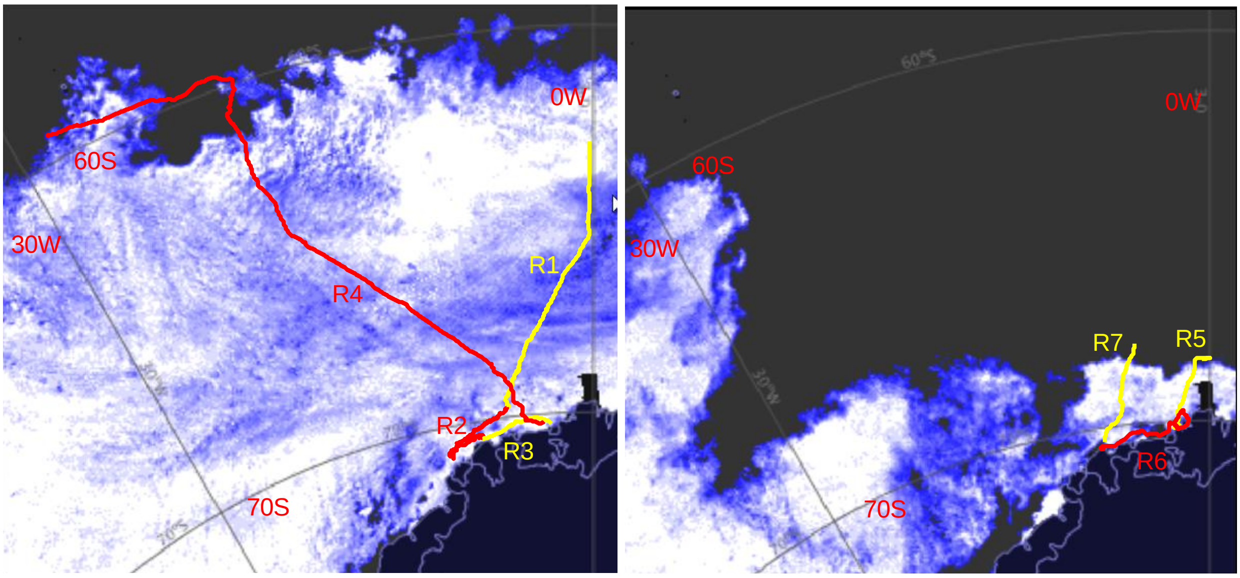

Figure 2 : The ice transit of S.A. Agulhas II. The ice concentration charts are for 7th December 2013 and 23th January 2014 (http://www.polarview.aq).

The thickness averages, calculated in time and space domains, are in Table 2. Both EM and observation based averages are shown. The time domain averages exclude periods of standing still. The space domain EM averages are taken over 5 m thickness segments. For the observations the averages were calculated from the 10 minute periods and by weighting with distance covered during the 10 minutes. The thickness values range generally from one to two meters. The correlation between speed and thickness is very clear. The time domain averages are larger as expected, but the difference is less pronounced for ice observations. The correspondence between EM and observed thicknesses is very good in the time domain and better for thicker ice types, while in space domain the EM averages are about 60-80% from the observed values. Probable reason is the difficulty of observing thinner ice types from overturning floes, especially during faster passage in lower concentration ice.

The last two columns of Table 2 give ice concentration and the percentage of high signal amplitude laser data used to calculate the EM thickness statistics. It is seen that for the first part R1-4 the of the ice voyage it is a good proxy for ice concentration while for the R5-7 this is less so. For R5 and R7 the possible reason is snow melt water on ice, while for R6 it may be underestimation of observed concentration as a>1770 should be a lower bound for true concentration.

Table 2: The average EM and observed thicknesses (combined snow and ice thickness,in meters) in space domain (sd) and time domain (td)

	HEM sd	HEM td	Hobs sd	Hobs td	Speed m/s	Concentration %	a>1170 %
R1	0.62	0.99	1.09	1.30	3.25	64	61
R2	1.65	2.14	1.93	2.02	0.81	80	77
R3	1.09	1.36	-	-	2.53	-	38
R4	0.74	1.04	1.12	1.14	6.03	17	19
R5	1.07	1.51	1.45	1.60	2.57	70	56
R6	1.25	1.64	1.67	1.75	1.47	28	42
R7	0.92	1.11	1.25	1.26	3.94	49	35

COMPARISON OF OBSERVED AND EM THICKNESS VARIATION

Figure 3 shows the 6 hour thickness averages for the complete voyage. Not counting R3 from where no observations are available, for all red regimes and R4 the agreement between EM and observations is generally good. For R2 and R6 which had largest percentage of ramming the agreement is in part good while in other parts the two thickness values appear to oscillate around a common level. This is apparently related to the large amount of ramming which affects both the EM measurements and observational practices trough repeating and milling over one and same ice mass. For less severe ice conditions the agreement can be very good, as is seen from Figure 4 that shows one hour thickness averages for R1. This correspondence increases the reliability of the combined data set and also demonstrates that good thickness data can be obtained by careful observations.

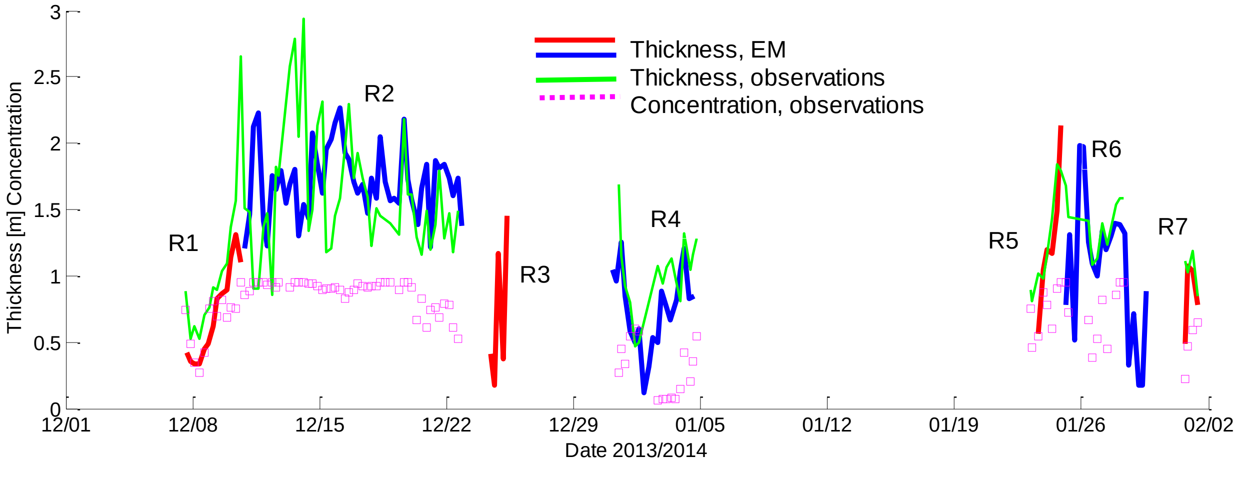

Figure 3. Comparison of 6 hour thickness averages for EM and observations.

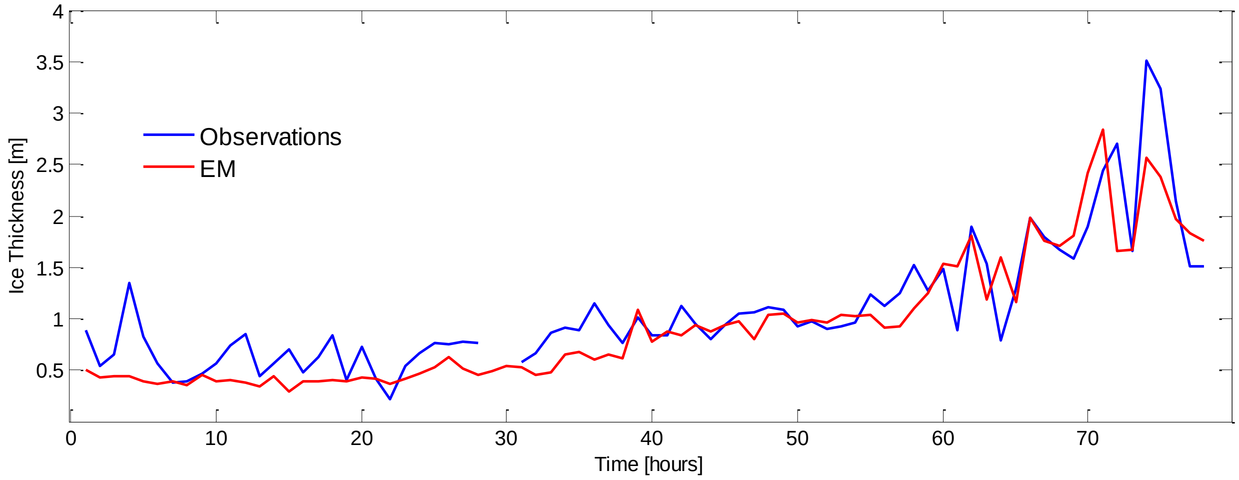

Figure 4. Comparison of Regime 1 one hour thickness averages for EM and observations.

THICKNESS DISTRIBUTIONS

Thickness distributions were calculated for the 5 m segment average data for which the mean thicknesses are in Table 2 (column HEM sd). The distributions are shown in Figure 5 for regimes R1-4 of mid melting season and R4-7 for late melting season respectively. However, the seasonal change does not show very clearly unlike the regional variation between *Group 1* consisting of R1, R4-5 and R7, or transits approaching ice shelf or moving away from it, and *Group2* consisting of R2-3 and R6, or transits along the shelf close to it. The distributions for *Group 1* can be characterised as a superposition of normal and exponential distributions, representing level and deformed ice types respectively. The exponentiality of tails is very clear and also otherwise the distributions have very similar characteristics. These characteristics are not shared by the distributions of *Group 2*, which represent extremely deformed ice with little or no level ice types. The distributions have no clear mode and for R2 and R6 the main part of the distribution approximates uniform distribution. *Group 2* has also exponential tails but these start at about 2.5 thick ice while for *Group 1* this occurs at about 1.5 m.

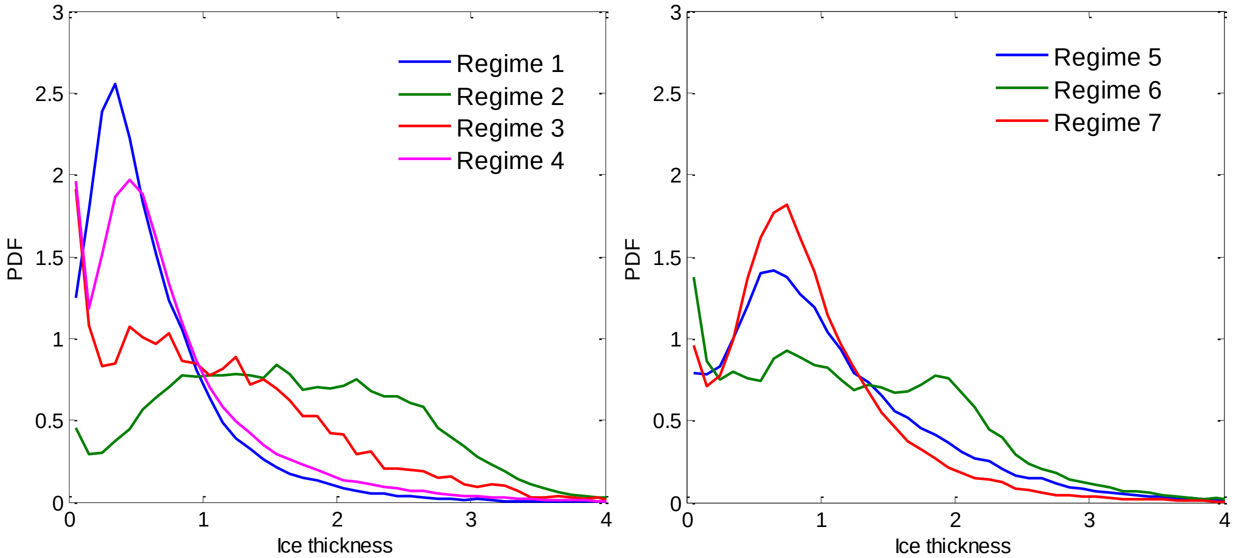

Figure 5. Thickness distributions (probability density functions) for the regimes.

THE EFFECT OF RAMMINGS IN THE THICKNESS STATISTICS

In *Group 1* the regime R2 has extremely large number of rammings, R6 less so, and R3 had no rammings. As during a ramming sequence the EM thickness data has been obtained several times, sometimes even tens of times, over the same ice masses, the effect of this repeating to the thickness data must be clarified. As the distribution shape for R3 is somewhat different, this may suggest that the repeating might have effect.

For all regimes R1-7 the time share of ramming was 25% leaving 75.% steaming. The total track distance relative to ice was 5176 km from which 705 km was ramming and 4471 km steaming. However, unlike for steaming the track distance for ramming does not well represent the advancing towards destination as the manoeuvres of each ramming cycle are included. Calculating for each ramming sequence the distance between entering and exiting the sequence gives an estimate 104 km for the real advance gained by all ramming transit, or one kilometre per seven kilometres of track length.

The overall thickness distribution for R1-7 is shown in Figure 6. The mean value is 1.05 m and standard deviation 0.83 m. The right hand panel of Figure 6 separates this into distributions corresponding to steaming and ramming. The mean values are 0.87 m and 1.59 m, and the standard deviations 0.72 and 0.87 m respectively. It is seen that the steaming part has the characteristics of the *Group 1* distributions, while the ramming part resembles the distribution of R2 which regime also includes the overwhelming majority of rammings. For thicknesses exceeding 2.5 both distributions have exponential tails.

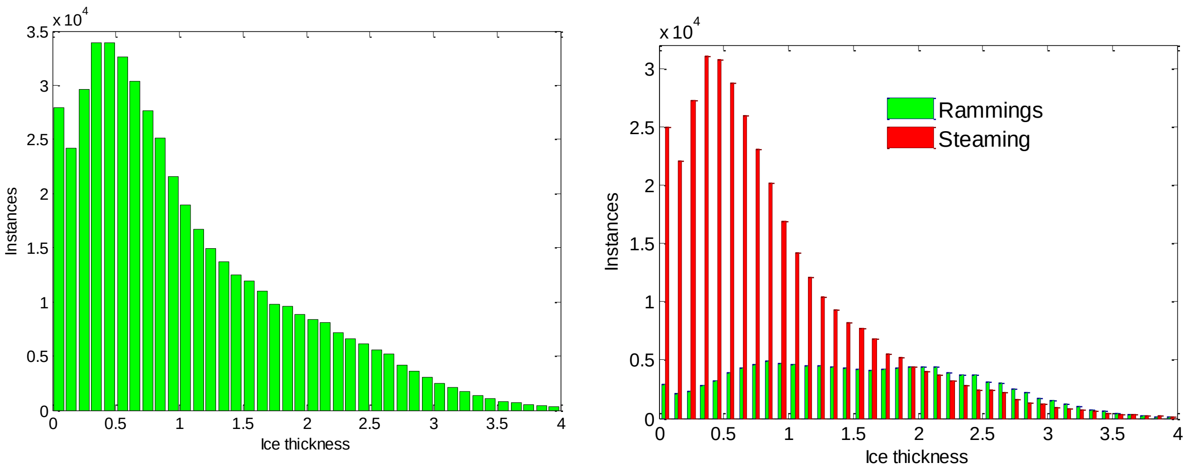

Figure 6. a) Ice thickness distribution for all ice transit. b) Ice thickness distribution separated between steaming and ramming modes.

In addition to the along track statistics in time or space domain the ice thickness distribution can be also defined for in terms of areal cells. The value in the cell is the average of all thickness observations in the cell. If the cell contains several ramming cycles, these do not increase the weight of the encountered thick ice as is the case for along track thickness distributions. Putting in another way, the cell averages represent the thickness with respect to the true advance of the ship. The cell averages can also be compared with geophysical sources of thickness data, especially thickness fields retrieved with satellite methods or simulated by dynamic-thermodynamic ice models.

As a final exercise all these three distributions, or along track time domain, along track space domain, and grid cell distributions, were calculated for R2 data. As the grid cell size should be large enough to cover a typical ramming cycle it was chosen to be 200 m x 200 m. The along track segment length was put to 200 m as well, and the time period to little less than 5 minutes; for this choice the numbers of segments and periods were the same. The result is shown in Figure 7. It is seen that the shape of the distribution is similar in all cases. The thickness means for the 5 minute period, 200 m track segment, and 200 x 200 m grid cell data are 2.08, 1.72 and 1.81 respectively. The larger value in time domain is expected and explained by slower speed in thicker ice types. The segment and cell data distributions are almost identical except for the first bin. This also explains the difference between the mean values, and the mean values for thicknesses exceeding 0.5 m are 1.86 and 1.83 respectively. As the thickness statistics calculated from the track segments gives a good estimate for regional thickness variation also for R2 this can be assumed to hold in general. This is not clear from the outset, as one cell can correspond to one or even tens of segments.

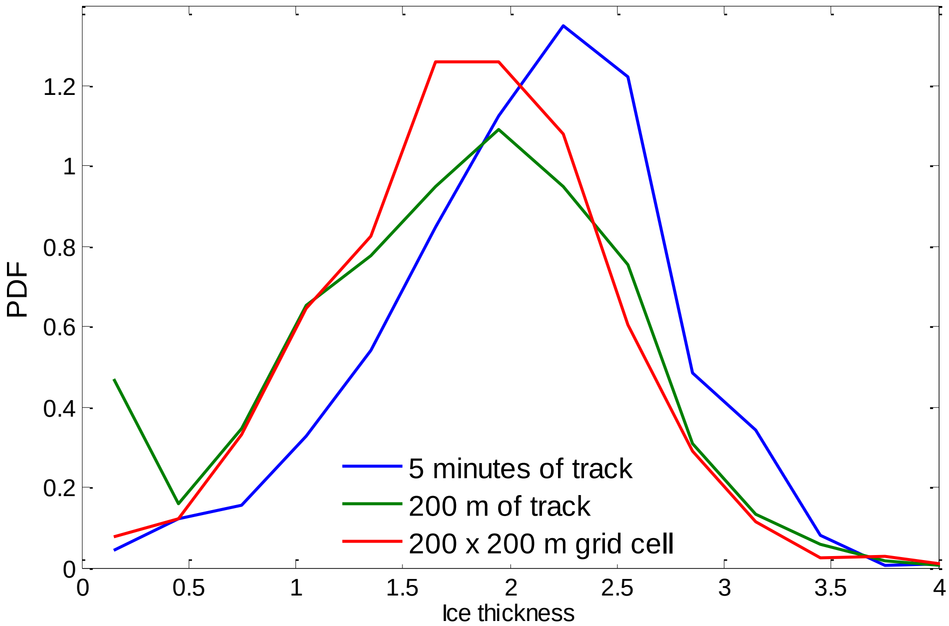

Figure 7. The thickness distributions for R2, determined by three different methods.

DISCUSSION

Time series data from shipborne ice thickness measurements can be directly related ice loads and ship speed which are also described as time series. To interpret such thickness statistics as regionally representative requires additional arguments however. On the other hand, the regional variation is needed when the ship ice performance results are extended to the whole lifetime of a ship which includes the consideration of different ice regimes and their seasonal and interannual variation. The results show that along track thickness data can provide reliable regional statistics for the Antarctic ice cover and thus ice climatological data can be used for long term trafficability analyses. The results also showed a good agreement between observed and measured thickness values. This demonstrates the benefit of the employed observation practice when compared with the standard ASPeCt style where ice parameters are estimated at one glance once an hour.

In the Arctic ships are often able to circumvent thicker ice fields which may introduce a bias to shipborne thickness, but in more homogenous Antarctic ice cover this is less so. Along most Antarctic circumference the thickness gradients have interannually persistent meridional character. This is also corroborated by the present results where the ice transit could be divided to meridional and zonal regimes with strikingly different characateristics. These features make Antarctic especially suitable for long term ship peformance research.

However, the present good results are in part due to averaging over large amounts of data which reduces errors that show in shorter time and length scales. Also, snow thickness variation has not yet been analysed. This introduces a systematic error to the ice thickness statistics as the EM values include snow thickness. Another such source is the limited penetration depth of the EM instrument. This is likely to affect little the average thicknesses but the statistics of ridge keels and other very thick ice formations, important from the ship performance point of view, is not obtained. Further analyses utilising the laser surface profile, stereocamera data and shipborne ice video are expected to improve the datasets and also the instrumentation and measurement practices during forthcoming voyages.

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