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Interannual sea ice thickness variability in the Bay of Bothnia

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Abstract. While variations of Baltic Sea ice extent and fast ice thickness have been extensively studied, there is little information about the sea ice thickness distribution and its variability. In our study, we quantify the interannual variability of sea ice thickness in the Bay of Bothnia during the years 2003-2016. We use various different data sets: official ice charts, drilling data from the regular monitoring stations in the coastal fast ice zone and from helicopter- and ship-borne electromagnetic soundings. We analyze the different data sets and compare them to each other to characterize the interannual variability, to discuss the ratio of level and deformed ice, and to derive ice thickness distributions in the drift ice zone. In the fast ice zone the average ice thickness is 0.58 +/- 0.13 m. Deformed ice increases the variability of ice conditions in the drift ice zone where the average ice thickness is 0.92 +/- 0.33 m. In heavily ridged ice regions near the coast, mean ice thickness can be even manyfold thicker than in a pure thermodynamically grown fast ice. Drift ice exhibits larger inter-annual variability than fast ice.

1 Introduction

The Baltic Sea belongs to the seasonal sea ice zone, extends from 54° N to 66° N, and has a total area of 422 000 km^2. According to the classification of the Finnish Ice Service the Baltic ice season is mild when ice extent is below 115 000 km^2, severe when the extent is above 230 000 km^2 and extremely severe when it is above 345 000 km^2. The last occurrence of almost complete ice cover was in 1987 (96%, Vihma and Haapala, 2009). Comparable major seas that are ice covered seasonally include the Sea of Okhotsk and Bohai Sea in Asia and Hudson Bay and Gulf of St. Lawrence in North America.

Bay of Bothnia is the northernmost basin of the Baltic Sea north of the sound of Quark at 63.5° N. It is a semi-enclosed basin with a length of about 300 km, width of 100-150 km and an area of approximately 36 000 km^2. The average depth is 41 m and maximum depth 146 m (Leppäranta and Myrberg, 2009). During the last 100 years the Bay of Bothnia has failed to freeze completely over only during extremely mild winters 2014/2015 for sure and most probably also in 1929/1930 (Uotila et al., 2015). The width of the fast ice varies with the sheltering of the archipelago and in more open areas its boundary follows roughly the 10 m depth contour. In the drift ice zone, the flux of ice trough the 25 km wide passage of Quark is small and has only a minor effect on the ice mass balance of the basin which is mostly determined by the thermodynamic and dynamic processes within the basin itself, i.e. there is little exchange of ice with the Gulf of Bothnia in the south.

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In the fast ice zone ice grows only thermodynamically because the ice is attached to the coast and does not move. Along the coastline of Bay of Bothnia there is a large area where the shallowness of the sea allows fast ice to form every winter. Depending on the ice thickness the boundary of the fast ice zone is where the depth is 5-15 m (Leppäranta and Myrberg, 2009). On the contrary, in the drift ice zone ice floes move along the currents and winds and pile up to ridges. Ridges can grow up to several meters. When ice is piling up in one region, open water forms in another, and favorable conditions for formation of new ice turn out. Thus, the growth of ice in the drift ice zone consist of thermodynamic and dynamic processes.

Forcings in the thermodynamic and dynamic processes are different. Sensible and long wave radiation fluxes and snow accumulation are the main factors to drive thermodynamic growth. The thicker the ice grows the more it insulates itself and grows slower. Snow layer on the ice acts also as insulation. On the other hand, if there is lots of snow on the ice, sea water floods on the ice and can form snow-ice on top of the ice cover. Dynamic processes are more complicated than thermodynamic ones. Ice motion is driven by winds and currents and can form rafted, ridged or brash ice.

The fast ice zone of the Bay of Bothnia consists of level ice types which in more sheltered areas grow purely thermodynamically. As the fast ice boundary advances offshore during the ice season the ice types in more exposed areas may drift and experience deformations. This initial thickness variation is smoothed by thermodynamic growth after the ice stabilizes into fast ice. The drift ice zone is a mixture of level and deformed ice types of different kinds and ages, and typically has a high ridge density. In heavily ridged areas the largest ridges may reach 20 m below the surface (Palosuo, 1975). The variability of thermal and dynamic forcing leads to large ice thickness variations both in space and time. In addition there are large coastal gradients generated by coastal process cycles like lead opening, refreezing and deformation (c.f. Pärn and Haapala, 2011, Oikkonen et al, 2016).

Sea ice conditions are typically characterized by ice extent, ice thickness and ice concentration. Baltic ice charts, providing the ice covered area, have been drawn and the phases of the ice season have been followed systematically since 1915. In the Bay of Bothnia there is an over 100 years long record of drill-hole measurements and of the dates of freeze up and melt from fixed sites. These have been restricted to the fast ice zone. The thickness of level ice types within the drift ice zone is measured or estimated by icebreakers and reported in the ice charts. These values usually seek to characterize the regional level ice thickness for navigation purposes and have limited accuracy. The thickness of deformed ice has been studied in individual campaigns: from thickness profiles determined by air- and ship-borne electromagnetic (EM) sounding since 2003 and indirectly from surface profiles since 1988. These data sets do not cover all years, and the individual campaigns do not cover all parts of the Bay of Bothnia. Also almost all campaigns have been conducted during the midwinter period from February to March, when the ice may still grow and deform further.

Previous studies of the long term thickness statistics in the Bay of Bothnia have mostly concentrated on annual maximum level ice thickness in the fast ice zone, especially at Kemi which is close to northernmost end of the basin. Leppäranta and Seinä (1985) determined that there was a statistically significant increasing trend in the maximum annual ice thickness at Kemi from 1912 to 1984. An increasing trend at Kemi was also recorded in later research for the entire time series (Jevrejeva et al., 2004; Haapala et al., 2015). The mean maximum annual ice thickness at Kemi for the entire time series is 73 cm (Haapala et al., 2015).

The interannual variability of ice conditions generally follows the variations in large-scale atmospheric forcing. In the Baltic Sea the North Atlantic Oscillation (NAO) index is a good proxy for this. Strong westerlies blow over the North Atlantic during positive phases of the NAO index and conditions over the Baltic Sea are mild and moist. During negative NAO phases westerlies weaken or are blocked totally and then winters are more severe. Vihma and Haapala (2009) found that during the winters with strongly positive NAO index the average of maximum annual ice extent in the Baltic Sea was 121 000 km^2, whereas during the winters with strongly negative NAO index it was 259 000 km^2. However, for example in 1985-1986 the NAO index was negative only in February, while the seasonal NAO index was positive, and the ice extent was very large in that winter. The influence of NAO to ice thickness has not been studied in the northern Baltic Sea. Specifically it is not known, how the different wind and temperature statistics, characteristic to positive and negative NAO, combine to generate a specific ratio of level and deformed ice types in the ice volume budget.

The shortness of our data sets restrict us to determine the effect of NAO on ice thickness. However, our hypothesis is that in winters with negative NAO more ice is produced. The study period is too short for defining climate variations, too. Especially because the interannual variability in the area is so large.

It is important to investigate sea-ice changes in the seasonal sea ice zone for two reasons. First, for hundreds of years, there has been interest in sea-ice observations to help navigation. Second, interest in climate change is increasing, and sea-ice changes strongly reflect the changing climate.

The average ice season in the Bay of Bothnia lasts from November to May (Haapala et al., 2015). Thus, sea ice is an essential factor in the area. Every winter ships need assistance from ice breakers. Winter navigation has continuously increased and more information on the ice conditions is required. Especially ridged areas can cause major problems to ships. Milder winters are not necessary easier to navigation. It depends more of the ice thickness distribution and the amount of ridges.

We are now using accumulated data sets from EM field campaigns to determine the variability of sea ice thickness in the Bay of Bothnia in more detail. The aim of our study is to combine and compare these data with existing in situ drilling data from fast ice zone and ice chart thickness information. We believe that the pooled data set from the campaigns is sufficiently

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extensive to reveal the main features of regional and interannual variation in ice conditions. An observation made already after the first EM campaign in 2003 was that level ice thickness was close to the values reported in ice charts but the actual mean ice thickness is much larger due to ridged ice (Haas, 2004). We now estimate, for the first time, the interannual changes in the drift ice region and generate ice thickness distributions for individual years and for selected areas for which multiannual data are found. We also provide an estimate of the climatologically averaged thickness distribution for the Bay of Bothnia.

2 Data and methods

Ice thickness can be measured by several methods: visual observations from ships, drilling, electromagnetic induction (EM) sounding from sledges, ships, or aircraft, upward-looking sonar from moorings or submarines and satellites altimetry. We use several different data sets to get the best possible overview of the variability of sea ice thickness. Ice charts divide the ice cover in regions representing ice fields with different characteristics and age, and the thickness values seek to represent the typical thickness of level ice in each region. Drilling data at fixed observation stations are accurate and long term but have been made only in the fast ice zone. The EM data resolve the detailed ice thickness distributions in the drift ice zone, but study regions and times have so far been limited to few campaigns during the maximum ice extent.

To define the sea area we examined, we used the definition of the southern boundary of the Bay of Bothnia (Leppäranta and Myrberg, 2009): Iskmo-Raippaluoto-Björkö-Lappören-Valassaaret-Hadding Peninsula. The area of the Bay of Bothnia is 36 260 km^2. We indicate the winters so that for example 2003 means the winter 2002-2003.

2.1 Ice charts

During ice winters, ice charts are published daily by Finnish Meteorological Institute ice service. At the very beginning and end of the season, frequency of the charts is usually reduced to bi-weekly maps. Apart from graphic charts gridded versions with different resolutions are prepared for various purposes. These include grids for concentration, average thickness, maximum thickness, minimum thickness, deformation numeral (degree of ice ridging), and sea surface temperature. The deformation numerals from 0 to 5 denote level ice, rafted ice, slightly ridged ice, ridged ice, heavily ridged ice, and brash barrier. The graphic charts, on the other hand, represent these types with qualitative symbols only.

The main information sources for the charts are satellite images and observations. The thickness values are based on observations made by icebreakers and, for nearshore fast ice, at fixed stations. The station values are from drilling while the icebreaker values are estimates from upturning floes and occasional drillings. The thickness values refer to ice types with a flat surface that can be level ice or rafted ice and seek to characterize the regional conditions. The deformation numerals are based mostly on visual icebreaker observations and seek to be a regionally representative description of the conditions from the point of view of navigational difficulty. No rules for estimating total thickness from ice chart thicknesses and the numerals have been established yet although a clear correlation exists (Gegiuc et al., 2018).

We calculated the average annual statistics for the Bay of Bothnia using gridded ice charts for the 14 season period 2003-2016. The grid resolution is 1/60 of degree in NS direction and 2/60 degree in EW direction. True grid cell areas were used in calculations and the effect of land point occurrence in the cells was estimated. The common period was chosen to be from 1st October to 31st May. For ice-free days grids with zero values for ice parameters were used. During the very early phases of ice season the charts are bi-weekly and the latest ice chart was assumed to stay valid during the intermediate days. The same was assumed for the few gaps, usually one day in duration, during the main ice season.

2.2 EM data

One of the cost efficient ways to measure sea ice thickness over a large area is electromagnetic induction (EM) sounding. EM sounding allows sea ice thickness measurements from a moving aircraft or icegoing vessel. Here we use data from a helicopter-towed EM-bird (HEM, Haas et al., 2009) and ship-borne Geonics EM-31. EM instruments induce eddies of alternating electric current in conductive layers in the underground and measure the amplitude and phase of the resulting EM fields. From these, the distance to the different layers can be accurately determined (e.g. Haas et al., 1997). With sea ice thickness measurements, the seawater is assumed to be a half-space of constant, known electrical conductivity underneath the resistive sea ice, and the distance to the ice-water interface can be retrieved with a single measurement frequency.

A single-frequency EM device cannot differentiate between snow and ice because they are both highly resistive. Therefore snow thickness is always included in the measured total ice thickness. Similarly, conductive layers like flooded snow on ice or porous ridge keels cannot be distinguished but will lead to underestimates of total ice thickness.

For regional or basinwide measurements an EM instrument can be suspended from a ship, helicopter or an airplane. In these installations the distance to sea ice is not fixed and needs to be measured separately by a laser distance sensor and subtracted from the EM-retrieved distance to seawater to get ice thickness.

Results of ice thickness surveys are commonly displayed as thickness distributions (histograms). Caution is due when interpreting and comparing thickness histograms and their mean values. First, thickness refers to the distance between the ice surface and ice underside. Considerations involving ice mass balance, especially the transition of level ice types to ridged ice, must take into account the relative void content (porosity) which can be 20-40% for the unconsolidated part of ridge keels (Leppäranta, 2005).

The thickness measurements have also different scales and footprints. In addition, EM measurements are affected by smoothing over the footprint, i.e. the area over which an EM device receives the return signal. The footprint size depends on the distance of the instrument to the ice-water interface. It is a few meters for the ship-borne EM-31 and between 3 to 4 times the flying altitude of approximately for HEM bird. Typical altitude for the HEM bird is about 15 m, resulting into a footprint size in the order of 50 m. Thickness variations on scales smaller than the footprint are smoothed and therefore ridge keel depths are underestimated or closely arranged keels may join into one signature. This affects especially the tail part of the thickness histogram. Usually the EM thicknesses are accepted at their face value and interpreted as average thickness over footprint.

To present the distribution of ice thickness we computed normalized frequency histograms with a bin width of 0.1 m from EM data. In some years the spatial density of EM surveys is much higher in certain areas than elsewhere, especially close to the land base of EM flights. To avoid bias from the dominance of such areas we first calculated histograms in 1 NM grid for each grid cell and then averaged all histograms from the grid cells to one histogram. In addition to histograms pertaining to each campaign, a histogram for all five years of helicopter EM data was constructed by averaging the annual histograms.

2.2.1 Helicopter EM data

HEM surveys were carried out in the Bay of Bothnia in years 2003, 2004, 2005, 2007 and 2011. The flights were mostly made during a short time period from the end of February to the first half of March, i.e. potentially before the ice reached its maximum annual thickness. The measurements are from different routes in different years. The most extensive campaign was in March 2011. Thus, comparison of the measurements in different years is not unproblematic.

Haas (2006) has shown that ice thicknesses are overestimated in brackish water shallower than 15 to 20 m at the signal frequency of 4 kHz used here. This is due to induction in the seafloor with its lower conductivity than of seawater. To prevent this error, we masked the data when water depth was less than 15 m.

The 2011 campaign was used by Gegiuc et al. (2018) as validation data for the ice chart deformation numeral (degree of ice ridging). The agreement between the two datasets was generally good.

2.2.2 Ship EM data

EM ice thickness measurements have been made on scientific cruises in 2012 and 2016. In these, the EM-31 instrument is placed in an enclosure and hung from a boom or a crane outside the ship hull (Haas, 1998). The ship measurements are generally biased, as ship crews tend to avoid thickest ice and turn back from impenetrable areas. These effects were minimized by deliberately searching for challenges (2012) or instructing the ship crew to make transects in straight lines whenever possible (2016).

The instrument is not directional, but the majority of readings represent a footprint of approximately 5 meters. The instrument sensitivity decreases with increasing distance to sea water, and in general thicknesses greater than 4 meters are seen as unreliable. One notable reason is that ridge keels deeper than four meters are often also narrow and porous, so the EM instrument will detect seawater both inside and beside the ridge keel. The typical average keel depth in the Bay of Bothnia is 5 meters. We estimate that we underestimate ridge keel volume by 4 % due to this effect, assuming an exponential distribution model for keel depths.

The EM-31 instrument was generally 1-2 meters above sea level during the measurements to avoid impacts from sea ice. Distance to snow surface was measured using an attached laser rangefinder with a 10 Hz measuring frequency and a negligible footprint. Sea ice thickness is calculated separately for each rangefinder reading and these thicknesses are averaged once per meter.

2.3 Drilling observations

The in-situ ice thickness measurements were made by drilling in the regular monitoring stations in the coastal fast ice zone. The original observations have been made weekly throughout the winter. The length of the time series vary a lot; the longest time series is from Kemi station, where observations have been made since 1912. There is no detailed documentation of the measurement sites available, so the sites might have moved or the environment changed during the longer observation periods. For the period 2003-2016, which is used in our analysis, the Hailuoto station has been located on the southwest coast of the island (64°56´ N, 24°40´ E).

2.4 Atmospheric variables

To solve the reasons behind the variability of ice thickness we calculated freezing degree days from air temperature observations in Hailuoto Keskikylä station (65°1´ N, 24°43´ E). Monthly mean air temperatures are available since 1959. Freezing degree days means annual cumulative sum of daily mean air temperatures below 0° C. Since we had only monthly mean temperatures, the monthly mean values were first multiplied by the amount of days in the month in question and then summed up to entire winter values.

Another factor affecting the variability of ice thickness is wind. We used days with wind over 14 m/s during the winter months January, February and March (JFM) in Hailuoto Marjaniemi station (65°2´ N, 24°33´ E). The wind has been defined as 10-minute average wind speed and observations have been made 8 times per day since 1984. In some days in the 1980s and in the beginning of the 1990s less observations have been made.

In addition, to find out the influence of large-scale atmospheric forcing we used NAO index values from the NOAA Climate Prediction Center. The monthly values were averaged over December, January and February (DJF).

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2.5 Severity of the EM data winters

The severity of the winters from which we have EM data is presented in Table 1. This does not represent the severity of the winters in time period 2003-2016 due to lack of measurements in the two really mild ice winters 2008 and 2015. The years that are presented here include only one winter which is classified as mild. However, five of the seven winters are milder than average between 1961-2010. The sum of freezing degree days is remarkably higher in the two severe winters 2003 and 2011.

3 Results

3.1 Ice charts

The results are calculated over 14 seasons 2003-2016. The length of ice season (Fig. 1) varies from 69 days in the Quark to 157 days in the northern inlets. Basin mean value is 106 days. In addition to that ice season is longer in the north than in the south, a clear tendency to longer season in more shallow coastal areas is seen.

The average ice thickness (Fig. 2) does not include days of open water. The values range from 0.11 m by southwest coast to 0.44 m of the northeast shorefast ice, the basin average being 0.28 m. The effect of recurring coastal leads can be seen, more prominent along the Swedish coast due to prevailing westerly winds. Also the extent of fast ice becomes delineated by the coastal leads. Coastal processes and average northeast direction of ice drift affect also the areal distribution of ridging (Fig. 3). Close to northeastern midseason fast ice boundary there are on the average up to 57 days with ridged or heavily ridged ice.

The seasonal development of the decomposition of Bay of Bothnia ice area into ice types is in Fig. 4. The types are fast ice and the six classes of ice deformation. The values for a given day are averages over the 14 seasons. The fast ice expands on the average to the mid-March, begins to decline rapidly in mid-April, and disappears at mid-May. That drift ice remains after fast ice has melted is a feature typical to the basin. In the drift ice the level ice area increases to the beginning of February at which stage also about half of the pack is rafted or ridged. The level and rafted ice areas then decrease gradually while the ridged ice types increase so that in March three fourths of pack ice area is rafted or ridged. The total ice area remains quasi constant during February and March before the onset of melting season in April. The apparent faster decline of ridged ice in comparison with level ice in late May is probably in part due to the disappearance of surface ridge signatures in radar images of the melting pack.

The thickness time series in Fig. 5 is derived for the daily basin averages for fast ice and drift ice thicknesses. Both the scattered values for individual seasons and the average over all 14 seasons are shown. The fast ice growth rate slows down until the thickness reaches 0.52 m before the last third of March. After this the thickness remains constant a month and declines then rapidly. The average of ice chart ice thickness in drift ice zone, which refers to regionally representative level or slightly rafted types, reaches 0.43 m before the melting period. The growth before this is linear. The pack ice remains about ten days after fast ice has disappeared, probably due to its larger mean thickness.

3.2 Helicopter EM data

Grid-averaged HEM data from all years are compared with ice chart data in Fig. 6. The EM data were gathered during several days before and after the dates of the ice charts. The values in ice chart data are up to 0.5 m. The helicopter EM values exceed the scale, which is up to 1 m, in many measurement points. This is due to the fact that the ice chart values are for ice with flat surface, which is level or rafted ice. The helicopter EM measurements show the real situation with ridged ice in the drift ice zone.

Although the maps are not from exactly the same day from year to year, there is a large interannual variability seen in these five years. The mildest ice winter based on both data is 2005. In the severest years 2003 and 2011 the entire Bay of Bothnia was ice covered and over 100 cm thick ice was measured also in the south near the Quark.

In ice charts spatially the most severe ice conditions are in the north. In addition, especially in 2003 and 2011 there is more ice in the eastern side of the bay. The EM data from 2003 and 2005 show that the ice is thicker in the northeastern part. This is because the southwest winds are dominant in the area.

Histograms of grid-averaged HEM ice thicknesses are shown in Fig. 7. The mean of ice thickness in 2003 is 0.98 m and the mode class is 0.6-0.7 m. The data from 2004 (Fig. 7b) are not as evenly distributed as the 2003 data. There is a strong mode of 0.1-0.2 m, representing thin new ice which has grown in coastal polynyas. However, the mean is 1.17 m and thicknesses over 1 m are more common than in other years. The thicker ice indicates that there has been widely ridged ice. The 2004 campaign was done in the northern Bay of Bothnia in a quite small area near Hailuoto.

The ice thickness from helicopter EM data from 2005 is presented in Fig. 7c. The mean is 0.78 m and the mode class 0.3-0.4 m. The data from 2007 (Fig. 7d) has a high peak. The mean (0.76 m) is close to the mode class (0.5-0.6 m). Thick ice is rare in this campaign, which covered a wide region of the northern Bay of Bothnia. Thus, in 2007 ridged ice was rare. Instead, the observed distribution points to the fact that level ice and rafted ice might have been the dominating ice types. In 2011 the mean is 0.89 m and the mode class 0.3-0.4 m (Fig. 7e). The average from all five years is presented in Fig. 7f. The mean is 0.92 m and the mode class 0.4-0.5 m.

3.3 Interannual variability

In Fig. 8 we have compared the different ice thickness data sets to each other in winters between 2003 and 2016. Drilling observations from Hailuoto represent the fast ice zone. The ice chart data, helicopter EM mean data and ship EM mean data

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are averages over drift ice area west of Hailuoto. The limits of the area are in latitude 64.5° N-65.5° N and in longitude 23° E-24.5° E. Helicopter EM mode and ship EM mode are modes over the same drift ice area west of Hailuoto. In this figure the EM mean and mode values have been calculated from the entire data differently from the histograms. The ice charts are from 1st March and open water has not been taken into account in mean values. The drilling measurements are made weekly, so the day of the measurements varies between 26th February and 4th March. Figure 8 shows also the NAO index values for each winter. In addition, we have listed the amount of freezing degree days, wind days and the value of NAO index in Table 2 together with the ice thickness values.

The highest values of ice thickness are in the helicopter EM data, which indicates the drift ice thickness. The histograms of the helicopter EM data in this area are in Fig. 9. To avoid areal focus we have also calculated histograms in 1 NM grid for each grid point and then averaged all histograms from the grid points. The mean and mode marked in histograms are calculated from the histograms unlike the values in Fig. 8 and Table 2. In 2004, when all the measurements have been made in this area, there is a lot of thin ice. Also thick, ridged ice exists during this average winter in terms of freezing degree days. These kind of ice conditions would be expected when there is a lot of wind. However, in 2004 there has been only 10 days of wind over 14 m/s, which is less than average of 2003-2016.

Compared to the results of the entire campaign in 2005 there is more thick ice in the selected area. That is clearly seen also in Fig. 6, where the thickest ice is found in northern parts of the campaign in 2005. Year 2007 was mild and there were 9 wind days. Thus, the thick ice is missing almost completely. In 2011 there is a higher peak in the histogram of the selected area compared to the histogram of the entire campaign. The 2011 campaign was the broadest of all campaigns. It was the most severe winter in terms of freezing degree days, but in spite of the 15 winds days there was not much thick, ridged ice.

The histograms of ship EM from the selected area are also included in Fig. 9. In both winters 2012 and 2016 the modal thickness is 0-0.1 m. Especially in 2016 there has been a lot of thin ice and the mean is only 0.29 m. This winter was the mildest from the EM data years in terms of freezing degree days and maximum annual ice extent in the Baltic Sea.

The ice chart mean values show that there is much variability between years in the drift ice zone level ice thickness. Based on ice charts the mildest ice winters have been 2015 and 2008. Instead, in the drilling observations year 2009 was milder. In the freezing degree days mildest winter was 2015 and the severest 2011. The most wind days occurred in the mild winter 2015. Nevertheless, the second windiest winter was the severe winter 2003. Then the EM data has its highest values and there has been much ridged ice.

4 Discussion

Our data shows that large interannual variability exists between ice seasons. In some years areas with heavily ridged ice form and there is much deformed ice in the Bay of Bothnia. However, in other years, for example in 2007, thinner ice dominates and there is no thick ice. Winter 2004 was milder and less windy than average. Yet, we found that both thick, ridged ice and thin, new ice formed during that year. In 2015 the Bay of Bothnia remained partly ice-free for the first time so that it has been reliably recorded (Uotila et al., 2015). In our atmospheric data that winter was the mildest and windiest. The ice chart mean ice thickness in the area west of Hailuoto indicates level ice thickness of only 0.12 m. The winter air temperature was still so low that in Hailuoto there was 0.62 m fast ice in 2nd March 2015. Generally, ice thickness in the fast ice varies much less than the thickness of drift ice.

The average extent of the fast ice zone can be seen in Fig. 2. In Hailuoto the maximum ice thickness in the fast ice zone in years 2003-2016 was over 0.80 m. The maximum value is usually reached in mid-March. The record value is from 1985 in Tornio, 1.22 m (Leppäranta and Myrberg, 2009). The most ridged areas are in the northeastern Bay of Bothnia near the line of the fast ice zone. This is because of dominating winds from southwest. Even in mild winters high ridges form in the Bay of Bothnia. However, they cover a smaller area than in more severe winters.

Heavily ridged areas are found near the fast ice boundary. In the Bay of Bothnia they lie mostly in the northeastern corner as can be seen from Fig. 3. Oikkonen et al. (2016) defined the region affected by the coast as coastal boundary zone (CBZ) and found out that the drift of ice was anisotropic on CBZ and that was due to effect of the coast. The alongshore component of the drift was larger than the cross-shore component. Our EM data shows that the ice thickness in the heavily ridged areas in scales of tens of km^2 can be even manyfold thicker than the fast ice. These areas are challenging for winter navigation and biological hot spots in spring as the ice melts last.

The effect of large-scale atmospheric circulation on ice extent and ice concentration has been studied in the Baltic Sea (Vihma and Haapala, 2009; Vihma et al., 2014). Positive NAO index values indicate milder ice conditions and negative NAO index values more severe conditions. In addition, Koslowski and Loewe (1994) showed that accumulated areal ice volume was negatively correlated with NAO index in a small area in the southwestern Baltic Sea. Research on the correlation of NAO purely with ice thickness is still lacking. However, ice thickness is a more complex variable than for example ice extent. Winters with strongly positive NAO index, such as 2015, are generally mild and windy. Wind piles up the ice and conditions can be like in 2004, when in our study both thick, ridged ice and thin, new ice existed.

The correlation coefficient of the NAO index and the ice chart level ice thickness is -0.53 in our study period 2003-2016 (Fig. 10). The correlation of NAO and drilling data is -0.38. Neither of the correlations is statistically significant. Thus, our study

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does not show any significant correlation between NAO and level ice thickness. However, our time period is too short to capture the long-term behavior of the variables.

The amount of days of wind over 14 m/s has no notable correlation with the amount of freezing degree days. This can be due to that circumstances change during the winter, like in 1986 when NAO was strongly negative in February and positive in other winter months (Vihma and Haapala, 2009).

5 Conclusions

We have examined different data sets of ice thickness from the Bay of Bothnia in order to define the interannual variability of sea ice thickness. Different data sets describe different parts or different ice types in the Bay of Bothnia. Nevertheless, we found large variability both in time and space.

The interannual variability in the fast ice zone is much smaller than in the drift ice zone. Deformed ice has a major role in the drift ice zone. In some years there is mainly thin, thermodynamically grown ice even in the drift ice zone and in some years large areas with thick ridges. Most of the years are a mixture of these two. Ice thickness varies even in few days time, especially in the drift ice zone. Thus, our observations do not describe the absolute interannual variability.

Also large regional differences can be detected. In a similar way than to interannual differences, wind and air temperature affect the most. Ice conditions are more severe in the north because of the colder air temperatures. Therefore the ice in this region is older and experiences more deformation to accumulate more ridges. Typical wind direction in the area is southwest. Southwest winds gather ice towards the northeastern area of the Bay of Bothnia, where ice conditions are more severe. The southwest corner is the mildest.

We emphasize that the ice charts show only thickness of ice with flat surface, but the reality is much more severe. Especially in the drift ice zone ice ridges can be several meters thick, whereas the flat ice thickness is only few tens of centimeters. This is obvious when comparing the ice charts and EM data (Haas, 2004).

Our attempt to solve the interannual variability showed that the winters are really different from each other. However, there is so much variability between years and between measurement methods that the results must not be seen as absolute differences from year to year, only as guidelines for ice thickness changes in the seasonal sea ice zone.

Competing interests. The authors declare that they have no conflict of interest.

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References

Gegiuc, A., Similä, M., Karvonen, J., Lensu, M., Mäkynen, M., and Vainio, J.: Estimation of degree of sea ice ridging based on dual-polarized C-band SAR data, The Cryosphere, 12, 343-364, https://doi.org/10.5194/tc-12-343-2018, 2018.

Haapala J., Ronkainen I., Schmeltzer N., and Sztobryn M.: Recent Change - Sea Ice. In: BACC II Author team (Ed.), Second Assessment of Climate Change for the Baltic Sea Basin, Springer, pp. 145-153, 2015.

Haas, C.: Evaluation of ship-based electromagnetic-inductive thickness measurements of summer sea-ice in the Bellingshausen and Amundsen Seas, Antarctica, Cold Regions Science and Technology ,27, 1-16, 1998.

Haas, C.: Airborne EM sea-ice thickness profiling over brackish Baltic sea water. In: Proceedings of the 17th international IAHR symposium on ice, June 21-25, 2004, St. Petersburg, Russia. All-Russian Research Institute of Hydraulic Engineering (VNIIG), Saint Petersburg, Russia, 2004.

Haas, C.: Airborne electromagnetic sea ice thickness sounding in shallow, brackish water environments of the Caspian and Baltic Seas, Proceedings of OMAE2006 25th International Conference on Offshore Mechanics and Arctic Engineering, June 4-9, 2006, Hamburg, Germany, 6pp, 2006.

Haas, C., Gerland, S., Eicken, H., and Miller, H.: Comparison of sea-ice thickness measurements under summer and winter conditions in the Arctic using a small electromagnetic induction device, Geophysics, 62/3,749-757, 1997.

Haas, C., Lobach, J., Hendricks, S., Rabenstein, L., and Pfaffling, A.: Helicopter-borne measurements of sea ice thickness, using a small and lightweight, digital EM system, Journal of Applied Geophysics, 67(3), 234-241., doi:10.1016/j.jappgeo.2008.05.005, 2009.

Jevrejeva S., Drabkin V.V., Kostjukov J., Lebedev A.A., Leppäranta M., Mironov YE.U., Schmelzer N., and Sztobryn M.: Baltic Sea ice seasons in the twentieth century. Climate Research 25: 217-227, 2004.

Leppäranta, M.: The Drift of Sea Ice, Praxis Ltd, Chichester, U. K., 2005.

Leppäranta, M. and Myrberg, K.: Physical Oceanography of the Baltic Sea. Springer-Praxis, Chichester, 378 p, 2009.

Leppäranta M. and Seinä A.: Freezing, maximum annual ice thickness and break-up of ice on the Finnish coast during 1830-1984. Geophysica 21(2): 87-104, 1985.

Koslowski, G. and Loewe, P.: The western Baltic Sea ice seasons in terms of mass related severity index 1879–1992. Tellus 46A, 66–74, 1994.

Oikkonen, A., Haapala, J., Lensu, M., and Karvonen J.: Sea ice drift and deformation in the coastal boundary zone, Geophys. Res. Lett., 43, 10,303–10,310, 2016.

Palosuo, E.: Formation and Structure of Ice Ridges in the Baltic (Winter Navigation Research Board, Rep. No. 12). Board of Navigation, Helsinki, 1975.

Pärn, O. and Haapala, J.: Occurrence of synoptic flaw leads of sea ice in the Gulf of Finland. Boreal Env. Res. 16:71-78, 2011.

Uotila, P., Vihma, T., and Haapala, J.: Atmospheric and oceanic conditions and the extremely low Bothnian Bay sea ice extent in 2014/2015. Geophys. Res. Lett., 42, 7740–7749, 2015.

Vihma, T. and Haapala, J.: Geophysics of sea ice in the Baltic Sea: A review. Progress in Oceanography 80, 129–148, 2009.

Vihma, T., Cheng, B., Uotila, P., Lixin, W., and Ting, Q.: Linkages between Arctic sea ice cover, large-scale atmospheric circulation, and weather and ice conditions in the Gulf of Bothnia, Baltic Sea, Adv. Polar Sci., 25(4), 289–299, 2014.

Table 1: Maximum annual ice extent from the entire Baltic Sea (MIB), MIB anomaly based on years 1961-2010 and severity according to Finnish Ice Service compared to North Atlantic Oscillation (NAO) index and the amount of freezing degree days in Hailuoto. The data is from the years we have electromagnetic measurements.

Year	MIB (km^2)	MIB anomaly	MIB severity	NAO index	FDD (degrees)
2003	233000	+	Severe	-0.05	1256
2004	153000	-	Average	0.07	712
2005	178000	-	Average	0.89	549
2007	140000	-	Average	0.36	610
2011	309000	+	Severe	-0.68	1316
2012	179000	-	Average	1.37	687
2016	110000	-	Mild	1.31	538

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Table 2: Ice thickness observations, atmospheric variables and their statistics from winters 2003-2016. Drillings are ice thickness drillings from Hailuoto approximately 1 March, ice charts data is mean from the area west of Hailuoto 1 March (open water not taken into account), EM/mean is the EM mean ice thickness in the same area and EM/mode the mode thickness in the area. In EM data HEM means helicopter-borne EM and SEM ship-borne. FDD is the amount of freezing degree days during the winter in Hailuoto, wind days are days with wind over 14 m/s in JFM in Hailuoto and NAO index is average value for winter months DJF.

Year	Drillings (m)	Ice charts (m)	EM/mean (m)	EM/mode (m)	FDD (degrees)	Wind days (d)	NAO index
2003	0.81	0.41	1.42 (HEM)	0.41 (HEM)	1256	18	-0.05
2004	0.55	0.25	1.18 (HEM)	0.17 (HEM)	712	10	0.07
2005	0.55	0.19	1.06 (HEM)	0.37 (HEM)	549	15	0.89
2006	0.42	0.28			948	8	0.10
2007	0.51	0.24	0.75 (HEM)	0.57 (HEM)	610	9	0.36
2008	0.46	0.13			350	7	0.65
2009	0.39	0.26			614	13	-0.08
2010	0.82	0.36			1202	6	-1.67
2011	0.65	0.45	0.84 (HEM)	0.40 (HEM)	1316	15	-0.68
2012	0.48	0.34	0.77 (SEM)	0.57 (SEM)	687	11	1.37
2013	0.65	0.46			1070	8	0.02
2014	0.57	0.31			355	15	0.86
2015	0.62	0.12			307	24	1.66
2016	0.67	0.30	0.42 (SEM)	0.07 (SEM)	538	5	1.31
Mean	0.58	0.29	0.92	0.37	751	12	0.34
St. Dev.	0.13	0.11	0.33	0.19	347	5	0.88
Median	0.56	0.29	0.84	0.40	651	11	0.23
Min	0.39	0.12	0.42	0.07	307	5	-1.67
Max	0.82	0.46	1.42	0.57	1316	24	1.66

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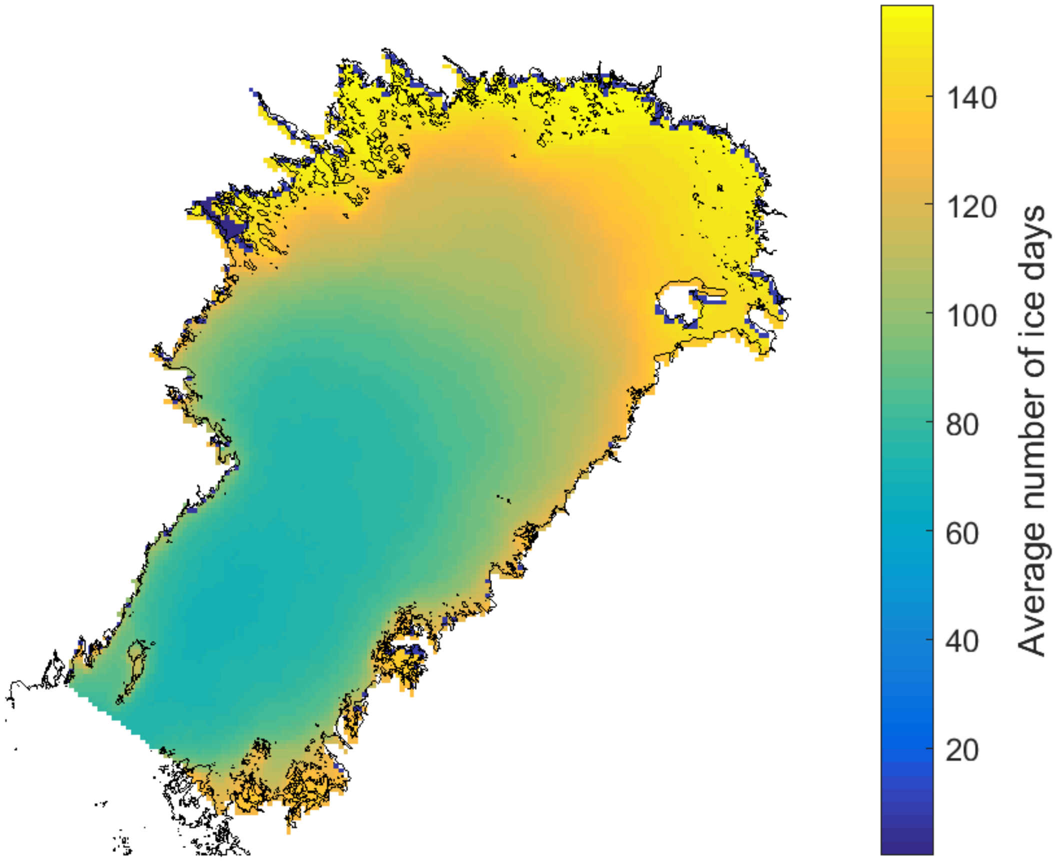

Figure 1: The average number of ice days per season determined from ice charts.

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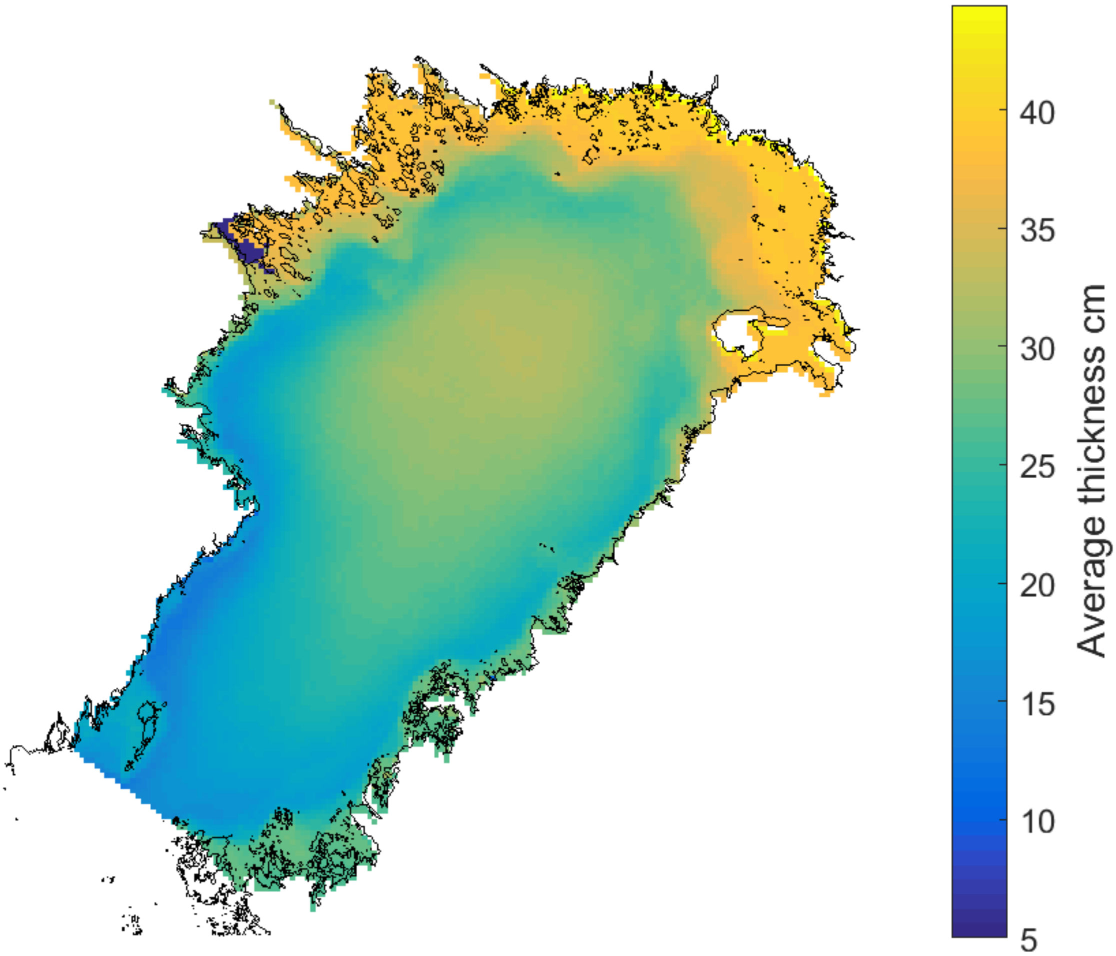

Figure 2: The average seasonal, level ice thickness from ice chart data. Values are averages of nonzero thickness values over 14 seasons.

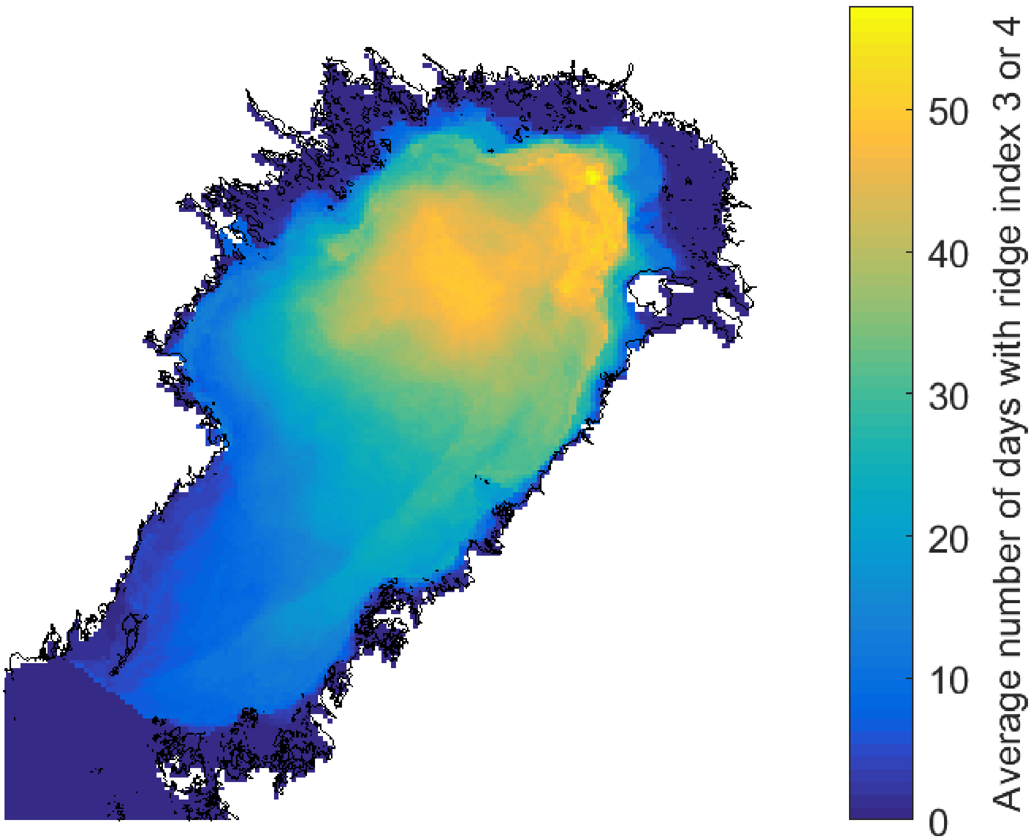

Figure 3: Average number of days with ice chart ridging index 3 (ridged ice) or 4 (heavily ridged ice).

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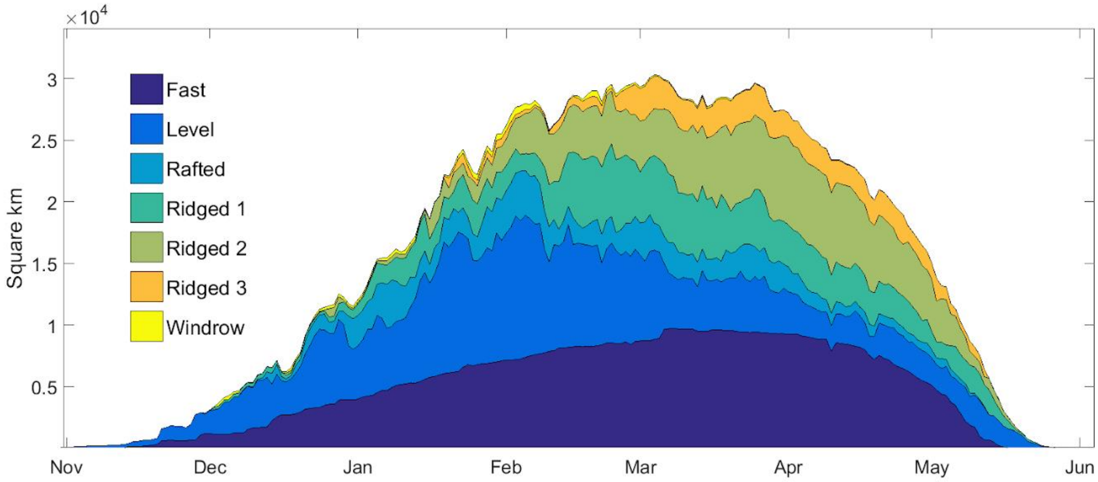

Figure 4: The seasonal development of charted ice area as divided into ice types. Season day averages over 14 seasons, including open water.

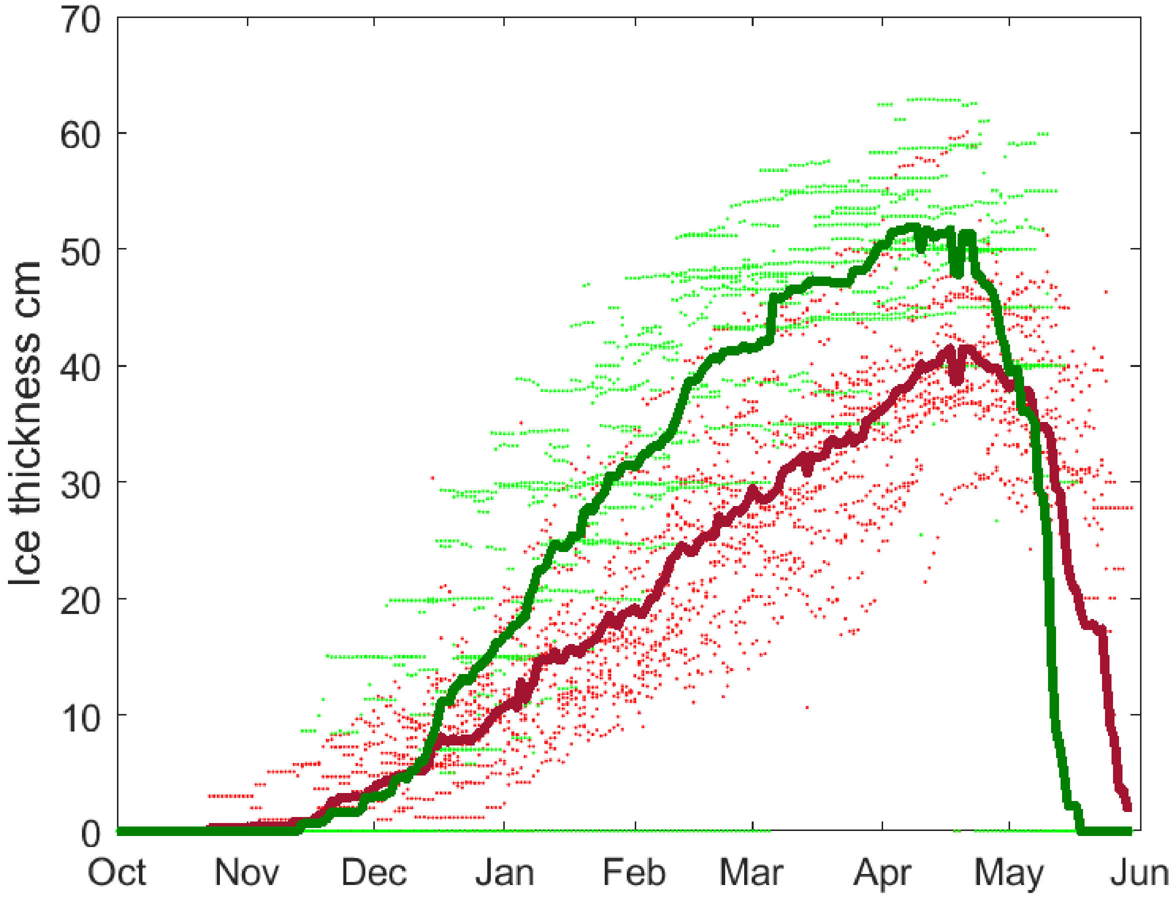

Figure 5: Seasonal development of level ice thickness. Data is based on ice chart information thickness for 14 seasons 2003-2016. The green and red dots are daily level ice thicknesses in the fast ice and pack ice zones for different seasons, the green line is fast ice thickness average over seasons and red line pack ice thickness.

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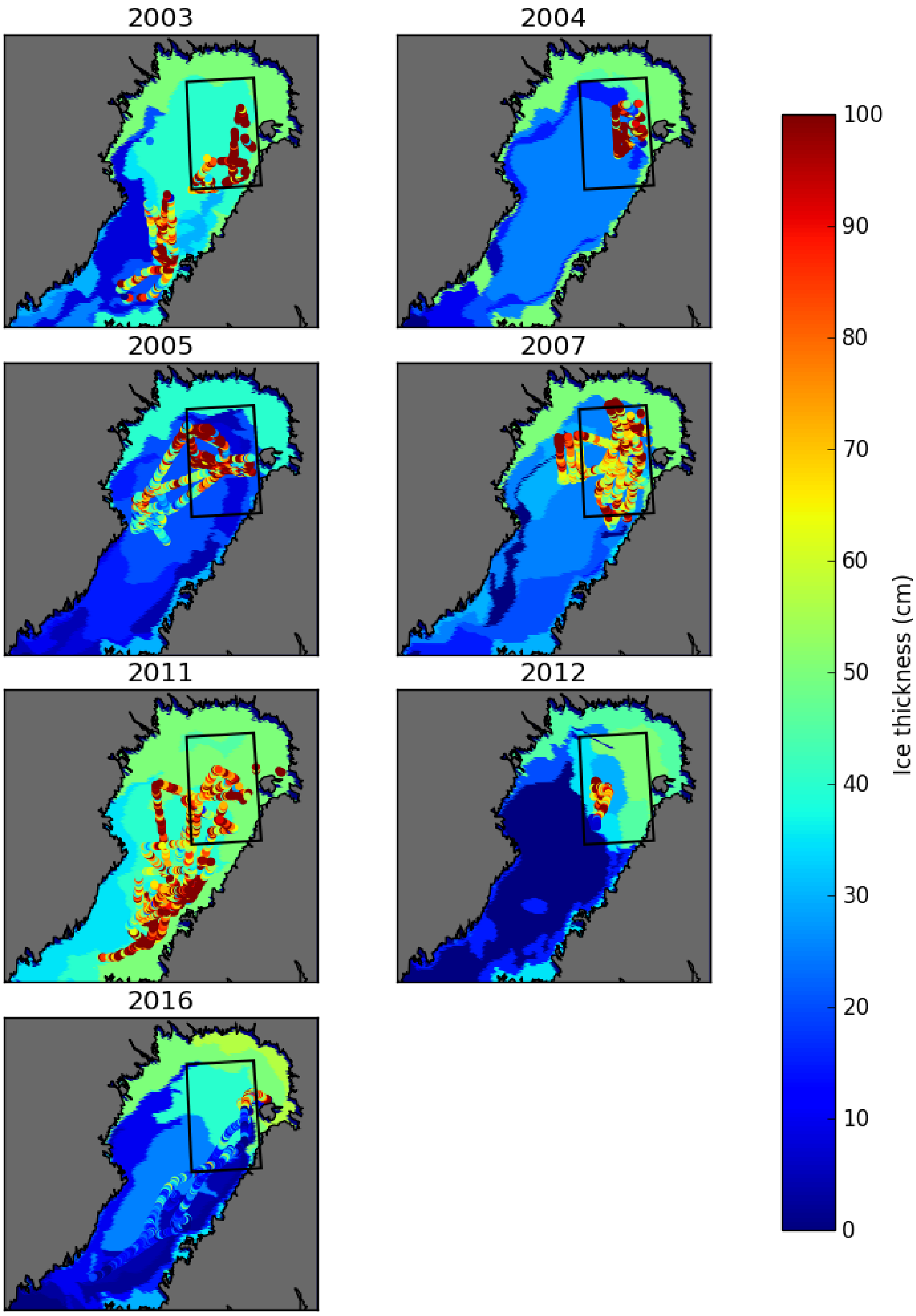

5 **Figure 6: Ice chart (on the background) and 1 nautical mile averaged EM data (with dots) from approximately 23rd February 2003, 14th March 2004, 13th March 2005, 14th March 2007, 4th March 2011, 21st March 2012 and 5th March 2016. Ice charts are from that particular day, whereas the EM data were gathered during many days around those dates. As we can see, the ice charts report uniform, thin ice, while in reality thick deformed ice types are typical. The black box is the area used in analysis.**

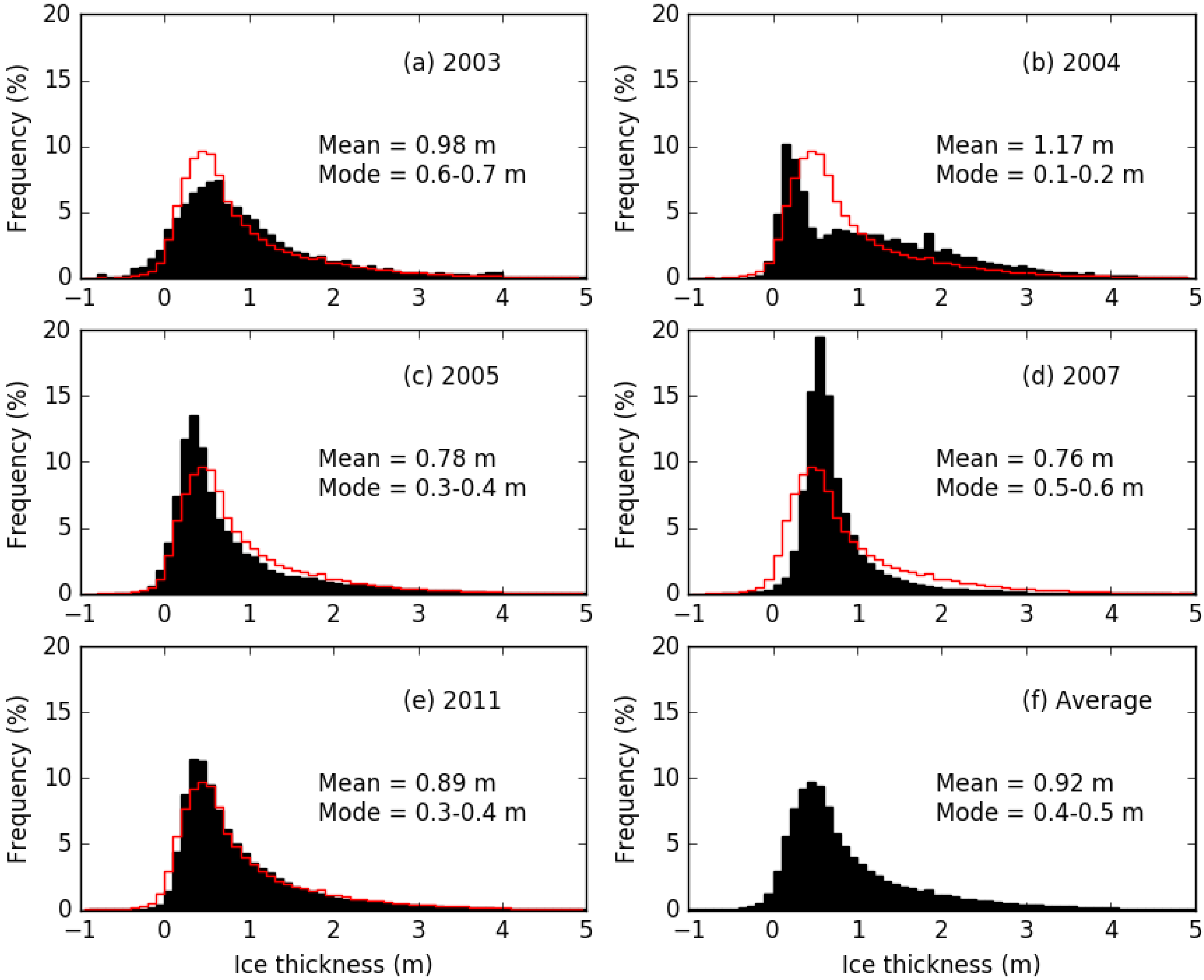

Figure 7: Frequency histograms of all helicopter EM ice thickness measurements in a) 2003, b) 2004, c) 2005, d) 2007 and e) 2011 (in black). The average of all years is in figure f and in red in other figures. To avoid areal focus we have first calculated histograms in 1 NM grid for each grid point and then averaged all histograms from the grid points.

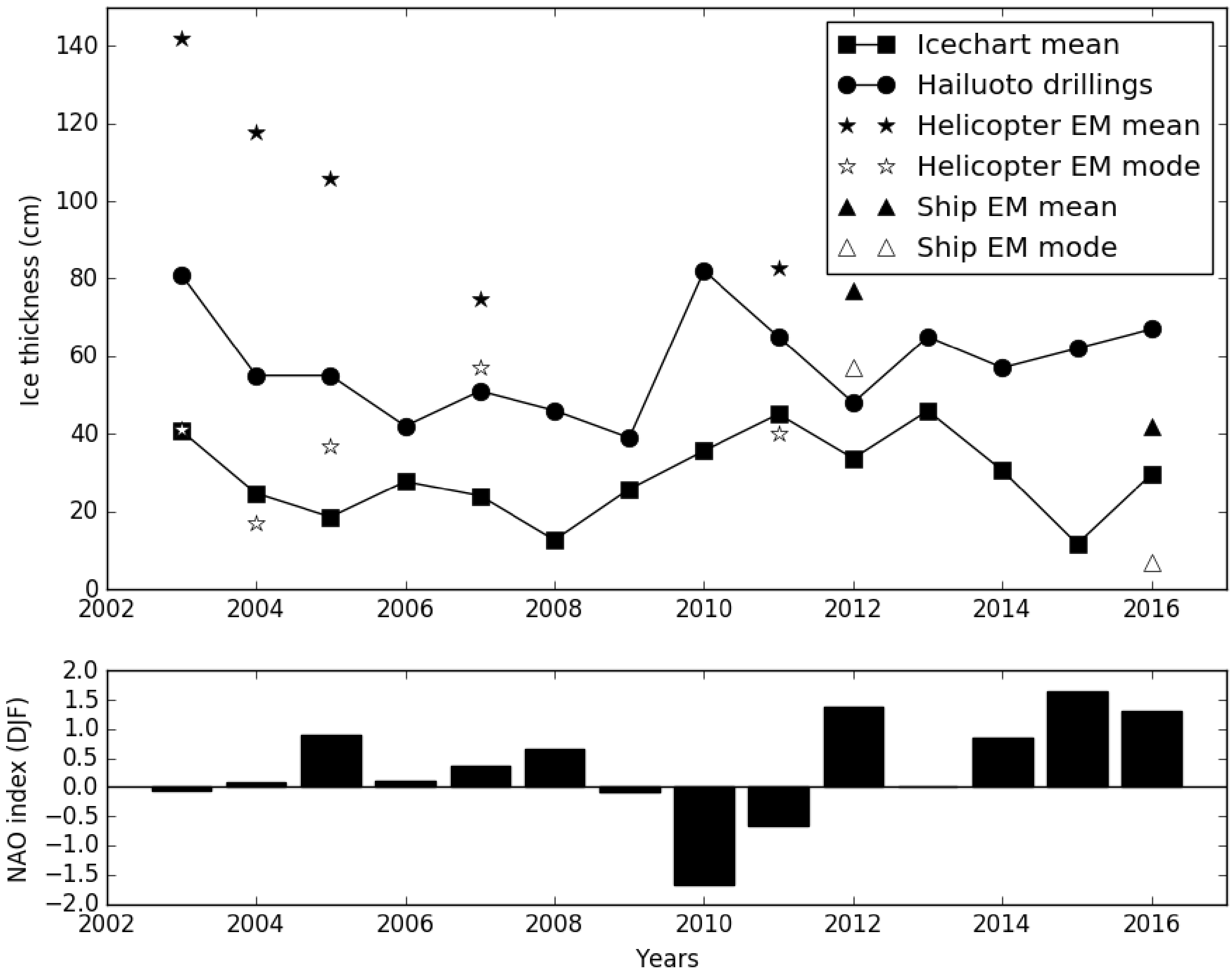

Figure 8: Time series of mean and modal ice thicknesses from Hailuoto drillings (circles) in the fast ice zone, and ice charts (squares), helicopter EM surveys (black stars) and ship EM surveys (black triangles) in the drift ice zone west of Hailuoto (upper panel). Helicopter EM modes (white stars) and ship EM modes (white triangles) were also observed over drift ice west of Hailuoto. Lower panel shows time series of mean NAO index of winter months DJF. Data from years 2003-2016.

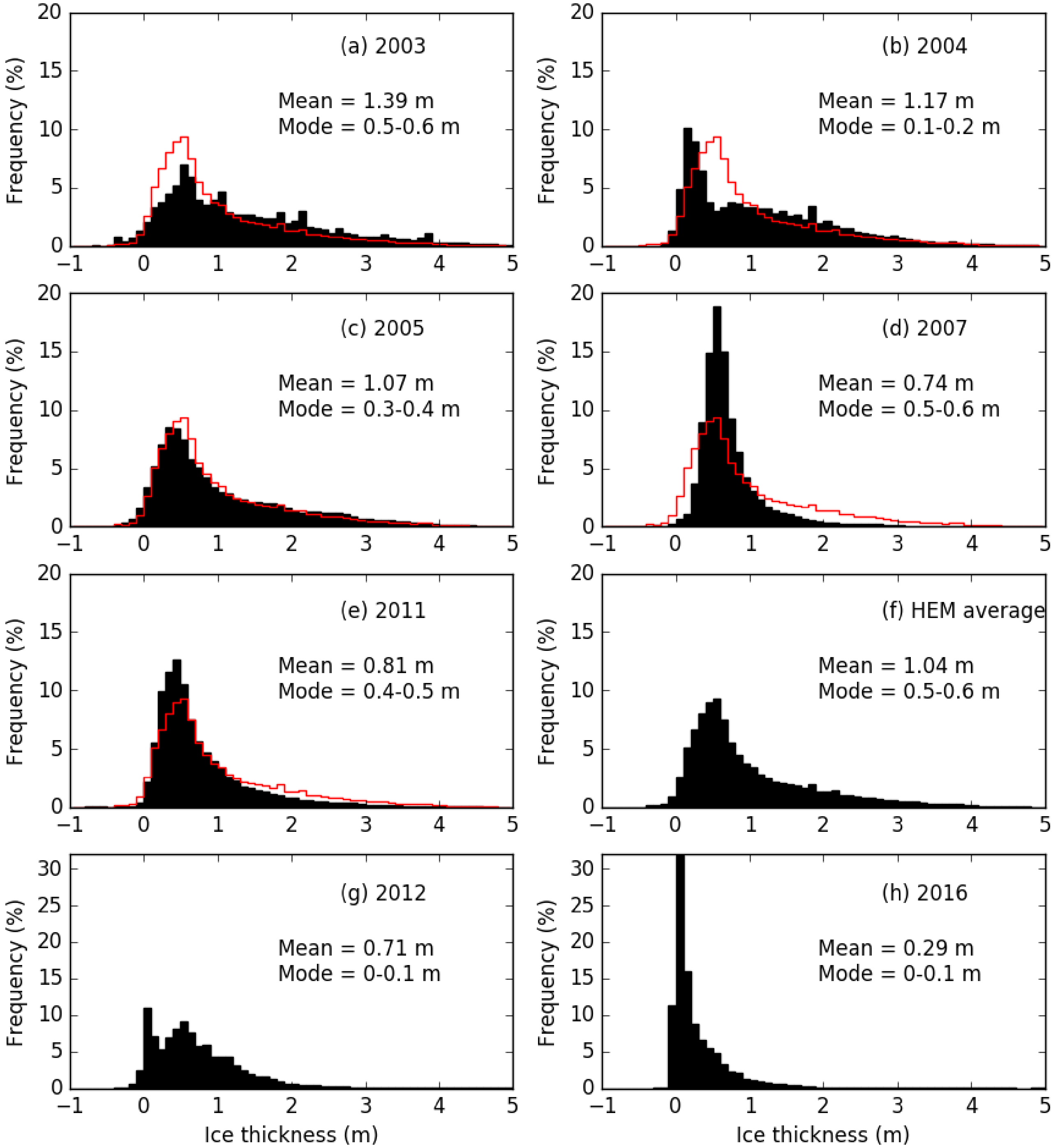

Figure 9: Frequency histograms of helicopter EM ice thickness in the drift ice area west of Hailuoto a) 2003, b) 2004, c) 2005, d) 2007 and e) 2011 (in black). The average of all years of HEM is in figure f and in red in other figures. Frequency histograms of ship EM ice thickness in the drift ice area of of Hailuoto g) 2012 and h) 2016. To avoid areal focus we have first calculated histograms in 1 NM grid for each grid point and then averaged all histograms from the grid points.

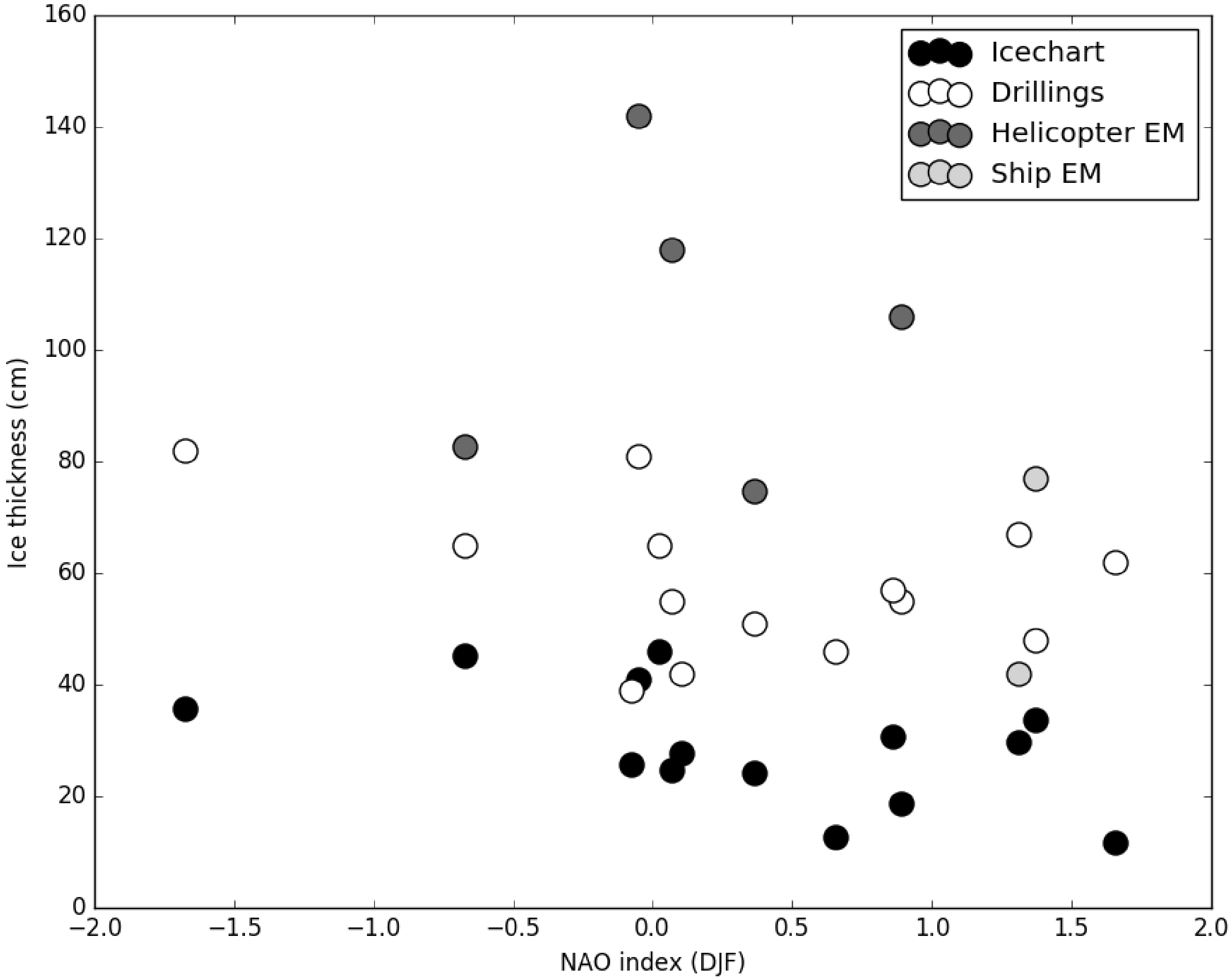

Figure 10: NAO index (DJF) and ice thickness from ice charts (black), drillings (white), helicopter EM surveys (dark grey) and ship EM surveys (light grey) 2003-2016.