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SUMMARY OF RECENT STUDIES ON THE CONTRIBUTION OF METEORIC ICE TO LANDFAST SEA ICE GROWTH IN THE BALTIC SEA

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ABSTRACT

This paper summarizes the results from recent studies on the texture and $\delta^{18}O$ properties of landfast sea ice in the Baltic Sea. These investigations provided the first quantitative estimates on the contribution of meteoric ice to sea ice mass-balance in the region. Both seasonal development and large-scale spatial variability were investigated. The Baltic Sea ice belongs to the seasonal ice zone and therefore represents rather mild ice climate conditions. The studies revealed that the contribution of meteoric ice, in the form of snow-ice and superimposed ice, to ice growth is highly significant, as high as 35% of the total ice mass, depending on season and year. However, interannual variability in meteoric ice contribution is large and years with low meteoric ice contributions were also observed. The mild climate conditions seem to contribute to the fact that superimposed ice formation is a reoccurring process at these latitudes, especially in spring when diurnal temperature variations can be high, with snow melt at daytime and refreezing at night. Also refrozen (liquid) rain contributes to superimposed ice formation. Overall snow (precipitation) is highly important for the development of Baltic Sea ice, not only for its mass-balance, and its role should be investigated in great more detail.

INTRODUCTION

Already Palosuo (1963) studied the role of snow-ice in the growth of Baltic Sea ice rather extensively. He observed that at best almost 50% of the total ice thickness could be composed of upward growth due to snow-ice formation (or *white ice* as he called it).

However, quantitative estimates of the mass fraction of snow (or more exactly precipitation) to the total sea ice mass could not be deduced by the methods used at the time of Palosuo's observations. Lately oxygen isotopes ($\delta^{18}O$) have been used to estimate the mass fraction of snow in sea ice (e.g. Lange et al., 1990; Jeffries et al., 1994).

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Furthermore Palosuo (1963) assumed that snow-ice formation was alone responsible for the high upward thickness growth. Recently superimposed ice formed of refrozen snow (e.g. Haas et. al., 2002) has been observed in Antarctic waters. The use of detailed textural and $\delta^{18}O$ properties of ice layers can help in interpreting the growth history and origin of these layers (e.g. Haas et al., 2001).

This paper draws together the results from recent studies in the Baltic Sea landfast sea ice region that used detailed textural and $\delta^{18}O$ observations of sea ice, snow and under-ice waters to estimate the contribution of snow (precipitation) to sea ice growth in the area (Kawamura et al., 2001; Granskog et al., 2003b; Granskog et al., 2004). Some preliminary results from Baltic Sea pack-ice is also reported (unpublished data, M. A. Granskog, 2002; Ikävalko et al., this volume).

METHODS

The methods used are described in detail in Granskog et al. (2003b, 2004). In short the textural and stable oxygen isotopic composition ($\delta^{18}O$) of ice layers were used to distinguish meteoric ice layers from other ice layers. The mass fraction of snow (or meteoric ice fraction) in sea ice was estimated using the isotopic mass balance equations of Jeffries et al. (1994) as described in Granskog et al. (2003b).

Granskog et al. (2003b) studied the textural and oxygen isotopic properties of landfast sea ice at 15 sites along the whole Finnish coast in spring 2000. Kawamura et al. (2001) and Granskog et al. (2004) studied the seasonal evolution of landfast sea ice salinity, texture and oxygen isotopic composition at one site in the Gulf of Finland in winters 1999 to 2001. Whilst the textural and isotopic properties of pack-ice in the Bothnian Bay was studied alongside some biological investigations in spring 2002 (see also Ikävalko et al., this volume).

RESULTS

The meteoric ice fraction along the Finnish coast in spring 2000 varied from 5% to 40%, with 21% on average (Granskog et al., 2003b), see also Table 1. While meteoric ice layers contributed 32% to the total ice thickness on average. This compares rather well to the observations of Palosuo (1963).

Large seasonal and interannual variations in ice thickness, salinity, and meteoric ice formation were observed in the Gulf of Finland (Granskog et al., 2004). From year-to-year the isotopic properties of the ice were very similar. Depending on season and year the meteoric ice fraction varied from 0% to 35% (Fig. 1). In winter/spring 1999 the meteoric fraction rose to 35% largely due to formation of superimposed ice (Kawamura et al., 2001; Granskog et al., 2004). At best about 20% of the total sea ice mass was estimated to be of superimposed ice origin in late spring 1999 (Granskog et al., 2004). In latter years (2000 and 2001) intermittent superimposed ice layers were observed, which to some extent were the results of refrozen rain at the ice surface.

Preliminary results of meteoric ice fractions in pack ice of the Bothnian Bay in spring 2002 showed values between 6% and 24% (Table 1). About one-third of the total ice thickness was generally composed of meteoric ice layers. This indicates that also in pack-ice meteoric ice formation is important for the development of the ice cover. Further studies in the pack-ice are although needed to assess the importance of different ice growth processes on the development of the sea ice cover.

Table 1. Summary of meteoric ice fractions in Baltic Sea ice

Study area	Time	Meteoric ice fraction (mass-%)	Remarks	Reference
Finnish coast, land-fast sea ice	Mar-Apr 2000	21	Average for all sites	Granskog et al. (2003b)
Gulf of Finland, landfast sea ice	Jan-Apr 1999	0 to 35	Seasonal development	Granskog et al. (2004)
Gulf of Finland	Jan-Apr 2000	0 to 20	As above	As above
Gulf of Finland	Jan-Apr 2001	0 to 20	As above	As above
Bothnian Bay, pack-ice	Feb and Apr 2002	6 to 24	Pack-ice	See Ikävalko et al. (this volume)

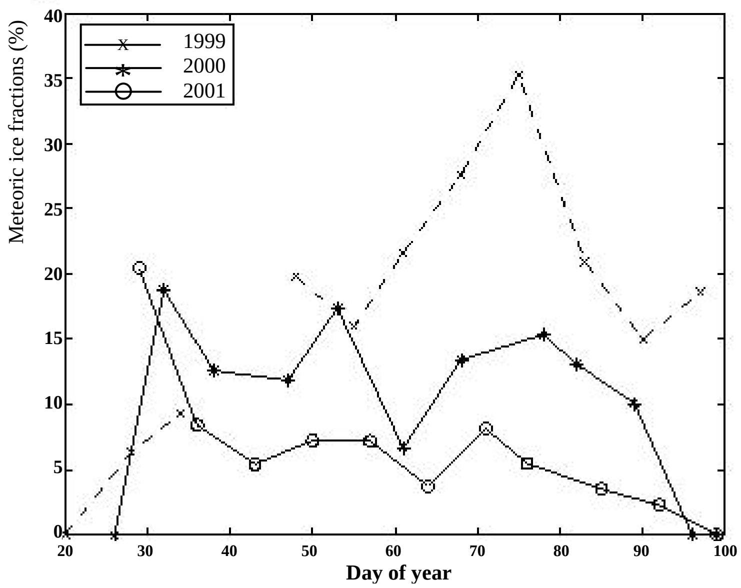

Fig. 1. Seasonal development of the meteoric ice fraction of landfast sea ice at a site in the Gulf of Finland. Data from Granskog et al. (2004)

CONCLUSIONS

Based on the above observations the role of snow (precipitation) is very important for the growth of Baltic Sea ice. This is also supported by the several modelling studies focusing on snow-ice and superimposed ice formation in the Baltic Sea (e.g. Saloranta, 2000; Cheng et al., 2003). Compared to other regions the contribution of meteoric ice seems higher in the Baltic Sea. For example in the subarctic Sea of Okhotsk the meteoric ice fraction has been estimated as 8% (Ukita et al, 2000).

The mild ice climate conditions in the area seem to support the formation of superimposed ice layers (Granskog et al., 2004). Melting and refreezing of surface snow but also refrozen rain contribute to superimposed ice formation (Granskog et al., 2004). Both aspects of superimposed ice formation should evidently be taken into account in sea ice modeling as well.

However, not only does the snow (precipitation) add to the mass of sea ice, but also strongly affect the nutrient budget of the ice cover, and also under-ice water layers during periods the ice is permeable (Granskog et al., 2003a). The control of the nutrient status of Baltic Sea ice by atmospheric deposition needs also to be further investigated. Also the trace metal geochemistry of sea ice is affected by atmospheric deposition and hence snow ice formation plays a major role in this as well (Granskog and Kaartokallio, 2004).

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HORIZONTAL VARIATIONS IN BIOGEOCHEMICAL CHARACTERISTICS OF LANDFAST SEA ICE IN THE GULF OF FINLAND (THE BALTIC SEA)

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ABSTRACT

In order to study the mesoscale variation in ice properties, horizontal variation of first-year landfast sea ice properties was investigated in the Gulf of Finland, the Baltic Sea. Several scales of variation were considered; samples at spacing of 0.2-, 2- and 20-m were sampled at several locations at different stages of the ice season. Spacing between these locations varied from hundreds of meters to kilometers. The variables measured included salinity, stable oxygen isotopes ($\delta^{18}O$), chlorophyll-*a*, nutrients, and dissolved organic carbon (DOC). Analyses of the data from the arrays did not show evidence of significant patchiness at scales <20-m. On scales of hundreds of meters to kilometers there was clear patchiness in several parameters (salinity, chl-*a*, snow depth and ice thickness). The results imply that the sampling effort in Baltic Sea ice studies should be concentrated at scales of hundreds of meters to kilometers.

INTRODUCTION

The patchiness of sea ice properties has been demonstrated in both the Arctic and Antarctic (e.g. Tucker et al., 1984; Eicken et al., 1991). In the cases of salinity and algae biomass this variation has been proposed to be linked to the variability in ice porosity (Eicken et al., 1991). However, for the horizontal patchiness of ice algae, snow depth is an important parameter, since the irradiance at the ice bottom is mainly controlled by snow depth (e.g. Gosselin et al., 1986; Robineau et al., 1997). Other factors that potentially control the patchiness of sea ice properties include latitude and large-scale processes of ice formation including, ice structure and growth rate and onshore-offshore salinity gradients in parent seawater (Swadling et al., 1997; Robineau et al., 1997).

Several issues make an investigation of the horizontal patchiness of sea ice in the Baltic Sea pertinent. For example, the attempts to calculate the contribution of sea ice to annual Baltic Sea primary production is hampered by lack of comprehensive temporal and

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spatial data. Furthermore the characteristics of sea ice in the Baltic Sea differ considerably from those in the Arctic or the Antarctic, since it is usually thinner and of considerably lower salinity (Granskog et al., 2003b). Baltic Sea ice also has usually a higher contribution of meteoric ice than sea ice elsewhere (Granskog et al., 2004, 2003a,b). Furthermore there are large variations in parent water characteristics, particularly along inshore offshore transects due to river runoff, that evidently affects the characteristics of the sea ice (Granskog et al., 2003a). The evaluation of data obtained through point sampling is made difficult if knowledge about the variability in the surroundings is lacking (e.g. Eicken et al., 1991). Therefore knowledge of the spatial variation helps in the extrapolation of discrete sample data to a larger context, increasing confidence in the extrapolation and also helping to direct the sampling effort to suitable scales (Swadling et al., 1997).

To address the evident lack in knowledge of Baltic Sea ice we undertook a pilot-study that covers meso (100-m to kilometers) and small (<20-m) scales. In the following section we describe the sampling and analysis methods. We follow with a description of the results and finally we discuss and conclude our findings.

MATERIALS AND METHODS

Sampling was conducted in February, March and April 2003 on landfast sea ice in the vicinity of the Tvärminne Zoological Station (University of Helsinki), located in the archipelago at the entrance to the Gulf of Finland, the Baltic Sea (Figure 1). Two sampling designs were used: Arrays with nine cores which were located at the apices of 0.2-m, 2-m and 20-m equilateral triangles, similar to that described by Eicken et al. (1991), were sampled at five occasions (Table 1). These arrays were located 50 m to 10 km apart (Figure 1). Table 1 summarises the measurements made in each array.

All sites were snow covered, although the sites were chosen (by eye) so that the snow was as evenly thick as possible. At each site ice thickness and snow depth was measured, and from one ice core the temperature profile was measured. Ice cores were taken using a MARK II corer (9-cm internal diameter; Kovacs Entreprise). The cores were immediately divided after retrieval as follows: Two five centimeter sections were cut from the bottom, the remaining was divided into 10 centimeter sections, with exception of the topmost section the length of which depended on the length remaining after all full 10 centimeter sections had been taken. The segments were cut using a stainless steel saw, and put into precleaned buckets with lids. Every effort was made to minimise brine drainage, and the elapsed time from the onset of coring until an individual section was segmented was usually less than 2 minutes, and considerably less for the bottommost sections. The samples were then melted at +4°C in the dark, and processed as soon as possible after they had melted completely.

Salinity was determined from the same melted samples using a temperature compensated conductivity meter (Schott handylab LF 1) and UNESCO (1983) algorithms. Brine volumes (%) were calculated according to Leppäranta and Manninen (1988) at high ice temperatures (>-2°C), and according to Frankenstein and Garner (1967) at lower ice temperatures. For $\delta^{18}O$ measurements water samples (0.5 ml) were equilibrated with CO_2 at +25°C. The oxygen isotope ratio of equilibrated CO_2 was measured on a mass spectrometer (Finnigan MAT Delta Plus XL) in continuous flow mode interfaced to a Gas Bench II. The $\delta^{18}O$ values are expressed as per mil relative to the V-SMOW standard (see e.g. Granskog et al., 2003a). The standard deviation of the $\delta^{18}O$ values for repeated measurements of laboratory reference water samples was better than 0.2 per mil.

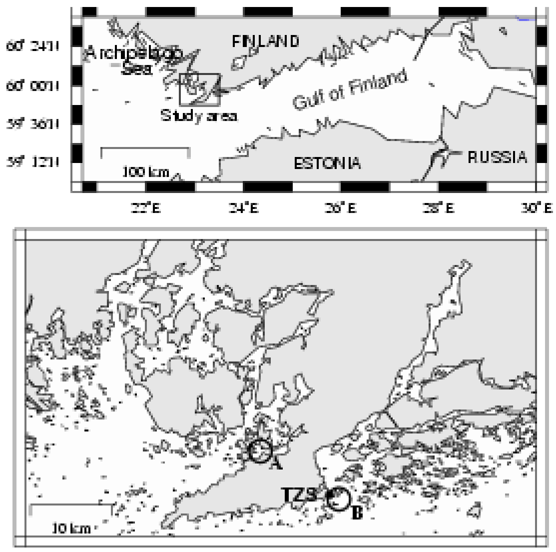

Fig. 1. (top) Location of the study area in the Gulf of Finland. (bottom) The location of the arrays (within circles). A denotes arrays sampled on 11 Feb and 17 Apr 2003, and B arrays sampled on 12 Feb, 15 Feb and 4 Mar 2003. The location of Tvärminne Zoological Station (TZS) is denoted with a small filled circle

Table 1. Analyses performed in the arrays sampled

Date	Ice thickness (cm, range)	Salinity	$\delta^{18}O$	Chl-a	Nutrients*	DOC
11 Feb	50-53	*y*	*y*	*y*	*y*	-
12 Feb	33-36	*y*	*y*	*y*	*y*	-
15 Feb	48-53	*y*	-	-	-	-
4 Mar	28-32	*y*	*y*	*y*	*y*	*y*
17 Apr	-	*y*	-	*y*	-	-

*Here *y* denotes that the measurement was made total nitrogen and total phosphorus

For chlorophyll-*a* (chl-*a*), determination 50-200 ml of thawed and a well stirred ice sample was filtered onto a GF/F glassfiber filters. The filters were placed in 10 ml of 96% ethanol and chl-*a* was extracted in the dark for 24 h. The extract was filtered through a GF/F filter and fluorescence was measured using a Perkin-Elmer LS 2B fluorometer calibrated against pure chl-*a* (Sigma). Chl-*a* concentrations were calculated according to HELCOM (1988). Nutrients were determined using a Quick Chem 8000 autoanalyzer (Zellweger Analytics) using standard seawater procedures (Grasshoff et al., 1983). Total organic and inorganic nitrogen (TN) and total organic and inorganic phosphorus (TP) were determined from unfiltered samples. DOC (dissolved organic carbon) was determined using high temperature combustion as described in Giannelli et al. (2001).

Statistical calculations were performed using the SAS software (SAS Institute Inc., NC, USA). Because much of the data was significantly different from normal ($p<0.01$; Shapiro-Wilk; SAS (1999)) relationships between parameters were studied using non-parametric Spearman rank-order correlation. A two-factor nested analysis of variance (ANOVA) was performed on the measured parameters (in the array data). In order to have normally distributed data some parameters were transformed (square root or $\log_{10}$) and the homoscedasticity of the data was verified using the Levene test (see SAS, 1999). The relative contribution of variance of each spatial scale (within and between arrays) towards the total variance was calculated from the untransformed data, and negative estimates were assumed to be zero (see also Swadling et al., 1997). Semivariograms (Cressie, 1993) were also computed for graphical interpretation of within and between array variations.

RESULTS

Figure 2 shows profiles of the mean and the standard deviation of salinity, $\delta^{18}O$, chl-*a*, nutrient and brine volume profiles for three of the sampled arrays. The average profiles show clearly that algal biomass (chl-*a*) and high brine volumes are confined to the bottommost section, since both showed characteristic L-shaped profiles in all cores. On the other hand $\delta^{18}O$ had its lowest values in the topmost layers, an indication of meteoric ice formation. Salinity and nutrients on the other hand showed quite variable tendencies, with relatively uniform vertical profiles. The emphasis of this report, however, is on the horizontal variations in sea ice properties at different spatial scales. As indicated in Figure 2 there are large variations especially in the bottommost ice sections for chl-*a* and brine volume (porosity), and in the surface layers for $\delta^{18}O$. Hereafter we look at the variations in the bottommost sections only, unless otherwise stated.

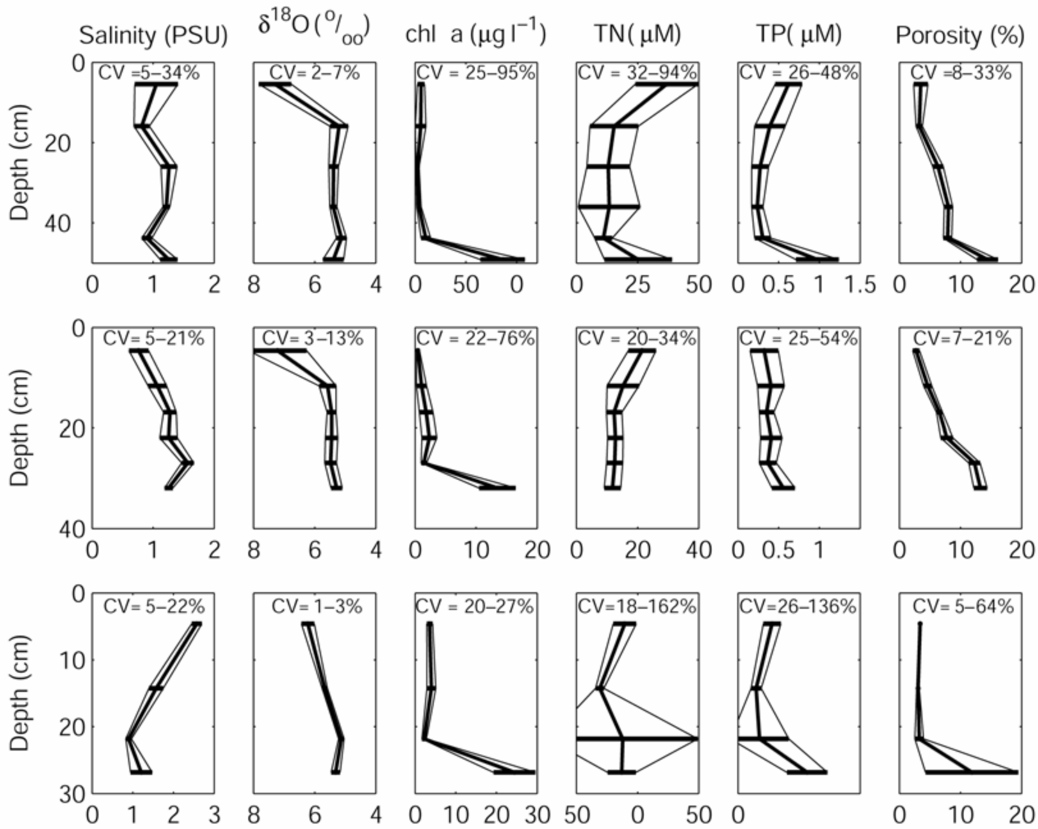

Fig. 2. Mean profiles and standard deviations for salinity, $\delta^{18}O$, chl-*a*, nutrient and brine volume (porosity) for arrays sampled on Feb 11th (top panels), Feb 12th (middle panels) and Mar 5th (bottom panels). In each panel the range of coefficient of variation (CV (%)) for individual depth levels is shown. Values are plotted at the average middepth of segments at each depth level

The standard deviations for salinity at individual depth levels within arrays (core spacing <20-m) range from 0.05 to 0.30 with a mean of 0.13 for all the sampled arrays. For the other parameters the corresponding values are; chl-*a* from 0.2 to 24.4 $\mu g\,l^{-1}$ and 2.1 $\mu g\,l^{-1}$, $\delta^{18}O$ from 0.1 to 1.0 per mil and 0.2 per mil, TN from 3 to 31 μM and 7.8 μM, TP from 0.10 to 0.85 μM and 0.21 μM, brine volume from 0.2 to 7.5% and 1.3%, DOC from 27 to 60 μM and 43 μM. Maximum differences for measured parameters in individual arrays are shown in Table 2. Salinity shows highest differences at all depth levels, TN and $\delta^{18}O$ in the surface layers.

Table 2. Maximum differences (MD) at individual depth levels within arrays (<20-m). The letter in brackets denote in what layer the MD was encountered, where t stands for topmost 10 cm, b for bottommost 5 cm and m for any of the layers in between

Array	Salinity	Chl-*a* ($\mu g\ l^{-1}$)	$\delta^{18}O$ per mil	TN μM	TP μM	DOC μM
11 Feb	0.90 (t)	36 (b)	1.6 (t)	42 (t)	0.9 (b)	-
12 Feb	0.50 (m)	8 (b)	3.2 (t)	19 (t)	0.6 (t)	-
15 Feb	0.42 (m)	-	-	-	-	-
4 Mar	0.84 (b)	15 (b)	0.6 (t)	97 (m)	0.8 (b)	184 (m)
17 Apr	0.57 (m)	-	-	-	-	-

Nested ANOVA revealed that there are significant variations on scales larger than a few hundreds of meters to kilometers (between arrays). Significant differences between arrays were found for salinity, chl-*a*, snow depth, and ice thickness (Table 3). No other spatial scale had significant effect, except for snow depth and ice thickness that showed significant variations within arrays. The contribution that each scale made to the total variance was computed (Table 4). Residual variances were generally low, except for TN and TP. Semivariograms of salinity and snow depth (not shown) indicate that patchiness in these parameters was of the order of a few hundred meters, as it was for ice thickness as well (not shown). Regrettably these were the only parameters measured in both of these arrays located 200 m apart. The same patchiness was obvious for chl-*a*, TN, TP, DOC, snow depth and ice thickness for the arrays located about 10 km apart.

Table 3. Summaries of analyses of variances for selected variables. Significant values at the 95% level are shown in bold

Source of variation	df	MS	F	P
	Salinity			
Between arrays	4	0.80	24.50	**0.0001**
Within arrays	10	0.03	1.61	0.1525
Residual	30	0.02		
	Chlorophyll-*a*			
Between arrays	2	2.99	49.34	**0.0002**
Within arrays	6	0.06	1.08	0.4089
Residual	18	0.06		
	Snow depth			
Between arrays	2	9.28	19.17	**0.0005**
Within arrays	8	0.48	4.77	**0.0013**
Residual	24	0.10		
	Ice thickness			
Between arrays	4	912.31	411.57	**0.0001**
Within arrays	10	2.21	2.20	**0.0462**
Residual	30	1.00		

Table 4. Variance components (percentage) calculated from the analyses of variance (untransformed data)

Source of variation	Salinity	Chl-*a*	TN	TP	Snow depth
Between arrays	78	80	9	42	71
Within arrays	4	0	48	9	17
Residual	18	20	43	49	12

Correlation coefficients between measured parameters in the whole array data set are shown in Table 5, Spearman rank-order correlation was used since the distributions were non-normal.

Table 5. Correlation coefficients obtained by Spearman rank-order correlation coefficients (non-parametric), those significant at the 99% level are in bold

	$\delta^{18}O$	Chl-*a*	TN	TP	Snow depth	Brine volume
Salinity	**-0.30**	**0.19**	-0.03	0.09	**-0.36**	**0.33**
$\delta^{18}O$		**0.23**	**-0.41**	-0.05	0.15	**0.32**
Chl-*a*			-0.04	**0.46**	**0.36**	**0.41**
TN				**0.65**	**-0.26**	-0.02
TP					-0.10	**0.37**
snow depth						**-0.22**

DISCUSSION

The observed variations are partly due to temporal changes, and not just due to spatial variations alone, since the arrays were sampled at different stages of ice development. However, even if all arrays were sampled simultaneously this could have been the case, especially if a large area is sampled where the development of the ice does not form and develop in unison over the whole area.

For salinity the variations at small scales are expectedly smaller than those observed in Arctic first-year sea ice, where Tucker et al. (1984) for five cores at 38 to 76 cm spacing found standard deviations from 0.20 to 0.78, with a mean of 0.39. However, the coefficient of variation (CV) that is of the order of 8% in Tucker et al. (1984) is higher in our data, between 11 to 32% for salinity at small-scales. The maximum salinity difference observed (0.9) at a certain depth level (Table 2) is very high when one relates it to the bulk salinity of the ice of 1.0. In comparison the maximum salinity difference of 2.0 observed by Tucker et al. (1984), with a ice bulk salinity of about 5. Also the other maximum salinity differences within the arrays (Table 2) are relatively high. This implies that there are larger horizontal variations of salinity in the low salinity Baltic Sea ice than observed in Arctic first-year sea ice.

The largest variability is evidently at scales larger than 20-m (except for snow depth and ice thickness), therefore the sampling effort in Baltic Sea ice studies should be concentrated on scales of the order of hundreds of meters or some kilometers. Why the variation in snow and ice thickness at small scales is not reflected in the chl-*a* (see also Robineau et al., 1997), remains to be investigated. Perhaps the snow cover present on the ice at the time of sampling does not necessary reflect the conditions during ice development, because short-term changes in the snow cover are often caused by external factors such as wind drift.

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17th International Symposium on Ice
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AIRBORNE EM SEA-ICE THICHNESS PROFILING OVER BRACKISH BALTIC SEA WATER

Christian Haas[1]

ABSTRACT

Helicopter-borne electromagnetic-inductive (EM) ice thickness measurements have been performed in February 2003 along the Finish Baltic Sea coast. Both, the Gulf of Finland and the Gulf of Bothnia were surveyed. Measurements have been performed with a small, two-frequency EM-Bird, a towed sensor suspended 20 m below the helicopter and operated 15 m above the ice surface. Results show that sufficiently accurate measurements were obtained even with minimum water salinities of 3 ppt in the Bay of Bothnia. Level ice thickness was in good agreement with information from ice charts. However, results also show the high degree of deformation of Baltic Sea ice, resulting in considerably higher mean ice thicknesses.

INTRODUCTION

In the EU-funded project IRIS (Ice Ridging Information for Decision Making in Shipping), led by the Ship Laboratory of Helsinki University of Technology, between 2003 and 2005 tools are developed for better detection and forecasting of sea ice pressure ridges, to support strategic ship navigation in ice infested waters. Detection and forecasting are mainly based on the use of satellite radar imagery and numerical model predictions. In order to validate remote-sensing ridge-detection algorithms and to support and validate model parameterizations of ridge formation and development, extensive ground-truth campaigns are performed to directly observe the frequency distribution of ridges and their temporal evolution. Because ridge distributions can only be described properly if large numbers of ridges are observed, airborne laser and electromagnetic-inductive (EM) thickness profiling are important components of the field programs. Although EM surveying does not yield the absolute thickness of pressure ridges (e.g., Kovacs and Holladay, 1990; Multala et al., 1996; Haas and Jochmann, 2003), their distribution and lateral extent, as well as their relative volume and temporal development can be well determined.

Here, we present results from the first airborne EM campaign performed in 2003. This campaign was performed as a pilot study for the main campaign planned for 2004. The main goals were the calibration of a new helicopter-borne EM sensor over brackish Bal-

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tic Sea water and a general assessment of the sea ice thickness distribution of the Gulf of Finland and Gulf of Bothnia.

MEASUREMENTS

After the pioneering work of Kovacs and Holladay (1990), airborne EM profiling has become an operational tool for sea ice thickness measurements, which is operationally used e.g. by the Canadian Ice Service (Prinsenberg and Holladay, 1993). With a fixed-wing aircraft EM system, Multala et al. (1996) have also performed thickness surveys over the Baltic Sea.

In short, an EM system consists of an assembly of coils for the transmission and reception of low-frequency EM fields and a laser altimeter. While the EM components are sensitive to the sensors height above the conductive sea water, the sensors altitude above the ice surface is determined with the laser altimeter. Over sea ice, the water surface coincides with the ice underside. Therefore, the difference of the height measurements of both components corresponds to the ice-plus-snow thickness. Because the low-frequency EM field is diffusive, its strength represents the some average thickness of an area of once or twice the instruments altitude above the ice surface. Due to this “footprint”, maximum ridge thickness can be underestimated by as much as 50% in the worst cases, depending on the geometry and consolidation of the ridge keel (Kovacs et al., 1995; Haas et al., 1997; Haas and Jochmann, 2003).

Together with industrial partners, Alfred Wegener Institute (AWI) has developed a small, lightweight helicopter-borne EM Bird. This is a 3.5 m long, 100 kg towed sensor suspended 20 m below a helicopter and operated at heights of 10 to 20 m above the ice surface. Due to its small dimensions, the bird is essentially platform independent and can be operated by any helicopter. The AWI bird operates at frequencies of 3.6 and 112 kHz, sensitive to the conductivities of sea water and sea ice, respectively. Coil spacing is 2.77 and 2.05 m for both frequencies, respectively, which is very short compared with conventional systems used in geophysical exploration. However, signal generation, reception, and processing are performed with a computer inside the bird and are thus fully digital, maximising signal-to-noise ratio. Sampling frequency is 10 Hz (laser altimeter: 100 Hz), corresponding to a measurement point spacing of approximately 3 m (0.3 m).

Figure 1 shows the flight tracks over the Baltic Sea surveyed between February 17 and 23, 2003. Both, the Gulf of Finland and the Gulf of Bothnia have been profiled, with salinities between 6 and 3 ppt corresponding to sea water conductivities between 600 and 300 mS/m, respectively. In total, 12 flights have been performed, each longer than 100 km.

Here, only results of the in-phase component of the low frequency signal are presented which is the strongest and most sensitive signal. Figure 2 shows measured and computed EM responses over the Gulf of Finland and Gulf of Bothnia, with salinities of 6 and 3 ppt, respectively. While measurements over open water agree well with model curves, the presence of sea ice leads to a reduction of the measured EM signal at the same laser height measurements, and therefore to a scattered cloud of data points. From the model curves and corresponding data, it can be seen that salinity has a strong impact on the amplitude and dynamic range of the EM signal. However, signals are still sufficient to resolve thickness changes of 0.1 to 0.2 m with a noise level of 10 ppm peak-to-peak. The open-water measurements with zero ice thickness in Figure 2 are used to derive an equation to transform the EM signals into a distance above the water surface (Haas and Pfaffling, in prep.). From these, the laser height measurement is subtracted to compute ice thickness. Ice thickness can therefore directly be obtained from the horizontal distance between EM measurement and model curve in Figure 2.

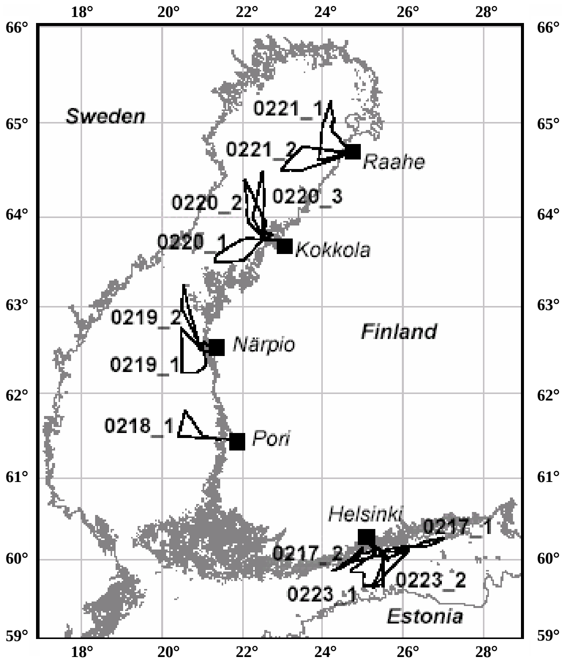

Fig. 1. Map of Northern Baltic Sea showing thickness flight tracks (see Table 1)

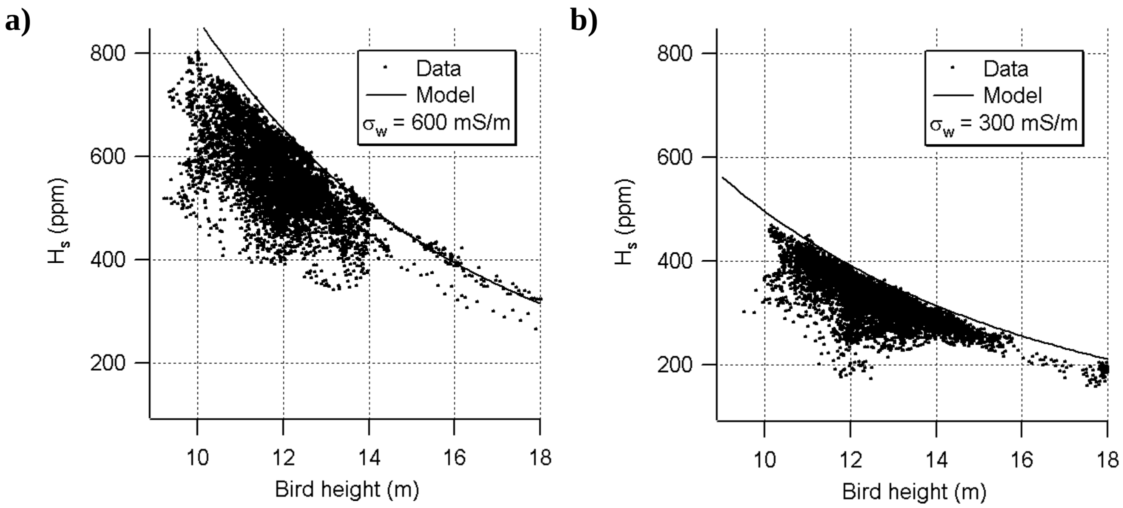

Fig. 2. Measured calibrated EM signal H_s (Inphase, 3.6 kHz) as a function of Bird height above the ice surface over the ice-covered (a) Gulf of Finland and (b) Bay of Bothnia

RESULTS

After early ice formation in 2002, the ice season 2002/2003 was more severe than average. In particular in the Gulf of Finland, ice navigation was severely hampered and became partially impossible. Table 1 summarizes the results of all thickness surveys. Flight labels mmdd_x correspond to the month mm (February), day dd, and flight number x (cf. Figure 1). Mean and typical thicknesses represent different ice regimes in the Gulf of Finland (Flights 0217_x & 0223_x), the Sea of Bothnia (0218_x, 0219_x), and the Bay of Bothnia (0220_x, 0221_x) very well. While the modes correspond well with typical ice thicknesses on Finish Ice Service ice charts, the table shows that the mean ice thicknesses can be much larger. This also explains the difficulties of navigation in the Gulf of Finland.

As an example, Figure 3 shows an ice thickness profile across the Gulf of Finland, from Estonia towards Finland, and a comparison with a Finish Ice Service ice chart. For flight-operation reasons, there was a gap between 38 and 46 km. A gradual thickness increase from the Estonian to the Finish coast can well be seen, corresponding to older ice towards the Finish coast due to prevailing south-westerly winds. The gradient is also suggested by the ice chart, showing only rafted ice on the Estonian side. However, our thickness data clearly show the presence of deformed ice with thicknesses in excess of 1 m in this rafted ice region. The typical level ice thickness of 0.6 m (Table 1, Fig.4), corresponds well to the upper thickness in the ice chart (Fig. 3). The obtained thickness distribution (Fig. 4) has another mode at 0 m, representing open water and very thin ice.

Table 1. Mean (± 1 standard deviation) and typical (mode) thickness for all 12 flights; cf. table 2 for more details

Flight	Mean, m	Mode, m
0217_1	1.65±1.51	0.5
0217_2	1.58±1.51	0.4
0218_1	0.35±0.47	0.3
0219_1	1.25±1.79	0.2
0219_2	1.81±1.88	0.6
0220_1	0.77±0.67	0.3
0220_2	0.95±1.24	0.6
0220_3	0.98±1.00	0.6
0221_1	1.84±1.52	1.1
0221_2	1.39±1.53	0.5
0223_1	0.92±0.88	0.6
0223_2	1.08±0.89	0.6

This was largely present in a flaw lead off the Finish coast, which was also accurately depicted by the Finish ice chart (Fig. 3). This polynya is also clearly visible in the thickness profile in Figure 3. That figure also shows that the fast ice adjacent to the northward edge of the polynya consists of very deformed, thick sea ice which has been attached to more level fast ice during a strong deformation event. This thick, deformed fast ice zone is clearly depicted on the ice chart as well, and seems to be typical for the majority of fast ice edges along the Baltic Sea coast.

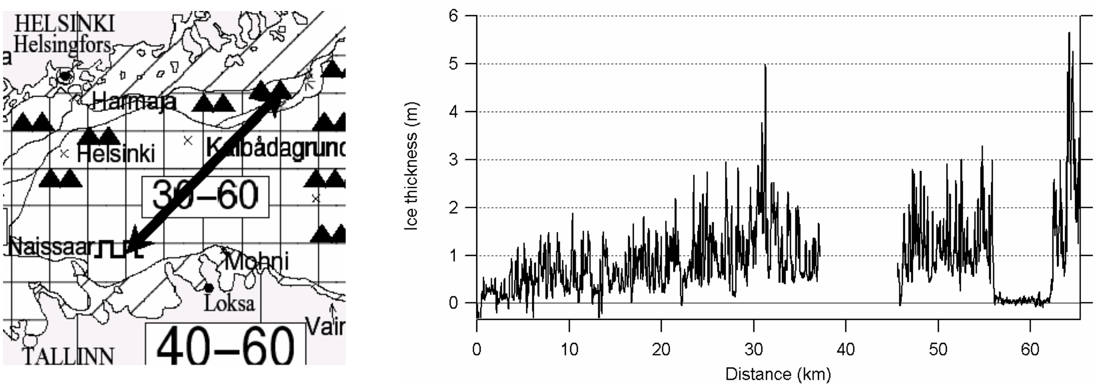

Fig. 3. Right: Ice thickness profile across the Gulf of Finland (from Estonia (left, southwest) to Finland (right, northeast)), obtained on February 23, 2003. Left: Ice chart of the same day, kindly provided by Finish Ice Service (Finish Institute of Marine Research, FIMR)

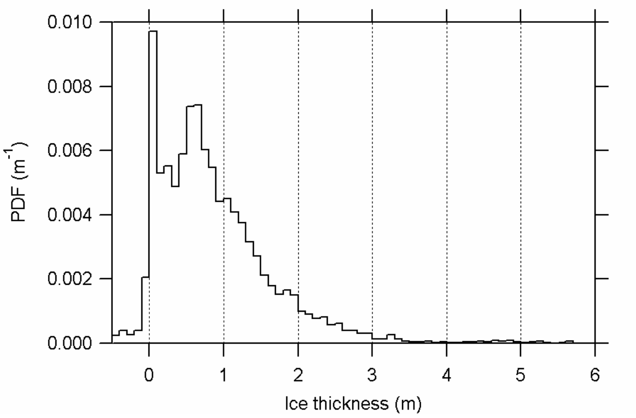

Fig. 4. Thickness distribution (probability density function pdf) of the thickness profile in Figure 3

DISCUSSION AND CONCLUSION

The results presented in this paper demonstrate the feasibility and gain of information obtained from airborne EM surveys in the Baltic Sea. Because details are hardly visible in plots of long profiles like those in Figure 3, Figure 4 shows an enlargement of a 10 km long section of the profile in Figure 3, revealing the degree of detail inherent in the data. Single keels and their lateral extent are clearly visible, although their maximum thickness is certainly underestimated. Comparison with ridge profiles obtained from the laser data will show the relation between these keels and the surface profiles. For example, the keels visible in Figure 4 suggest a mean keel density of 3-4 km^{-1}, which is relatively low compared with the visual impression of the ice surface. However, the lateral extent of the keels is quite large, as can be seen from the absence of larger level areas. This could explain the severe conditions for shipping.

Our measurements and visual observations during the flights confirm the high accuracy of Finish ice charts. However, our results also show that the mean ice thickness can be much larger than level ice thicknesses given in the charts. This demonstrates the importance of the IRIS projects, whose goal it is to quantify the ridging and deformed ice information in the ice charts.
In 2004, the IRIS project will perform an extended airborne and ground-truth campaign in the Bay of Bothnia, focussing on observations of the temporal evolution of the thickness distribution and the validation of satellite remote sensing ridge detection algorithms.

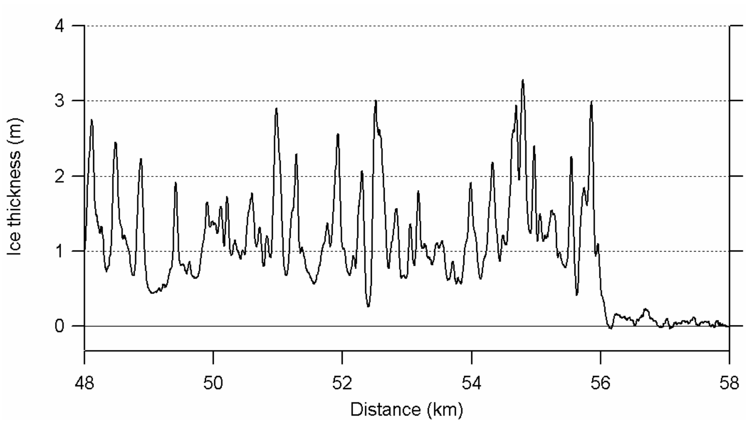

Fig. 4. Ten kilometre long section of the profile in Figure 3, adjacent to the prominent polynya at the right end of the profile

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Support by Mikko Lensu and Wolfgang Dierking during preparations and participation of the airborne campaign is greatly acknowledged. Professional Helitour Oy personnel made the airborne campaign a very enjoyable experience. David Flinspach processed most of the EM data. IRIS is EU project No. EVK3-CT-2002-00833.

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SEA ICE BIOTA IN THE NORTHERN BALTIC SEA IN FEBRUARY AND APRIL 2002

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ABSTRACT

Samples of drift and fast ice were obtained for the study of abiotic ice properties and biota in the Bothnian Bay during Feb 17 – 21, 2002 and Apr 8 - 12, 2002. Ice structure, $\delta^{18}0$ composition, nutrients (tot-N, tot-P), chl-*a* concentration, protists and metazoans of drift and landfast ice were analysed. A signifcant portion of ice was of meteoric origin. Nutrient concentrations, in particular tot-P, were always very low within ice. Chl-*a* concentrations doubled from February to April, and the concentration maxima were always in the bottom ice layers in April. The algal flora was significantly more diverse in drift than in landfast ice, and was dominated by chlorophytes and diatoms. Of the few metazoan taxa present within the ice, rotifers (*Keratella* spp.) were the most common with a maximum abundance 32 individuals l^{-1} melted ice.

INTRODUCTION

Large areas of the northern and eastern Baltic Sea are ice-covered each winter for 2-6 months, sometimes even longer. The water salinity is low particularly in the Bothnian Bay and eastern Gulf of Finland (salinity <3). The sea ice formation, however, takes place according to the same physical processes as described for polar sea ice (Palosuo 1961), and structurally sea ice with brine-channels penetrating the non-saline ice crystal component is formed. Brine cavities are unique habitats for rich sympagic communities consisting of bacteria, unicellular algae, proto- and metazoans (Norrman and Andersson 1994, Meiners and others 2002). While the groups of photosynthesising algae are to a large extent the same in the Arctic and the Baltic Sea (diatoms, cryptophytes, dinoflagellates, haptophytes, prasinophytes and euglenid flagellates) (Ikävalko 1997 and references therein), the sympagic meiofauna (here: metazoans > 20 µm) in the polar sea ice consists mainly of rotifers, copepods, nematodes and turbellarians (e.g. Friedrich 1997).

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In Baltic Sea ice, so far only rotifers and copepods have been recorded (Norrman and Andersson 1994, Meiners and others 2002, Werner and Auel in press).

The present study was carried out to describe the environmental conditions and biota of fast and drift ice in the Bothnian Bay in February and April 2002.

MATERIAL AND METHODS

Ice cores were drilled from fast ice and drift ice at 9 stations in the Bothnian Bay (Fig.1). At each site, an ice core was drilled for the study of ice structure and $\delta^{18}0$ oxygen isotope composition with a SIPRE-type ice auger (9 cm internal diameter). Ice structure, $\delta^{18}0$ composition and meteoric ice fractions were determined as described in Granskog and others (2003b).

At each sampling site, one ice core was drilled for the study of chl-*a* concentration, algae and heterotrophic protists (protist samples), and another for metazoans. Ice cores were cut into vertical sections of 2–11 cm thickness. The ice samples were transferred in plastic jars and polyethylene boxes to the laboratory onboard. Chl-*a* and protist samples were melted in GF/F filtered sea water, while metazoan samples were melted directly in darkness at +4 °C. For chl-*a*, 200-300 ml of each melted, unfixed ice sample was filtered onto a Whatman GF/F filter, and stored in 10 ml 96% ethanol and 20 ml glass scintillation vials in a –25°C freezer container onboard. In laboratory, chl-*a* was extracted by sonication (10 min) and incubating in room temperature for 24 h in darkness, and measured with a Shimadzu RF-5000 spectrofluorometer. Melted samples for protist studies were fixed with acid Lugol’s solution, and their species composition and abundance examined with an inverted Leica DMIL microscope, 12,5 x eye pieces and 40 x objective. Metazoan samples were concentrated on a 50 µm mesh and fixed with borax-buffered formalin (4% final concentration). Metazoan species and abundances were examined under a dissecting microscope (25-100x magnification).

Ice cores for nutrient analysis were obtained according to the sampling sampling procedure as for the study of ice biota (see above). Nutrient ice cores were stored in a freezer (-18 °C) until melted for analysis with a LaChat QC8000 autoanalyser according to Koroleff (1979) at the Finnish Institute of Marine Research.

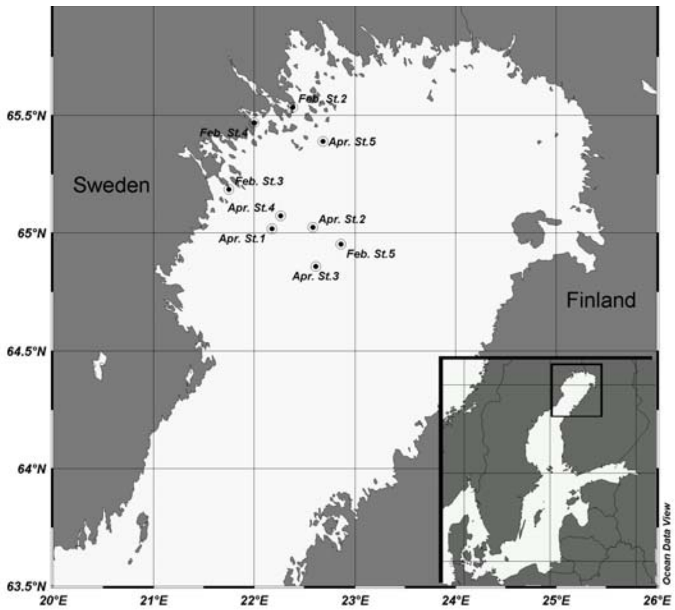

Fig. 1. Sampling sites in the Bothnian Bay, N Baltic Sea

RESULTS

ICE TEXTURE AND OXYGEN ISOTOPES

The texture and oxygen isotopic properties of sea ice samples showed very variable growth conditions. Granular ice, either meteoric (superimposed ice and/or snow-ice) or frazil ice, contributed significantly, about 1/3 of the total ice thickness on average. Based on isotopic properties, however, the majority of the granular layers were of meteoric origin, although some frazil ice was present in drift ice samples. The major part, 2/3 of the ice, was equally composed of intermediate granular columnar ice and columnar ice. Meteoric ice fractions by mass ranged between 5,6-23,4% of the total ice thickness.

NUTRIENTS

Total nitrogen (tot-N) in sea ice varied between 2.7-24.6 $\mu g/l^{-1}$, and total phosphorous (tot-P) 0-0.08 $\mu g/l^{-1}$ in February. In April, the respective concentrations were 3.5-29.4 $\mu g/l^{-1}$ (tot-N), and 0-0.16 $\mu g/l^{-1}$ (tot-P). Highest concentrations of tot-N were typically close to the upper surface of the ice cover, i.e. the ice-atmosphere interface. The only exception was recorded at station 2 in February, with a bimodal concentration peak of tot-N near the surfaces (upper and botttom) of the ice sheet. Concentrations of tot-P were always very low or below detection limit. The tot-N:tot-P ratio varied between 62-1600.

CHL

Vertical profiles of chlorophyll-*a* concentrations (chl-*a* mg l^{-1}) within sea ice are shown in Fig. 2. In February, the maximum chlorophyll value was close to 0.3 mg chl-*a* l^{-1}, observed in the bottom layer at station 1, and in the interior at station 3. In April, the chl-*a* maxima (approximately 0.6 mg chl-*a* l^{-1}) were always in the bottom layers of the ice cover (Fig. 2).

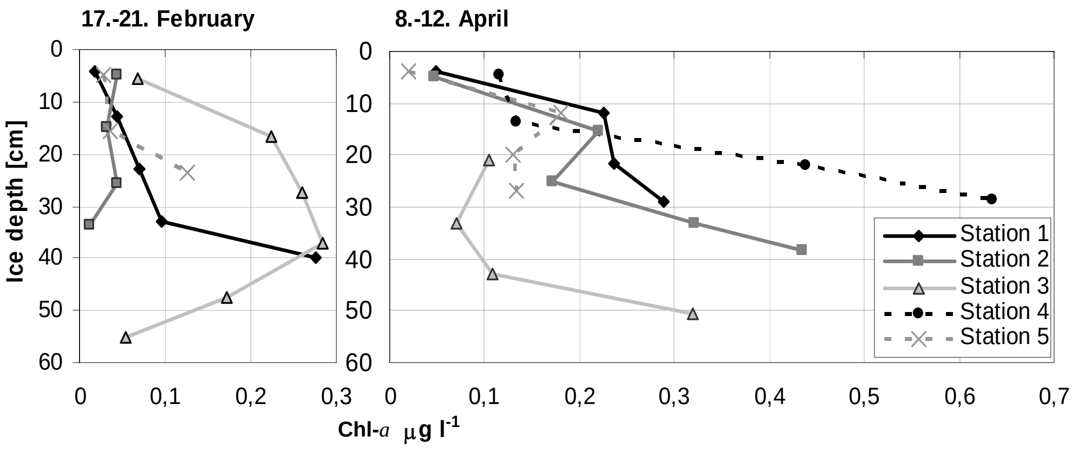

Fig. 2. Chlorophyll-*a* concentrations in sea ice in the Bothnian Bay in February and April 2002

SYMPAGIC PROTISTS

The most abundant algal groups (with examples of the most common taxa) were diatoms (*Melosira arctica*, *Navicula vanhoeffenii*, *Achnantes taeniata*), chlorophytes (*Monoraphidinium contortum*, further unidentified small coccoid chlorophytes), cryptophytes (*Rhodomonas lacustris*/*Chroomonas lens*), chrysophytes (*Dinobryon faculiferum*, *D. divergens*) and cyanophytes (*Merismopedia punctata*), (Fig. 3). In April, the abundance of nanoplanktonic heterotrophic flagellates increased significantly. The abundance maxima were always in or very near the bottom ice layer (Fig. 4.)

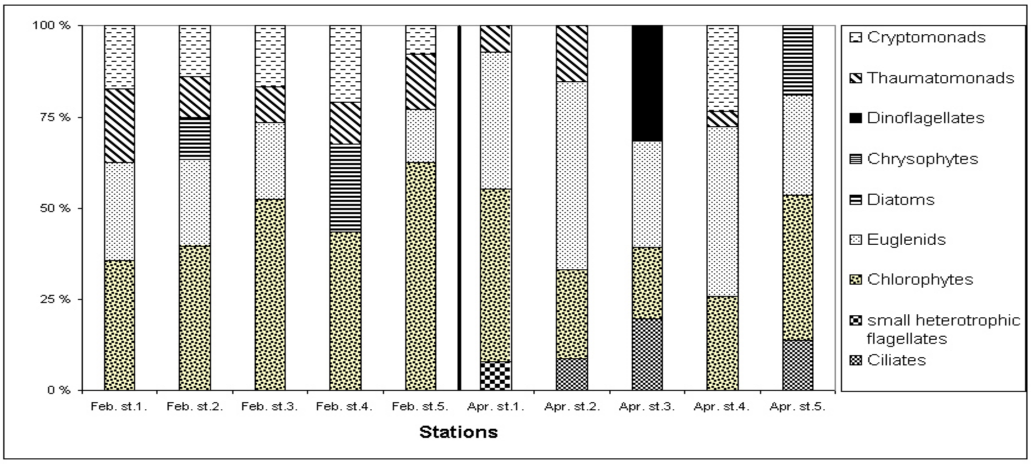

Fig. 3. The dominating sympagic protist groups and their relative abundance in sea ice in the Bothnian Bay in February and April 2002

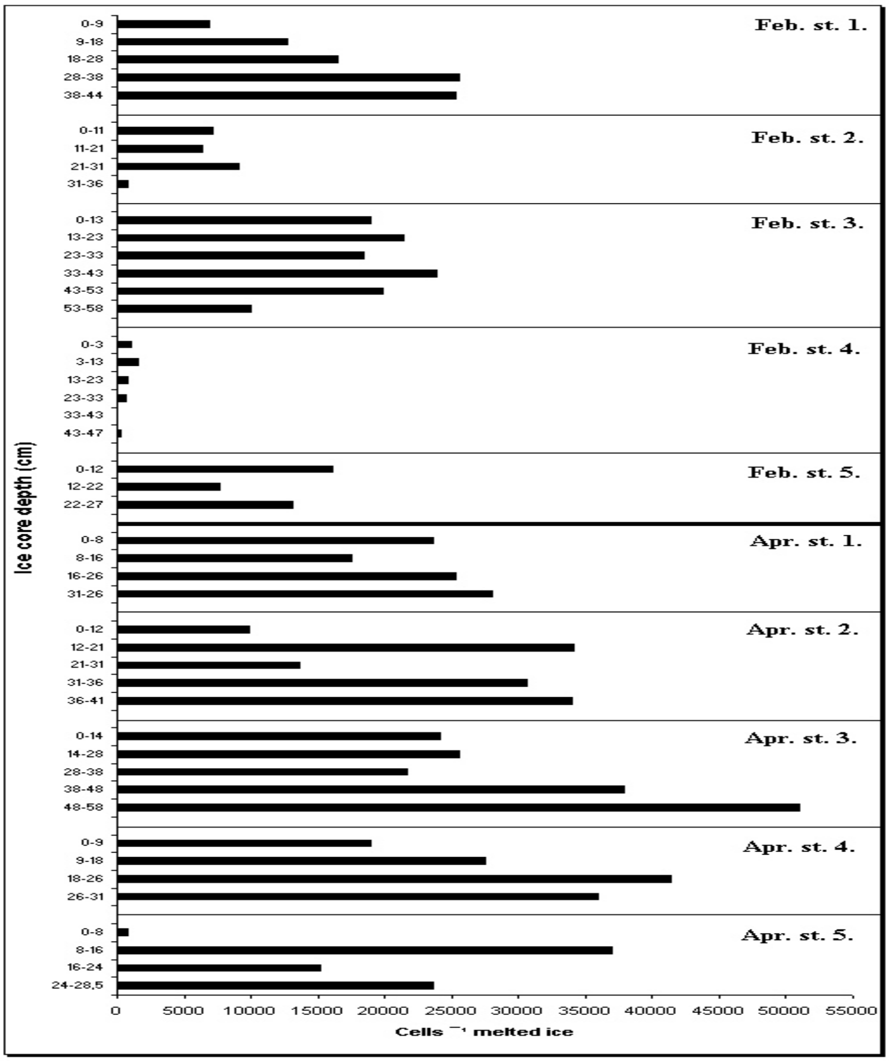

Fig. 4. Vertical distribution of sympagic protists within sea ice in the Bothnian Bay in February and April 2002

SYMPAGIC METAZOANS

Only four metazoan taxa were present in ice: rotifers *Synchaeta* sp., *Keratella quadrata* and *K. cochlearis,* and naupliar larvae and copepodids (CI–CIV) of the calanoid copepod *Limnocalanus grimaldii* (Fig. 5). However, copepods in the upper ice layers appeared to have died before our sampling. Metazoans were always clearly more abundant (by about one order of magnitude) in the ice than in water column (Werner, unpubl.). Rotifers dominated in the ice with abundances up to 32 individuals l^{-1} melted ice, apart from the fast ice station on Apr 12, 2002. Here, the abundance of copepod nauplii was 38 individuals l^{-1} melted ice in the lowermost ice layer. In fast ice, typical bottom communities of metazoans had formed. In drift ice no clear distribution pattern was observed (Fig. 5). In general, metazoan abundances were several times higher in fast ice than in drift ice, and increased in both habitats from February to April.

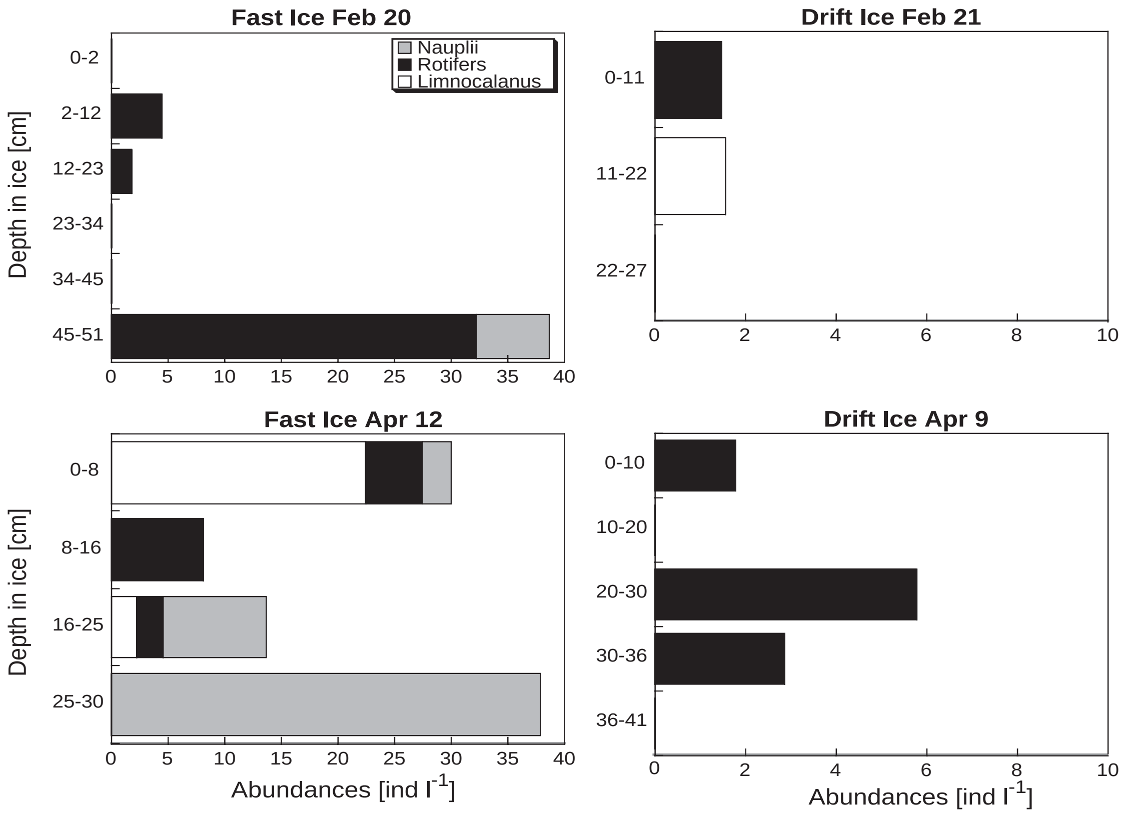

Fig. 5. Vertical distribution of sympagic metazoans in sea ice in the Bothnian Bay in February and April 2002

DISCUSSION

The meteoric ice fraction to total ice mass ranged between 5.6-23.4%. This shows the important role of snow in ice growth in the area (Granskog and others 2003b). The high concentrations of tot-N in in the upper layers of the ice sheet supports the observations of Granskog and others (2003a) where most of the nitrogen in sea ice is of atmospheric origin. The photosynthesis was phosporous limited in all depths of the sea ice at all times, which is reflected by very low tot-P and low chl-*a* concentrations in ice. Chl-*a* maxima developed in the bottom layers of ice from February to April. Near the ice-water interface, nutrients are transported from water column into the ice, which secures sufficient nutrient conditions for typically shade-adapted ice algae within the bottom ice layers, such as diatoms (Norrman and Andersson 1994, Meiners and others 2002).

Nanoflagelates (e.g. cryptophytes) can move within the brine pockets and thus seek for optimal light and nutrient conditions. The notable abundance of chlorophytes indicates the impact of fresh water inflow to the Bothnian Bay.

In contrast to polar sea ice rich in metazoans (Friedrich 1997, Schnack-Schiel and others 2001), Baltic Sea ice is colonized by few species of metazoans with low abundance. It seems that Baltic Sea ice is a suitable habitat for only a few pelagic rotifer taxa. Although the rotifer genera and partly species (*Synchaeta* spp., *Keratella* spp.), as well as their resting eggs, are common in sea ice in different regions in the Baltic (Norrman and Andersson 1994, Meiners and others 2002, Werner and Auel in press) their abundances are notably lower in the Bothnian Bay than in the Gulf of Finland. Nauplii and copepodids of calanoid copepods are found in the upper ice layers occasionally (*Limnocalanus grimaldii* in the Bothnian Bay, *Acartia bifilosa* in the Gulf of Finland). However, they are probably more likely trapped in the ice than actually thriving in this habitat. Metazoans in Baltic Sea ice contribute only 1% of the total sympagic biomass (Meiners and others 2002). This may be due to (1) the small brine volume and probably small diameter of channels due to low salinity of the water and ice (Granskog and others 2003a), or (2) the comparatively short duration of the ice covered season, and its perennial nature.

ACKNOWLEDGEMENTS

We are most thankful to Mr. Anders Backman who made it possible for us to use the icebreakers of the Swedish Maritime Administration as our sampling platforms. The crews of IB „Oden“ and IB „Atle“ are acknowledged for all their help and logistic arrangements during our sampling campaigns. The laboratory staff at the Tvärminne Zoological Station (Univ. of Helsinki, Finland) and the Finnish Institute of Marine Research helped us with the analysis of chlorophyll and nutrient samples. Funding was provided by the Walter and Andrée de Nottbeck Foundation.

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100 YEARS OF ICE OBSERVATIONS ON THE GERMAN BALTIC SEA COAST

Natalija Schmelzer[1]

INTRODUCTION

Ice climatological expert opinions are required for various construction projects at the baltic coast. Such reports containing information about the occurrence of ice, ice distribution, ice thickness etc, are provided in germany by bundesamt für seeschifffahrt und hydrographie upon request. Long-term ice observations at stations along the entire baltic coast are used as a basis for the studies. An analysis of ice observation data covering the past 100 years also allows conclusions on climate fluctuations and trends in the western and southern baltic sea.

INTRODUCTION

Ice services provide advice to shipping when coastal waters or open sea areas are covered with ice. The most important component in the organisation of an ice service is its network of observer stations. In Germany, about 80 ice observers at 55 stations on the North Sea coasts and 78 Baltic stations provide daily reports to the ice service on the ice situation and navigating conditions in their respective areas. The reports serve as a basis for ice reports and ice charts as well as ice climatological studies. Ice observations in Germany have been made routinely for more than 100 years now (since the winter of 1896/97). The long-term series of systematic observations at a large number of coastal stations provide valuable information on the year-to-year variability of ice conditions and possible periodic fluctuations of the ice coverage. In their joint compilation "I*ce conditions of the Baltic Sea during the last century" (Jevrejeva et al, 2002, 2003)*, colleagues from Finland, Russia, Estonia, Lithuania, Latvia, Poland, and Germany analysed the ice observation data from selected stations along the Baltic Sea coast. The data from the different Baltic areas were analysed individually and then compared with each other in order to identify common or different trends in the ice climatological development.

The analysis of ice conditions in the western and southern Baltic is based on data from 7 stations on the Baltic Sea coast: Eckernförde, Westermarkelsdorf, Unterwarnow, Warnemünde, Vierendehlrinne, Arkona, and Greifswalder Oie. The present study also

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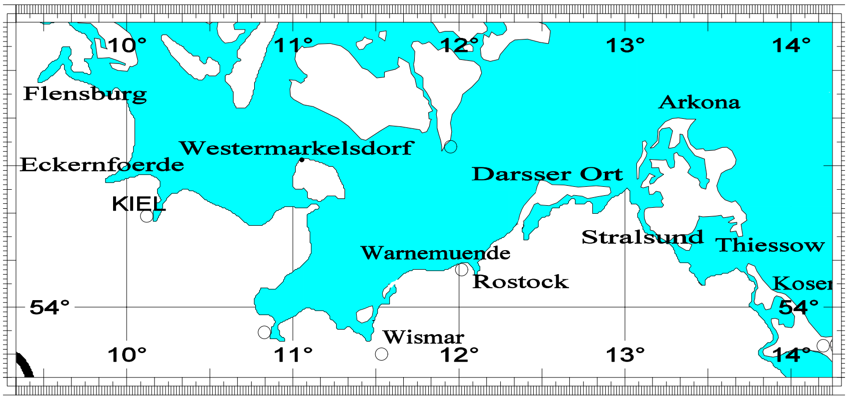
deals with the long-term development of ice conditions in another coastal region of the western Baltic, the inner Wismar Bight (53°55‘N 11°27‘E).



FREQUENCY OF ICE OCCURRENCE IN THE SOUTHWESTERN BALTIC SEA IN THE PERIOD 1901-2000 AND CLASSIFICATION OF ICE WINTERS

With its north-to-south extension of some 1,300 km, the Baltic Sea lies in two climate zones: moist, moderate climate in the southern and western parts, and moist climate with cold winters in the northern half of the Baltic (Schönwiese, 1994). This causes major differences in the development of ice coverage in the individual Baltic Sea regions. While the probability of ice occurrence in the north and east is 100 %, ice rarely occurs in the southern and western parts of the Baltic, with the exception of the inner coastal waters. Ice conditions in a particular area of the western and southern Baltic may differ considerably from one winter to the next. In several winters during the past 100 years, many areas were completely free of ice while in other years the Baltic Sea had a complete ice cover. Nevertheless, there are some characteristic common features to certain ice winters allowing them to be divided into different groups. Ice winters on the German Baltic coast have been classified into 5 main groups using a criterion introduced by Koslowski – the accumulated aria related ice volume (Koslowski, 1989). The accumulated aria related ice volume takes into account the length of the ice season as well as the ice thickness and extent in specified coastal sections. According to this classification, 4 extremely strong, 8 very strong, 10 strong, 39 moderate, and 39 mild ice winters occurred in the western and southern Baltic in the past century. It is interesting to note the distribution of the different classes of ice winters through the years (Fig.1). Mostly moderate ice winters occurred at the beginning of the past century. The percentage of mild and strong ice winters was low, and very strong or extremely strong ice winters were not recorded at all. Toward the end of the 20th century, we noted an increase in mild and very strong ice winters and a decrease in moderate ice winters. In the 9th decade, for example, there were 6 mild, 2 strong, and 2 very strong ice winters. Extremely strong ice winters are considered to be rather an exception in our latitudes. They occurred in 1939/40, 1941/42, 1946/47 and 1962/63. The category of mild ice winters also includes the ice-free winters, which have become much more frequent in the area of the inner coastal waters in the past 20 years (Fig. 2).

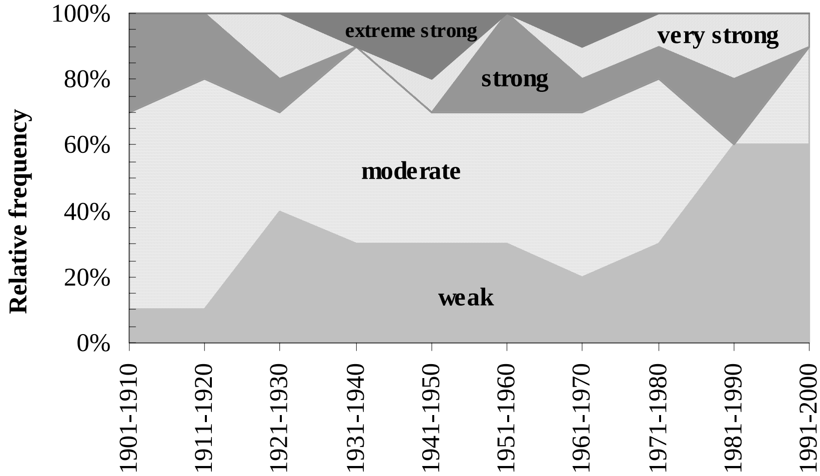


Fig. 1. Relative frequency of the ice winter classes in the western and southern Baltic

In the near-shore sea areas, the increase in ice-free winters during the same period is less conspicuous (see Fig. 3). On the open sea, major ice occurrence is only to be expected in very strong to extremely strong ice winters. Despite the trend toward milder winters which has been observed in the past 20 years, there have always been strong to very strong ice winters in between, with ice formation also reported at sea stations.

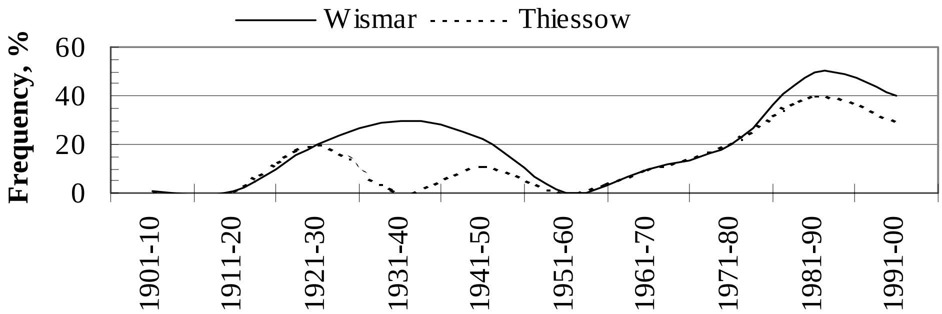


Fig. 2. Frequency of ice-free winters in the Wismar Bight and Greifswalder Bodden

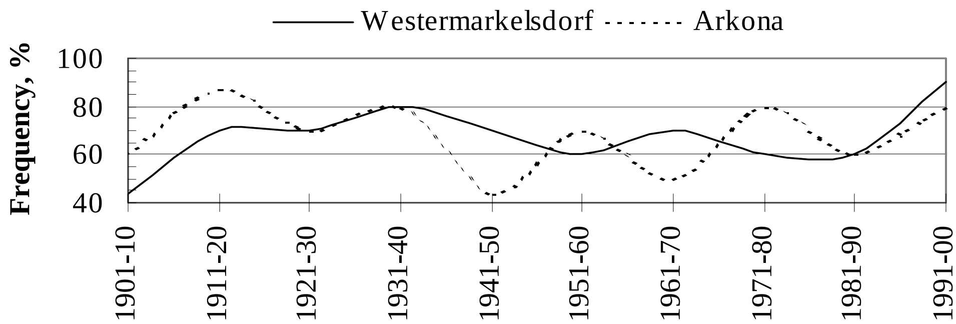


Fig. 3. Frequency of ice-free winters in the near-shore sea area

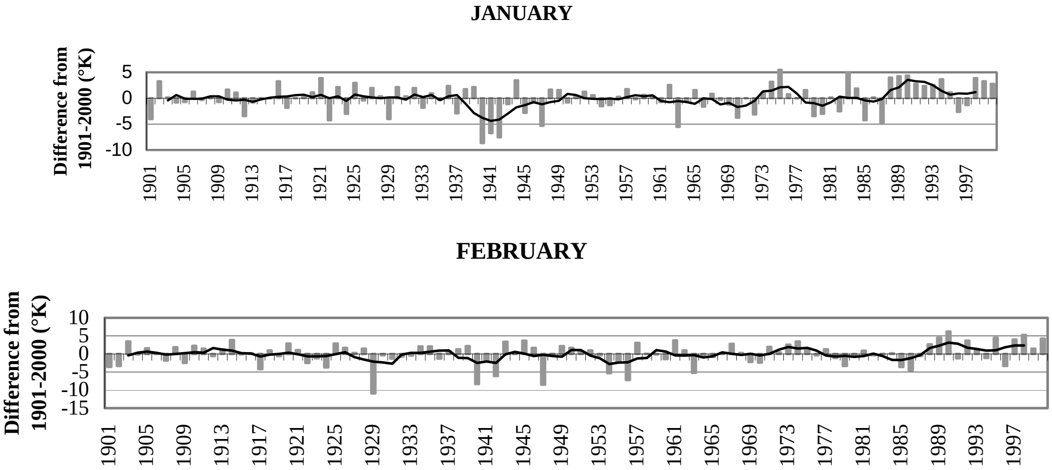


Fig. 4. Monthly means of air temperatures at the Rostock-Warnemünde station relative to the average of 1901-2000; the solid curve shows 5-year variations smoothed with a running mean.
(Data from Meteorologischer Dienst der DDR, Dienststelle Schwerin for the period 1901-1970 and from German Weather Service for the period 1971-2000)

The long-term change of ice conditions, especially in the protected inner coastal waters, reflects primarily changed air temperatures. Figure 4 depicts the monthly deviations of air temperatures from their 1901-2000 mean value at the Rostock-Warnemünde station. Rostock-Warnemünde is located a small distance east of Wismar Bight. However, in this discussion of long-term trends, the 100-year series at Rostock is considered to be representative of the Wismar area as well. The clearly positive trend of temperatures in the winter months of January and February during the past 20 years explains the increase in mild ice winters in the inner coastal waters.

LONG-TERM DEVELOPMENT OF ICE CONDITIONS ON THE GERMAN BALTIC COAST

To identify possible trends in the development of ice conditions, data covering a sufficiently long period must be available – the longer the period the better. The question is, however, how long such data series should be in order to ensure a realistic assessment of current ice conditions in a particular area.

Beginning of freezing and end of ice season (see Table 1 and Figure 5)
On average, ice winters in the Wismar Bight during the past 100 years have begun in the first ten days of January and ended in mid-February. During this period, there have been considerable variations in these ice parameters from one year to the next. In the second half of the century, the trend toward a later beginning and somewhat earlier end of ice occurrence was particularly obvious in the 1970s. However, this development was interrupted in the 9th decade. In the last decade, the average beginning of ice formation hardly differed from the 100-year mean value, and ice winters on average ended about one week earlier.

Table 1. Average data of the ice parameters in the inner ***Wismar Bight***

	Date of first ice, DD.MM.	Date of last ice, DD.MM.	Number of days with ice		Maximum of ice thickness, cm	
	(*)	(*)	all winters	(*)	all winters	(*)
1901-00	**07.01.±23**	**17.02.±30**	**27±30**	**33±30**		
1940-00					**14±17**	**18±17**
1901-10	28.12. ±17	16.02. ±27	37±27	37±27	-	-
1911-20	08.01. ±22	12.02. ±26	30±20	30±20	-	-
1921-30	29.12. ±30	14.02. ±33	37±36	46±34	-	-
1931-40	08.01. ±22	18.02. ±34	22±27	31±27	-	-
1941-50	09.01. ±22	27.02. ±31	34±44	44±48	18±22	24±22
1951-60	11.01. ±24	24.02. ±25	21±17	21±17	13±11	13±11
1961-70	15.01. ±30	17.02. ±31	23±33	26±34	14±19	16±19
1971-80	14.01. ±18	03.02. ±27	16±23	20±25	10±13	13±14
1981-90	30.12. ±12	01.03. ±41	28±36	56±32	16±19	26±19
1991-00	09.01. ±26	09.02. ±41	19±31	32±36	8±10	13±10
(*) only winters with ice						

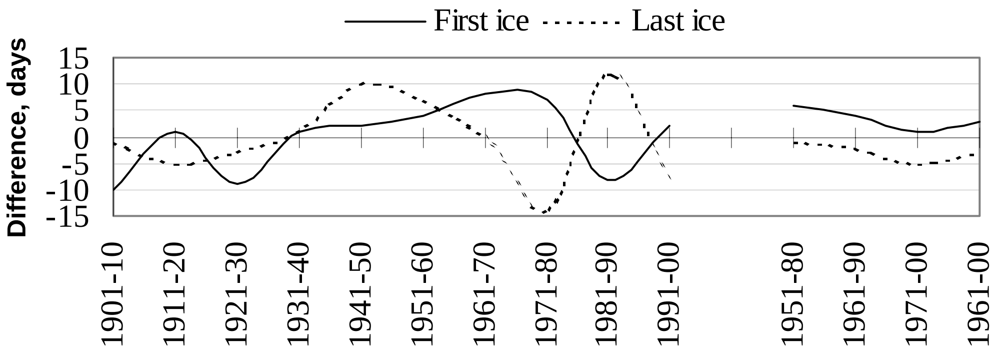


Fig. 5. Deviation from average of the beginning of freezing and end of the ice season in the inner ***Wismar Bight*** in the 1901-2000 period

Number of days with ice (see Table 1 and Figure 6)
Ice winters in the western coastal waters lasted about 30 days on average. Numbers of days with ice decreased noticeably in the second half of the period investigated. If one includes all winters in the analysis, the difference is about one week. The most favourable ice conditions, with a lower number of days with ice, prevailed in the 1930s, 1950s, 1970s, and 1990s. The winters with most ice occurred in the first third of the century as well as in the 1940s and 1980s.

Ice thickness (Table 2 and Figure 7)
Reliable ice thickness data have been available since the winter of 1940. Thermal ice growth is either measured (smaller bodies of water) or estimated (open sea, inner fairways). In winters with ice, ice thicknesses in the Wismar Bight in the period from 1940 to 2000 reached 18 cm on average. The most severe winters with higher ice thicknesses occurred in the 1940s and 1980s. The maximum ice thicknesses generally decreased toward the end of the study period.

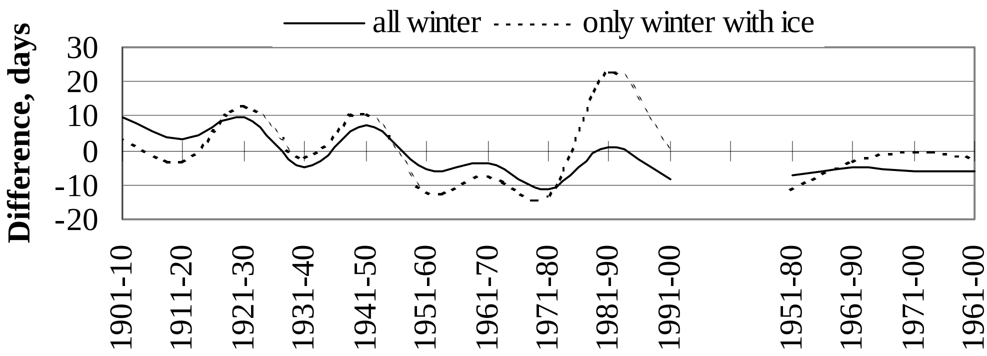


Fig. 6. Deviation from average of the number of days with ice in the inner ***Wismar Bight*** in the 1901-2000 period

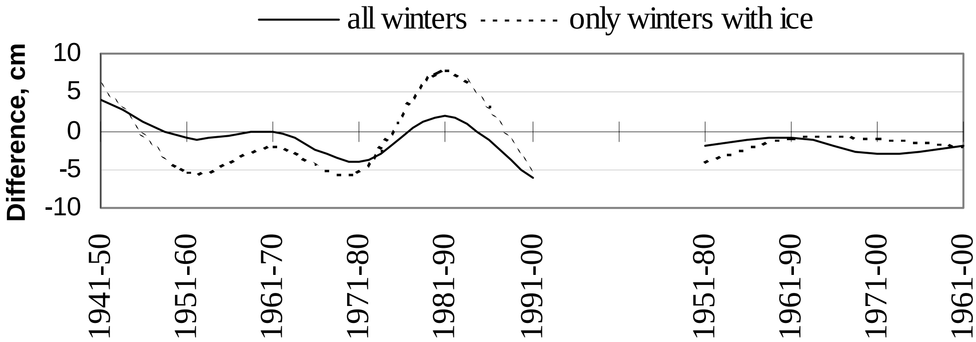


Fig. 7. Deviation from average of maximum ice thicknesses in the inner ***Wismar Bight*** in the 1941-2000 period

OPTIMAL DATA SERIES FOR ICE CLIMATOLOGICAL REPORT

As a basis for an ice climatological report, it is advisable to use a data series that describes the current ice situation optimally. Analogous to a meteorological normal series which covers 30 years, the ice data series should cover at least 30 years and should include all winter types with extreme parameters. The mean ice parameters for the last three normal series are compared in Table 2 and Figures 5, 6 and 7. A slight trend towards an earlier beginning and earlier end of ice occurrence is apparent. Taking into account all winters, the mean values of the normal series for the number of days with ice and maximum ice thickness are below the mean values of the 100-year data series. However, they hardly differ from each other. The mean values relating only to the winters with ice are similar to the mean values of the 100-year data series. Although the number of ice-free winters increased in the second half of the past century, the intensity of ice winters has increased as well. Strong to extremely strong ice winters are still likely to occur. The last time that extreme ice conditions prevailed in the southern Baltic was in the ice winter of 1962/63. In order to take into account the complete range of ice conditions, our ice climatological report has been based on the 40-year data series covering 1961 – 2000, which not only provides a good description of current ice conditions in the coastal waters but also includes extreme ice parameters.

Table 2. Average data of ice parameters in the inner ***Wismar Bight***

	Date of first ice, DD.MM.	Date of last ice, DD.MM.	Number of days with ice		Maximum of ice thickness, cm	
	(*)	(*)	all winters	(*)	all winters	(*)
1951-80	13.01. ±23	16.02. ±28	20±25	22±25	12 ± 14	14 ± 14
1961-90	11.01. ±23	15.02. ±32	22±31	30±32	13 ± 17	17 ± 17
1971-00	08.01. ±20	12.02. ±35	21±30	33±32	11 ± 14	17 ± 15
1961-00	**11.01. ±23**	**14.02. ±34**	**21±31**	**31±32**	**12 ± 16**	**16 ± 16**
(*) only winters with ice						

SUMMARY

Toward the end of the 20th century, more mild and more very strong ice winters were recorded in the western and southern Baltic than at the beginning of the century, while the number of moderate ice winters decreased. The frequency of ice free winters increased in the inner coastal waters but remained unchanged on the open sea.

Ice conditions in the western and southern Baltic vary considerably from one winter to the next. However, the largest variability of ice parameters in the inner coastal waters was observed in the second half of the 20th century. Taking into account all winters, the number of days with ice and the maximum thickness of level ice decreased. In the Wismar Bight, ice winters in the last 50 years have been 10 days shorter on average than in the preceding years.

On average, ice winters in the Wismar Bight at the end of the study period began about one week later than at the beginning of the period and ended only some days earlier, around mid-February.

Conditions favouring ice formation, caused by climatological cooling, prevailed in the period from 1900–1930, in the 1940s and 1980s. The shortest winters of the past century, beginning late and ending early and characterised by the lowest ice formation, corresponded to the climatological warming and occurred in the 1930s, 1970s, and 1990s.

For an ice climatological report, it is advisable to use a data series which optimally describes the current ice situation. It should cover at least 30 years and include all winter types with extreme parameters. We use the data from the 1961- 2000 period for this purpose.

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ANNEX 1

Ice climatological report for the inner Wismar Bight

To characterise ice conditions in the inner Wismar Bight, the ice data available at Bundesamt für Seeschifffahrt und Hydrographie (Federal Maritime and Hydrographic Agency), Hamburg and Rostock, for the station Timmendorf – Walfisch covering the period from 1961 to 2000 have been analysed.

During the 40-year observation period, the area between Timmendorf and Walfisch was completely ice-free in **12** winters, i.e. the relative frequency of ice occurrence in this area is **70 %**. Taking the average of all 40 years of observation, the mean number of days with ice per winter period is **21**. Considering only the winter seasons in which ice formation occurred, the mean value increases to **31** days. The number of days with ice varied considerably from one winter to the next, ranging from **1** day in the winter of 1983/84 to **98** days in 1995/96. The mean values of the beginning and end of ice occurrence shown in Table 1a relate exclusively to winters with ice. On average, the beginning of the ice winter has to be expected around **11 January**. As there are strong year-to-year variations in meteorological conditions, considerable scatter is observed in the dates marking the beginning of ice formation. For example, first ice may occur as early as **11 December**, as in 1998/99, or as late as **4 March**, which was the case in 1968/69. On average, the last ice melts in mid-February. The extreme values of this parameter also vary considerably: the earliest end of ice occurrence was recorded in 1997/98, on **13 December**, and in 1995/96 the last ice disappeared as late as **4 April**.

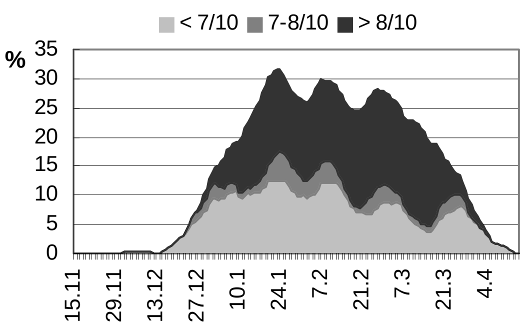

Fig. 1a. Distribution of ice concentration
Area: ***Wismar Bight, 1961 – 2000***

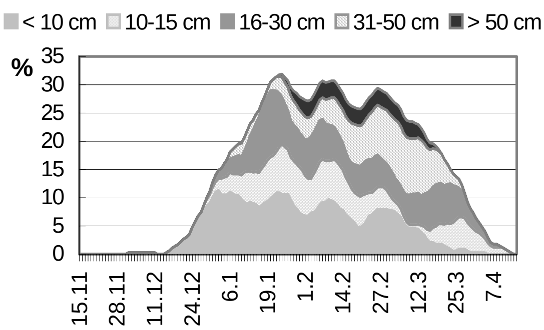

Fig. 2a. Distribution of ice thicknesses
Area: ***Wismar Bight, 1961 - 2000***

Table 1a. Mean and extreme data for the area Timmendorf-Walfisch in the 1961-2000 period

	Beginning	End		Number of days with ice	
				per winter	per ice winter
Mean:	**11 Jan.**	**14 Feb.**		**21**	**31**
Early:	11 Dec.1998	13 Dec.1998	Minimum:	0 several times	
Late:	4 March 1969	4 April 1996	Maximum:	98 in the winter of 1995/96	

Figures 1a and 2a show the distribution of ice coverage and ice thicknesses in the winter months (running 10-day mean). The outer curve represents the daily frequency of ice formation. The occurrence of ice in the Wismar Bight is most likely between **10 January** and **28 February**. The frequency distribution has several maxima, which is typical of the coast of Mecklenburg-Vorpommern and characterises our winter climate, with several freezing and thawing periods. In the period from 1961 – 2000, very thick to compact ice occurred at least as frequently as open to close drift ice. The ice data include predominantly ice thicknesses of less than 30 cm. Thicker ice was only recorded in strong to very strong winters. The maximum ice thickness of level ice observed in the extremely strong ice winter of 1962/63 was 64 cm. Compared to thermal growth of ice, breaking ice with subsequent rafting or ridging may cause ice thicknesses to increase considerably (to 50 to 100 cm) within a shorter period of time. A coincidence of several unfavourable conditions (breaking ice, certain current and wind directions) may lead to a rapid build-up of ice barriers that are up to 2 m high.