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Fourth Workshop on Baltic Sea Ice Climate

Norrköping, Sweden · 22–24 May, 2002

Conference Proceedings

Editors: Anders Omstedt and Lars Axell

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Sponsored and organised by SMHI, the SWECLIM programme, Göteborg University, and the Swedish Maritime Administration.

Cover image: Dr. Bertil Håkansson inspecting deformed ice in the Northern Quark near Vasa, Finland, during the BASIS-98 experiment. Photo by Maria Lundin, scanned by Stefan Gollvik.

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Preface

The Baltic Sea ice is strongly influenced by the atmospheric circulation and shows large interannual variability. At the same time the Baltic Sea is one of the most investigated regions on earth with long ice time series. To detect trends in climate change and to relate these to natural or anthropogenic causes are of central importance in the present Baltic Sea research. This was also the main topic during the Fourth Workshop on Baltic Sea Ice Climate held in Norrköping, 22-24 May, 2002. The workshop was organised by SMHI, the SWECLIM program, the Department of Oceanography at the Earth Sciences Centre of Göteborg University, and the Swedish Maritime Administration.

The workshop is a continuation of meetings every three years around the Baltic Sea. The First Workshop on Baltic Sea Ice Climate was held in Finland, 1993, the second in Estonia, 1996, and the third in Poland, 1999. During three intensive days, about 35 scientists and end users were actively participating in the workshop. The participants presented research activities in Canada, Japan, China, Finland, Estonia, Poland, Germany, and Sweden.

The main achievements since the last workshop in 1999 can be summarised as follows:

- New data sets are soon freely available, both due to the BALTEX/BASIS project and the measurements at ice station Santala.
- More long-term time series are now converted into digital form and analysed.
- We have now improved possibilities to get forcing data through the BALTEX data centres.
- More data on optical and ecological properties are being available.
- Improved modelling, both regarding process-oriented and two-dimensional sea ice modelling.
- Coupled air-ice-sea modelling has started.

We were also discussing some challenging research areas for the future, and the following topics were mentioned:

- Non-linear aspects of ice dynamics from engineering to geophysical scales.
- Clever, accepted, and simple statistical methods for trend and time series analysis.
- Better understanding and better modelling of low-frequency changes in the atmosphere on decadal (NAO) and centennial (Little Ice Age) time scales.
- To measure albedo and develop albedo models.
- Improved knowledge about the interaction of snow and ice.
- New ice data sets from the Baltic Sea including measurements on ice thickness distribution.
- Improved sea ice climate data bases.
- Increased understanding of how biota influence the physical properties in ice (e.g. optical properties)
- Increased understanding on how ice influences the ecological conditions.
- Better understanding of the skill in climate scenarios.

The next workshop will be held in 2005 in Hamburg. Until then, the meeting recommended that the following actions should be taken:

Action A: The IDA data base should be expanded with some long-term ice data series as illustrative examples from each country around the Baltic Sea. Responsible persons: Anders Omstedt and Christin Pettersen.

Action B: All who are interested should be invited to construct a future ice season for 2049/50 with ±15 years statistics. Responsible persons: Markus Meier and Lars Axell.

Action C: Next meeting should actively invite scientists from other marginal ice zone seas. Responsible persons: Corinna Schrum and Matti Leppäranta.

Anders Omstedt and Lars Axell

PARTICIPANTS

Standing: Sabine Hafner, Matti Leppäranta, Jouko Launiainen, Ralf Döscher, Burghard Brümmer, Henrik Lindh, Roy Jaan, Anders Backman, Hardy Granberg, Amelie Kirchgassner, Philip Lorenz, Marzenna Sztobryn, Torsten Seifert, Kunio Shirasawa, Jaak Jaagus, Bin Cheng, Christin Pettersen, Peedu Kass, Maria Lundin, Karin Borenäs

Sitting: Keguang Wang, Johanna Ikävalko, Corinna Schrum, Arvo Järvet, Jan-Eric Lundqvist, Markus Meier, Anders Omstedt, Lars Axell

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Optical properties of the system "ice cover +water" in different type of water bodies

Ants Erm and Anu Reinart

Marine Systems Institute, Tallinn Technical University, Estonia

1. Introduction

Physical properties of ice and concentrations of sediments and other impurities in the ice of the Baltic Sea and some Finnish lakes were studied by *Leppäranda et al.* (1998 a, b). Optical properties of ice, which determine the penetration of solar radiation into under-ice water, have been investigated mostly for the Arctic and Antarctic ice cover (*Arrigo et al.* 1991, *Allison et al.* 1993, *Perovich* 1996). Field works for estimation of the optical properties of the Baltic Sea ice for remote sensing purposes started some years ago (*Rasmus et al.* 2002). Radiative and other characteristics of the ice cover have been measured during several years in Santala Bay (Finland) by Finnish and Japanese scientists (*Kawamura et al.* 2000 and *Leppäranta et al.* 2002 a). Optical and hydrophysical investigations in winter conditions have also been performed in the Santala Bay and in some Estonian lakes by *Leppäranta et al.* (2002 b) and *Erm et al.* (2002 a).

As known, there is a principal difference between the sea and lake ice. The sea ice contains ice crystals, gas bubbles, particles from air and water, and also brine channels where phytoplankton may grow even in winter conditions. Opposite to the sea ice, the lower part of fresh-water lake ice is typically clear and pure. Snowfall, wave action and air temperature during freezing processes determine the structure of ice sheet.

2. Investigation objects and methods

The out-door and laboratory investigations of the brackish water Santala Bay in Finland and also four Estonian lakes (Ülemiste, Harku, Maardu, Paukjärv) were performed within three winters (2000-2002). These lakes, characterized by different depth, transparency and trophic state, were investigated in each vegetation period since 1997 (*Arst et al.* 2002, *Erm et al.* 2002 b). The main purpose of our winter studies was to determine the influence of the optically active substances (OAS) to the optical properties of ice cover and the forming of the under-ice light field in different types of ice+snow cover.

The *in situ* works consist of fixing the ice/snow thickness (z_i and z_s), collecting water and ice samples and measuring the irradiance E_d (in the PAR region of the spectrum) above and below the ice cover. A special device was built to measure the light field under ice (Fig.1). This device in its "compact form" (the consoles (2) are alongside the telescopic probe (1)) is lowered in the water through a 30-cm hole in the ice and fixed on the tripod (3). Then the consoles by means of cords will be positioned across the probe (1). After that with changing the length of the probe and angle of legs of tripod, the necessary depth of measurements will be arranged. Two radiation sensors are used in this system: LI-192 SA and LI-193 SA (*LI-COR*, inc. USA): the first for measuring the plane irradiance, the second for scalar irradiance in the photosynthetically active region (PAR) of spectrum (400-700 nm). Both sensors are calibrated in the units µmol s^{-1} m^{-2} (1 µmol s^{-1} m^{-2} $=6.022*10^{17}$ photons s^{-1} m^{-2}) calibration coefficients being different for air and water measurements. Our measuring system allows taking the records at the distance about 1 m from the ice-hole in the horizontal direction and at different depths under ice down to 2.25 m. During mesurements the device is lowered down and then lifted up.

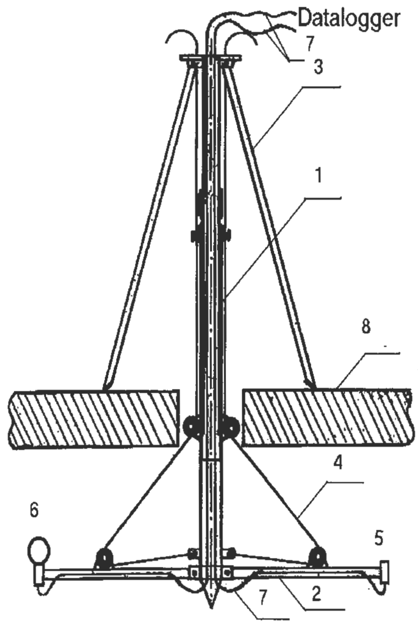

Figure 1: Device for under ice light field measurements. (1) telescopic probe, (2) console, (3) tripod, (4) cord, (5) plane sensor (LI-192 SA), (6) spherical sensor (LI-193 SA), (7) underwater cable, (8) ice layer.

The values of albedo were determined by two additional LI-192 SA sensors: one for measuring the incident irradiance and second for the backscattered from the snow or ice cover irradiance.

As a first step, the surfaces of the ice samples were photographed. After that the ice samples were melted (the whole sample or distinctive layers separately). The water and meltwater samples were filtered and the spectra of light attenuation coefficient ("spectrometric" attenuation coefficient by *Arst et al.*1999a) measured by spectrophotometer Hitachi U1000 ($c^*(\lambda)$[1/m] and $c_f{}^*(\lambda)$[1/m], respectively for unfiltered and filtered water). From the water and meltwater samples the concentrations of suspended matter and chlorophyll *a* (C_s[g/m^3] and C_{chl}[mg/m^3]) were determined in the laboratory. Relying on the spectral values of filtered water the effective concentration of yellow substance $C_{y,e}$ [g/m^3] was estimated by the equation (*Højerslev* 1980, *Baker and Smith* 1982, *Mäekivi and Arst* 1996):

$$a_y(\lambda) = a`_y(\lambda_o)C_{y,e}\exp(-S(\lambda - \lambda_o)), \qquad (1)$$

where $a`_y(\lambda_o)$ (0.565 L mg^{-1} m^{-1}) is the specific absorption coefficient of the yellow substance at the reference wavelength λ_o (380nm) and S (0.017 nm^{-1}) is the slope parameter.

The concentration of suspended matter was determined by its dry weight after filtering the water through cellulose acetate filters (pore size 0.45 μm). The same filters were used also to determine the values of $c_f^*(\lambda)$. The amount of chlorophyll *a* was determined by filtering the water samples through Whatman GF/C glass microfibre filters (pore size 1.2 μm), extracting the pigments with hot ethanol (90%, 75°C) and measuring the absorption at the wavelengths of 665 and 750 nm. The concentration was calculated by the *Lorenzen* (1967) formula.

3. Results and discussion

3.1 Ice cover and underwater light field

Before the sunlight reaches water under the ice cover, its intensity decreases due to backscattering from snow or ice and attenuation in snow and ice. We could measure the incident irradiance (E_{d+}), backscattered from snow and ice irradiance (E_{bs} and E_{bi} subsequently) and downward irradiance in several depths of the water column ($E_{dw}(z)$) down to 2.25m. From these data it is possible to calculate at first the albedo of snow (A_s) and ice (A_i):

$$A_s = E_{bs} / E_{d+}, \tag{2}$$

and

$$A_i = E_{bi} / E_{d+}. \tag{3}$$

Values of albedo were very variable (see Table 1), depending on the snow and ice conditions (we got the limits 0.1-0.8).

Relying on $E_{dw}(z)$ measurement data the vertical diffuse attenuation coefficient of light $K_{dw}(z_1,z_2)$ can be determined by well-known relationship (*Dera* 1992, *Arst et al.* 1999 a):

$$K_{dw}(z_1,z_2) = 1/(z_2-z_1) \ln [E_{dw}(z_1)/E_{dw}(z_2)]. \tag{4}$$

Correspondingly, in case of a vertically homogeneous water column

$$E_{dw}(z) = E_{dw}(0) \exp(-K_{dw} z). \tag{5}$$

Here $K_{dw}(z_1,z_2)$ is determined for the layer between the depths z_1 and z_2, $E_{dw}(0)$ is the measured irradiance in the depth 0m, i.e. just under the ice cover. The averaged over the depth values of the attenuation coefficient K_{dw} can be estimated by semilogarithmic plot of $E_{dw}(z)$ vs. z.

Table 1: Average albedo (A_s and A_i) in the PAR region for snow and ice cover (averaging based on 20-55 separate readings)

Water body	Date	Description	A_s (st. dev.)	A_i (st. dev.)
Harku	29.01.01	Smooth slick ice 19.5 cm, thin layer of snow	0.10 (0.0017)	0.08 (0.0013)
Harku	19.02.01	Smooth slick ice 22 cm, some snow patches	-	0.26 (0.0137)
Ülemiste	30.01.01	Snow 3-5 cm, ice 23 cm	0.82 (0.0030)	0.29 (0.0620)
Ülemiste	19.02.01	Dark ice 27 cm	-	0.19 (0.0164)
Ülemiste	16.03.01	Snow 2-3 cm, ice 30 cm	0.73 (0.0016)	-
Maardu	01.02.01	Snow 4 cm, ice 24 cm	0.81 (0.0019)	0.37 (0.0068)
Maardu	20.02.01	Slush 1 cm, gray aqueous ice 28.5 cm	0.18 (0.0089)	0.23 (0.0134)
Santala	05.02.01	Snow 0.5-1 cm, ice 25.5 cm	0.67 (0.0564)	0.56 (0.0129)
Santala	06.02.01	Heavy snowfall, snow 3-15 cm, ice 34 cm	0.83 (0.0065)	0.61 (0.0170)
Santala	28.02.01	Snow removed, ice 34 cm	-	0.54 (0.0052)
Santala 1	19.03.01	Gray ice 40 cm	-	0.30 (0.0175)
Santala 3	20.03.01	Hoarfrost on the ice, ice 40 cm	-	0.51 (0.0314)
Santala	02.04.01	Gray ice, some hoarfrost patches, ice 38 cm	-	0.40

Analogous to K_{dw} attenuation coefficients of the light in the ice cover (K_{di}) can be determined by the following way:

$$K_{di} = 1/z_i \ln [(1\text{-}A_i)\, E_{d+}/\, E_{dw}(0)]. \qquad (6)$$

It is a formal approach, because we are not sure about the character of the vertical distribution of the light in ice (exponential or not). The same approach can be used for snow cover (the respective light attenuation coefficient K_{ds}):

$$K_{ds} = 1/z_s \ln [(1\text{-}A_s)\, E_{d+}/E_d(z_{is})]. \qquad (7)$$

z_i and z_s are respectively the thickness of ice and snow, and $E_d(z_{is})$ is the irradiance on the boundary between snow and ice. $E_d(z_{is})$ can be calculated by the equation (5) modified for ice under the snow cover :

$$E_d(z_{is}) = E_{dw}(0)\ \exp(z_i\ K_{di}). \qquad (8)$$

Some values of K_{dw} and K_{di} are presented in Table 2. As we can see, K_{dw} increases when snow is removed from ice. The reason is the different spectral composition of the irradiance under the ice cover in comparison to that when ice is covered by snow. As the result, the integrated over PAR wavelengths diffuse attenuation coefficient K_{dw}(PAR) may have different values, depending on snow and ice conditions.

Table 2: Averaged (by depth) diffuse attenuation coefficients of ice (K_{di}) and water (K_{dw}) in the PAR region of spectrum

Water body	Date	K_{di}	K_{dw}	Remarks
Harku	19.02.01	0.77	1.67	Ice without snow cover
Harku	15.03.01	3.2	4.56	Ice without snow cover
Ülemiste	30.01.01		0.88	Snow+ice
		1.07	1.15	Snow removed
Ülemiste	19.02.01	1.03	0.79	Ice without snow cover
Maardu	01.02.01		0.28	Snow+ice
		0.55	0.96	Snow removed
Maardu	20.02.01	3.26	0.81	Dark patch of ice
		1.07	0.74	Whitish patch of ice
Santala	05.02.01		0.53	Very thin snow layer
		1.21	0.66	Snow removed
Santala	28.02.01	3.1	0.75	Ice without snow cover
Santala 1	19.03.01	5.2	1.38	Ice without snow cover
Santala 3	20.03.01	3.8	1.88	Ice without snow cover
Santala	02.04.01	2.0	0.76	Ice without snow cover

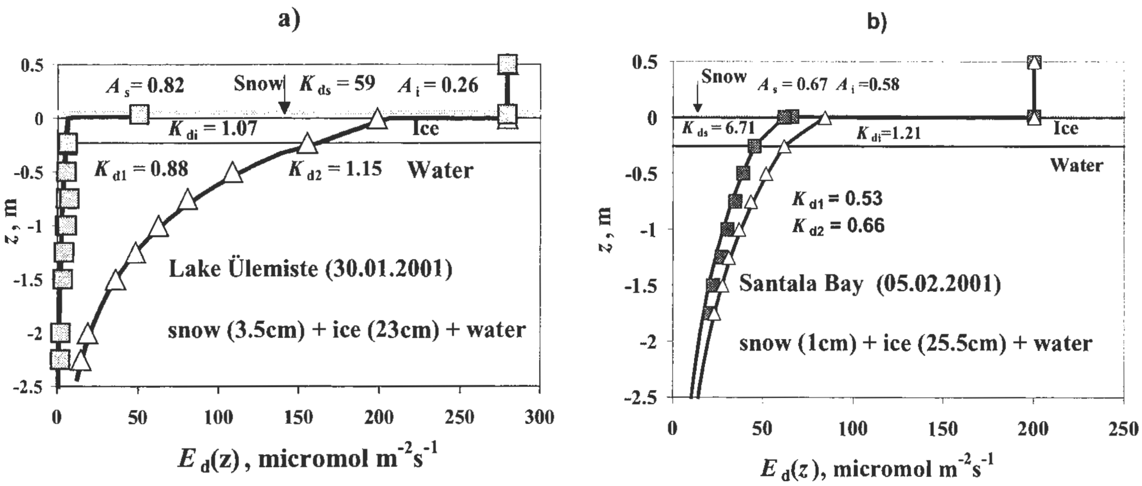

Figure 2: Measured (with snow cower – squares, without snow cover – triangles) and calculated (lines) light field in Lake Ülemiste (a) and Santala Bay (b).

Relying on Eqs.(5)-(8) it is possible to calculate the light field in ice and snow in both cases – with and without snow cover (assuming the dependence of K_{di} on snow cover to be negligible). Using the model, the light field in Lake Ülemiste (Fig. 2a) and in the Santala Bay (Fig. 2b) was calculated. As it can be seen, the under-ice light field is much more influenced by snow than by ice or water itself.

The great difference in K_{ds} values (59 m^{-1} on Lake Ülemiste and 6.7 m^{-1} on the Santala Bay) is surprising, but it can be explained by extremely different weather conditions. There was a warm (0°C) day on Lake Ülemiste, which means that snow was wet and tight. The day on the Santala Bay was could (-15 °C) and the ice was covered with white and slight snow.

3.2 Optical properties of ice and ice meltwater

The structure of ice is depending on the type of water body. Sea ice samples consisted of snow ice, congelation ice and brine channels (Fig. 3a). Lake ice was more homogeneous in Lake Paukjärv (Fig. 3d), but consisting of many distinctive layers in some other cases (Fig. 3 b,c). Besides, optically thicker layers may appear both at the top and inside the sheet of lake ice.

We had no technique to determine concentrations of OAS directly in ice, so we melted ice samples (by 20°C) and determined the concentrations of OAS and c^* from the meltwater samples both for the whole ice bulk and distinctive layers. As it can be seen (Fig.3) these distinctive layers accord to the variability of the OAS concentrations in ice meltwater.

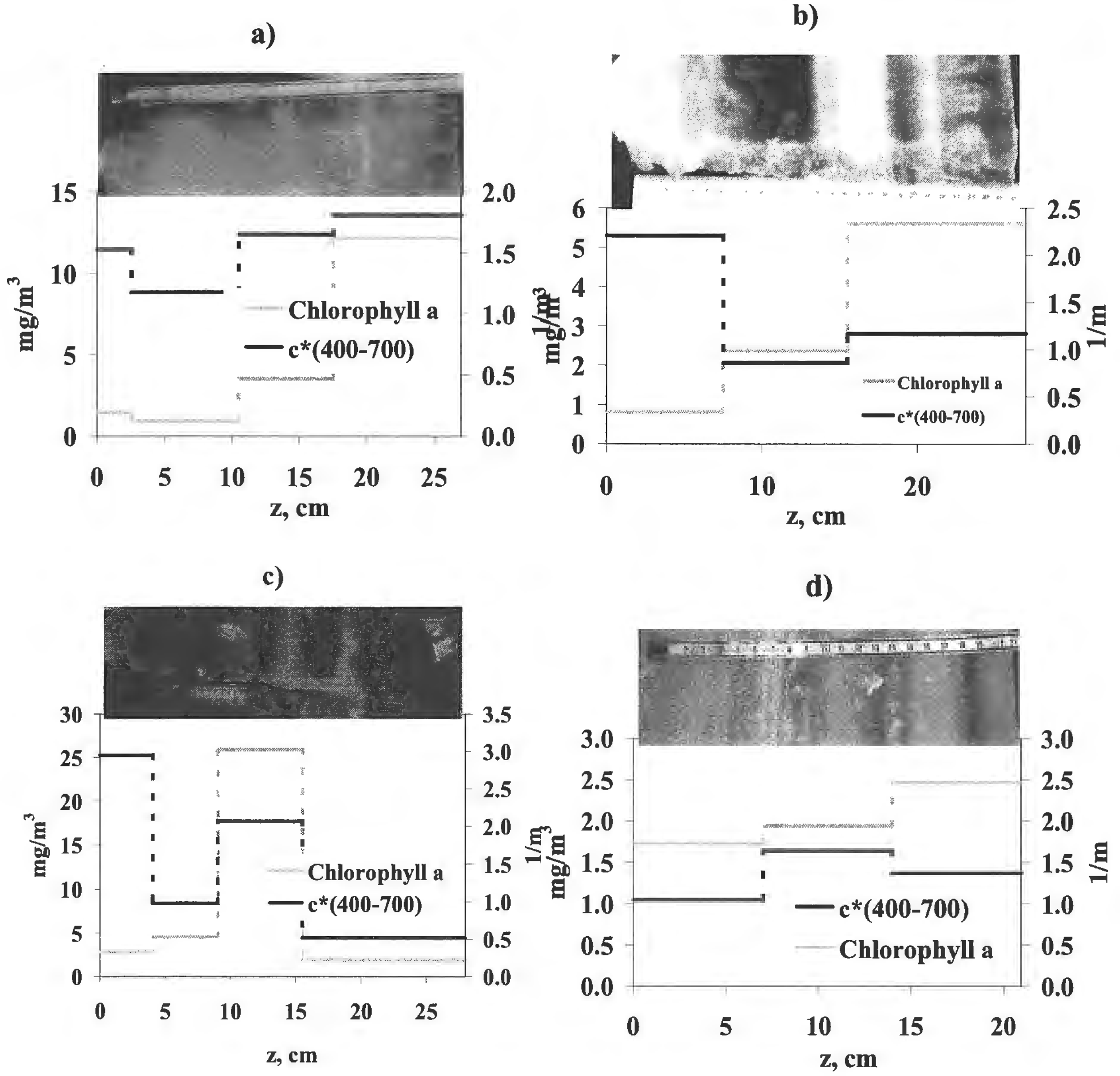

Figure 3: Vertical cross-section of ice and the profiles of chlorophyll *a* and *c**(PAR): Santala Bay (16.03.2000), b) Lake Ülemiste (15.02.2000), Lake Maardu (08.03.2000) and d) Lake Paukjärv (23.02.200).

In our previous works (*Arst et al.* 1999a, *Erm et al.* 2001, 2002a and *Reinart et al. 1998*) we have found strong correlations between K_{dw} and the Secchi disc depth (z_{SD}) and between c^* and K_{dw} for ice-free period An analogous correlation between K_{di} and c^* of ice meltwater was analyzed by *Leppäranta et al.* (2002a) and the value of the standard deviation (R) was found to be 0.91. In this study we got from the plot K_{di} vs. c^* (Fig. 4) the equation

$$K_{di} = 1.58\, c^* + 0.64;\ R = 0.7. \qquad (9)$$

We also studied the correlation between the concentrations of OAS and c^* determined from the whole ice bulk and estimated (by weighted average) from the data for distinctive layers of ice. The deviation of the suspended matter concentrations (Fig. 5.) was very systematic and needs some extra attention.

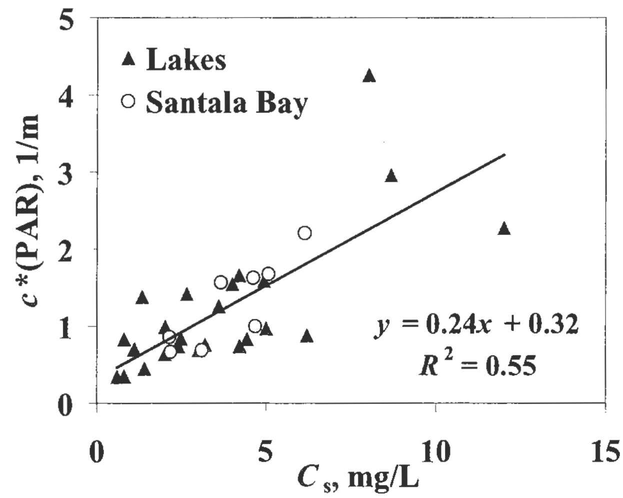

Figure 4: Diffuse attenuation cefficient of ice (K_{di}) vs. c^*(PAR) of ice meltwater.

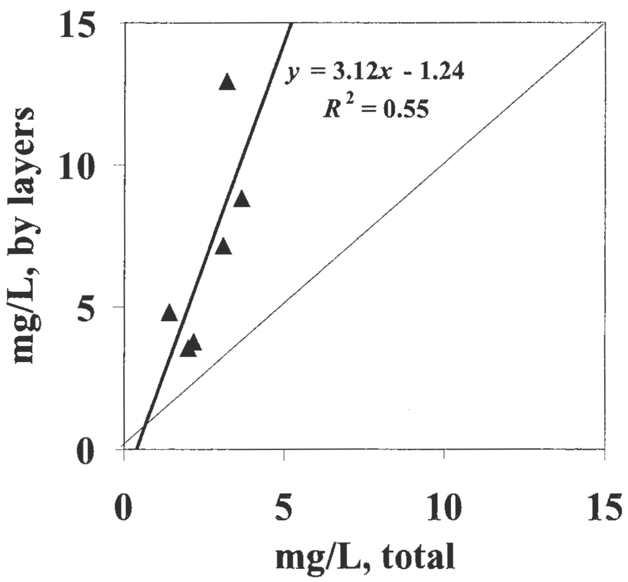

Figure 5: C_s calculated by ice layers vs. C_s determined from total ice sample.

The concentrations calculated from the data of distinctive layers are clearly overestimated compared with the concentrations estimated from the ice bulk. It indicates that at least any layer of ice must be chemically an oversaturated solid solution. Then a possibility emerges that the solution can be diluted in the process of ice bulk melting. By melting only the ovesaturated ice layer, the additional substance precipitates out. In our previous studies (*Arst* *et al.* 1999 b and *Erm et al.* 2002 a) we followed a similar phenomenon: an increase of C_s in lake water samples after freezing-melting cycle, but the mechanism of the precipitation is not known today. Values of the beam attenuation coefficient c^* averaged by layers were also overestimated in most cases, which accords with the C_s data.

4. Conclusions

The synchronous light field measurements on and under ice give sufficient information both about the under ice light field and optical properties of snow and ice. Using these data, the diffuse attenuation coefficients of snow (K_{ds}), ice (K_{di}) and water (K_{dw}) can be calculated.

In our climatic region the albedo of snow and ice can be very variable depending on the weather conditions (we got the limits 0.1-0.8).

Due to the spectral dependence of K_{dw}(PAR), it is different for the systems snow + ice + water and ice + water. In most cases K_{dw}(PAR) measured with the snow cover is higher than K_{dw}(PAR) measured when snow is removed.

The diffuse attenuation coefficient of ice (K_{di}) can be roughly estimated by measuring the beam attenuation coefficient (c^*(PAR)) of ice meltwater.

Many distinctive layers can be seen in the lake ice. These layers mostly accord with the concentrations of OAS in ice meltwater of the layer.

Concentration of suspended matter determined from the ice layers is much higher than determined from the ice bulk. The reason could be chemical oversaturation of some ice layers.

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Sea ice–water processes and interactions in the SW coast of Finland

Johanna Ikävalko[1], Jens Ehn.[2], Laura Forsström[1], Hermanni Kaartokallio[3], and Kristian Spilling[1]

[1]Department of Hydrobiology, University of Helsinki, Finland

[2]Department of Geophysics, University of Helsinki, Finland

[3]Finnish Institute of Marine Research, Finland

Low water temperature and light regime, and the presence of sea ice are characteristic in the northern and eastern parts of Baltic Sea in winter, where the probability of ice cover formation is 100% . Despite the evidence, that the Baltic Sea ice is structurally comparable with that in the polar regions, and consequently inhabited by a large variety of organisms, the importance of in particular biological processes in the Baltic Sea during winter has long been underestimated and thus undersampled.

A 3-year research project (2001-2003) is set to study the physico-biological processes and interactions in sea ice and the water column near the coastline in the SW coast of Finland and the Bothnian Bay. Some of the main issues in the project are:

- Physical properties of sea ice and their effect on biological processes therein
- The formation of sympagic (i.e. within ice) flora and fauna, its species composition and succession during the ice-covered period, and faith in spring
- The dynamics and ecophysiology of the sympagic foodweb; e.g. pathways of energy transfer, role of bacteria in nutrient dynamics, tolerance of major ice algae to environmental stress
- Interactions between ice and water: the effect of presence/absence of ice cover on microbial communities in the underlying water column

Four work packages have been designed for finding answers to the questions above and are described below. Large part of the field observations and experimental work is conducted at the Tvärminne Zoological Station (Univ. of Helsinki) in the SW Finland.

Baltic Sea ice biota

Johanna Ikävalko[1], Hermanni Kaartokallio[2], Kristian Spilling[1], Kimmo Karell[1], Jens Ehn[3], and Tuomo Roine[1]

[1] Department of Ecology and Systematics, Hydrobiology, P.O. Box 65 (Viikinkaari 1), FIN-00014 University of Helsinki, Finland

[2] Finnish Institute of Marine Research, P.O. Box 33, FIN-00931 Helsinki, Finland

[3] Department of Physical Sciences, Division of Geophysics, P.O. Box 64 (Nils Hasselblominkatu 2), FIN-00014 University of Helsinki, Finland

1. Background

Baltic Sea is ice-covered annually. Even during mild winters, ice is formed in its northern (Bay of Bothnia) and eastern (Gulf of Finland) parts. Water in the Baltic Sea is brackish, and ranges from 1 in the north to approximately 25 psu (practical salinity unit) in the west. When the water salinity exceeds 1 psu the structure of the forming ice is comparable to that in the "real" marine environment, i.e. ice which is formed of ca 30-34 psu water (Palosuo 1961). Consequently, like in the Arctic and the Antarctic, the Baltic Sea ice is composed of non-saline ice crystals and brine channels. The salinity of the brine is in positive correlation with the air temperature: the cooler the air, the higher the salinity of the brine solution (Maykut 1985, Weeks 1990). Sea ice can also be characterised as an environment with low light regime and temperature (Maykut 1985, Weeks 1990). Major inorganic nutrients (N, P and Si) for algae are, however, readily available.

2. Baltic Sea ice biota

Despite its harsh nature, brine pockets and channels in sea ice form the microhabitat that is occupied by various micro-organisms, such as bacteria, unicellular algae, rotifers and ciliates (Garrison 1991, Ikävalko & Thomsen 1997, Ikävalko & Gradinger 1997, Haecky 2000, Ikävalko 2001a). These are called the sea ice biota, or sympagic communities. The closer the site to the mainland, the more such communities comprise of biological material with a limnic (freshwater) origin. Farther out at open sea, sea ice biota reflects more that of the plankton of the open water. This is particularly pronounced in the coastal areas of the Baltic Sea (Ikävalko & Thomsen 1996).

Initially, ice organisms are incorporated into the newly forming sea ice (Ackley et al. 1987, Gradinger & Ikävalko 1998). Ice organisms have different strategies for staying alive in ice. However, characteristic to these communities is, that organisms thrive in their cold environment: they reproduce, swim or glide on surfaces, feed and copulate within ice (e.g. Ikävalko & Thomsen 1997).

3. Communities in sea ice

3.1 Bacteria and viruses

Bacteria in sea ice have two main functions within Baltic Sea ice: 1) bacteria act as decomposers of all biological production, and 2) they form the start motor (second step) of the microbial loop (Kuosa et al., in prep.; Kaartokallio, in prep). Active research on the role of bacteria in the Baltic Sea is currently ongoing. The role of viruses in sea ice, in particular in the Baltic, is still to be surveyed in much greater depth than has been done so far.

As ice organisms die, their remnants are soon colonised by bacteria. Energy is used for bacterial growth efficiently. In the microbial loop, dissolved organic material (DOM) excreted mainly by algae but also other ice organisms become utilised as energy source by bacteria and viruses (Azam et al. 1983). These, in turn, are consumed by small micro- and mesozooplanktonic animals (heterotrophic flagellates and ciliates; generally 10-30 μm in size), which then become food for larger planktonic predators such as cyclopoids and harpacticoids, and their nauplii (juvenile stages). The microbial loop is therefore a second pathway of energy, originally derived from the primary production of algae, ending up to top predators such as seals and the man itself. The "first" pathway would be the classical one where energy is transported from algae through small zooplankton and fish to the top of the food web. In this classical scheme, bacteria and viruses have only the role as decomposers of all biological production.

In addition to the microbial loop and the classical grazing chain that are mentioned above, it seems that the Baltic Sea ice microbial food web includes several "shortcuts" in matter and energy flow. These are e.g. ciliates grazing on bacteria, flagellate herbivory on larger algal cells, and possibly also a direct uptake of DOM by flagellates (Haecky and Andersson 1999, Kaartokallio, in prep).

Currently, our working hypothesis suggests that ice nutrient dynamics is regulated by physical and biological processes. Main physical processes influencing nutrient concentrations in ice are related to changes in ice temperature and subsequent brine movement. Nutrients of atmospheric origin (N) are transported downwards in the ice column, while P might be incorporated from the water column under the ice by intrusion of seawater into the brine channels. Main biological processes are nutrient uptake by ice algae and regeneration by heterotrophic organisms (Granskog et al., submitted; Kaartokallio, in prep).

3.2 Algae

Like in all ecosystems, both aquatic and terrestrial, plants and algae are the foundation of the food web. In the Baltic Sea ice, diatoms (approx. 10-100 μm in size) are the main primary producers, accompanied by e.g. unicellular green algae and flagellates (dinoflagellates, cryptophytes), and the first step of the microbial loop within ice.

All currently known unicellular algal groups are now encountered in the Baltic Sea ice (Ikävalko & Thomsen 1996, 1997, Ikävalko 1998a, b, Ikävalko 2001a, b). Evidence shows that the species composition is dependent on the location; the closer the site of study to the shore and freshwater source, the more freshwater species are present in ice. Our studies on the presence of limnic algae in sea ice have clearly showed that several freshwater algae actually tolerate much higher salinities than formerly assumed (Ikävalko & Thomsen 1996, 1997, Ikävalko 1998a).

Algae in sea ice possess extremely efficient ways of adapting to their environment. They must be tolerant to e.g. low light levels and temperature, and be capable of maintaining their physiological activities even under non-optimal conditions. Figures 1 and 2 show a good example of some of the results from our laboratory experiments on growth rates of two important ice algae in the SW coast of Finland, the dinoflagellate *Scrippsiella hangoei* and the diatom *Thalassiosira baltica* (Spilling, in prep). The culture media were rich in nutrients, i.e. the algal growth was not limited by nutrients. In good light conditions, i.e. light is not a restricting the algal growth either, the growth of the diatom *T. baltica* is remarkably faster than for the dinoflagellate *S. hangoei* (Fig. 1). However, in low light conditions, the ice alga *S. hangoei* shows its ability to adaptate: as *T. baltica* suffers greatly from too low light availability, the growth of S. *hangoei* is not restricted by light (Fig. 2). *T. baltica* being thus outcompeted, all nutrients in the culture were left for the efficient growth of *S. hangoei*. However, the adaptation of *S. hangoei* to low light conditions is a time demanding process: approximately 1 month was needed before the alga started to increase in number (Fig 2).

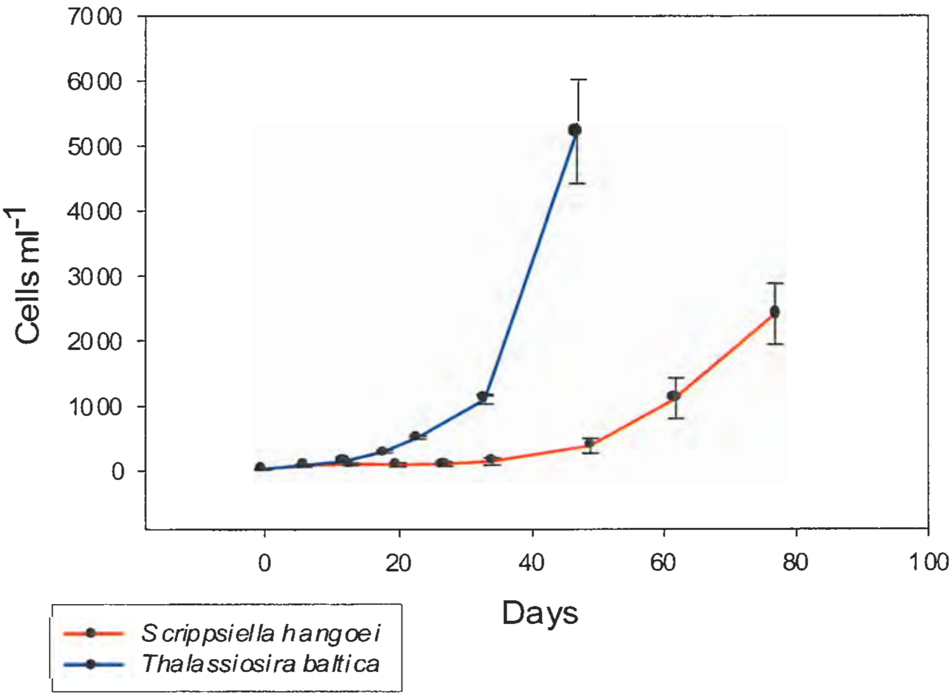

Figure 1: Growth of *T. baltica* and *S. hangoei* in 16 µE/s.

In these studies, Spilling and Rintala (in prep.) show another example of adaptations of ice algae: the formation of resting stages. Pelagic algae, especially diatoms and dinoflagellates, commonly form resting stages for survival over unfavourable periods such as winter. Many sea ice algae, in turn, form such "oversummering" stages to thrive through non-sea ice cover periods in the Baltic. A new type of a resting stage, or cyst, is documented for *S. hangoei* and will be described soon (Spilling & Rintala, in prep).

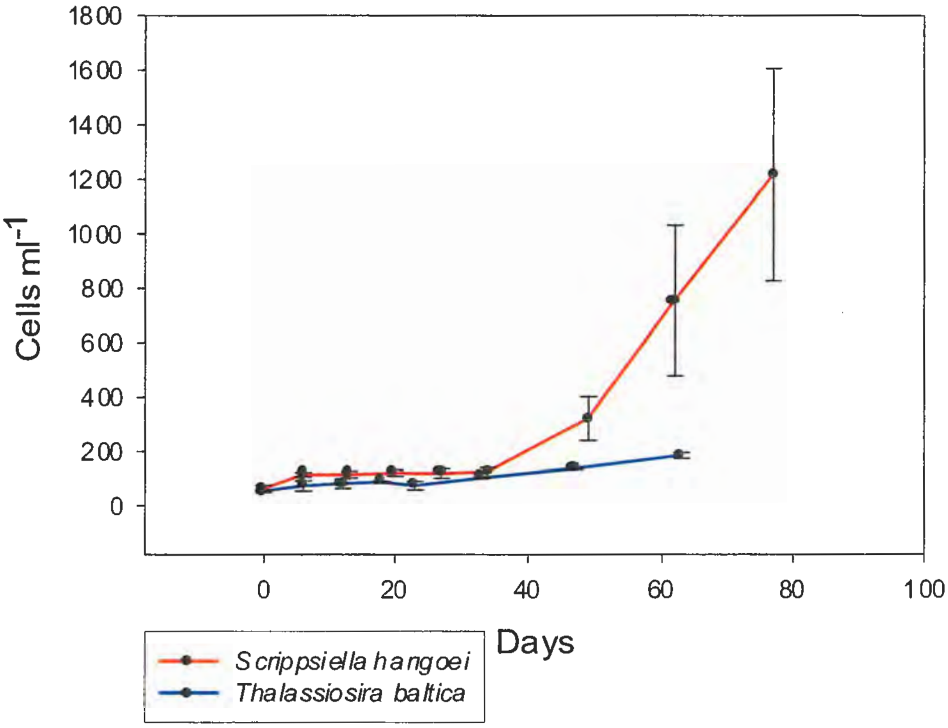

Figure 2: Growth of *T. baltica* and *S. hangoei* in 5 μE/s.

3.3 Heterotrophic organisms

Heterotrophic flagellates are present in several groups of protists (e.g. Patterson & Hedley 1992). In the Baltic sea ice, some of the main flagellates with a heterotrophic mode of nutrition belong to choanoflagellates, dinoflagellates are euglenids (Ikävalko & Thomsen 1997, Ikävalko 1998a, b). They are either free-living in brine, or live attached or gliding on the surfaces of the channels. Main energy sources are DOM, bacteria and small algal cells. Outside the sea ice biota, such flagellates are often found living on or attached to benthic substrates such as sand and mud. Thus, sea ice is a "planktonic" environment for most algae, and a "benthic" environment for a large group of flagellates. Larger heterotrophic consumers in ice (fourth step in the microbial loop) belong to ciliates, rotifers and planktonic crustaceans. After this step in the food web, organisms become too large to live in brine channels. Therefore, the rest of the sea ice based food web is located in the water column below the ice.

Sympagic communities are not totally isolated from the water column. Meteorological conditions can affect the interaction between ice communities and the water column. For example, the weight of a thick, moist snow cover may press the ice sheet downwards. This, in turn, leads to the migration of seawater, its nutrients and pelagic organisms into the sea ice. In spring, when the snow and surface ice is melting, the melt water migrates downward through the ice cover and flushes brine solution and its organisms with it, transporting them to the water column.

4. The fate of the ice biota

During the ice break-up in spring, the fate of the sympagic communities can be one of the following: 1) if the organism in question is not capable of adapting to the environmental conditions in the water column its fate is death and thus degradation. The morphology of the organism may not be suitable for life in water, or its physiological processes such as nutrient uptake may be so finely adjusted to function in sea ice that in water the cell is unable to survive. Whether the cell dies or not, it may also 2) become food for consumers, such as fish. 3) Formation of resting stages and the following dormance ("oversummering") is possible for organisms that are capable of cyst production, e.g. several diatoms and few dinoflagellates in the Baltic Sea. The last option is 4) adaptation of cell to changes in the environment and thus life in the water column. A number of diatoms have a wide ecological range, and are thus able to colonise the water column. The fate of ice biota has been widely discussed e.g. by Horner (1989), Haecky et al. (1998) and Narinen (2002).

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Atmospheric reflections to the Baltic Sea ice climate

Jouko Launiainen, Ari Seinä, Pekka Alenius, Milla Johansson, and Samuli Launiainen

Finnish Institute of Marine Research (FIMR), P.O. Box 33, FIN-00931 Helsinki, Finland

1. Introduction and data

High latitude atmospheric circulation and the interaction between atmosphere, ice and ocean are the key processes controlling the climate in polar regions. The coupled general circulation models (listed e.g. in IPCC, 2001) suggest the cold regions, foremost the Arctic, to be exposed to global warming. Main reasoning for this lies in the sensitivity of high latitudes, the snow and ice covered ones especially, to changes in earth-to-space thermal radiation balance and clouds. Accordingly, in addition to the sea ice being regarded as a sensitive indicator and signal of a climate change, it has a prominent physical feedback role to a change, via albedo and other thermal and dynamic interactions in the climate and earth system. During the recent years we have experienced and realized more and more that in wintertime the Baltic Sea area climate is controlled by the Northern Atlantic forcing, in a high degree. Therefore, it is expected that the sea ice climate in the Baltic Sea reflects larger scale forcing, and climate change. Locally and regionally of course, besides acting as a "slave" of the global forcing, the sea ice and the sea ice-atmosphere-ocean processes have strong local physical interaction, and important interactive effects and feedback modifications to the weather and sea ice conditions in the Baltic Sea.

A Baltic Sea ice climate study related to atmospheric and climate forcing is under way at FIMR, parallel to and in co-operation with SMHI, Sweden. In a contribution to the project AICSEX (Arctic Sea Ice Simulation Experiment; supported by the EC) we study the Baltic Sea ice conditions for comparing those with the Arctic, and detecting signals of the Global Change.

In this workshop report we summarize results found in the studies above. Most of the sea ice data used are observations and time series gathered by the Finnish Sea Ice Service (at FIMR). For several stations, high quality data used (Alenius et al. 2002) date back to the early 20th century. The data cover the ice extent and thickness, date of freezing and break-up, length of ice season and some winter navigation related items. The locations of the stations are given in Figure 1. For several stations, data on snow thickness are also available.

As the first sea ice characteristics, we give a note to the known historical long-term time series of the maximum annual sea ice extent in the Baltic Sea.

2. Results

2.1 Long-period time series of the maximum ice extent in the Baltic Sea

The Finnish "traditional" time series of the annual maximum extent of sea ice dates back from present to the year 1720. This data was first created by long-lasting, laborious and outstanding efforts by Jurva (e.g. 1937) and by Palosuo (1953), and completed by Seinä and Palosuo (1996). The data series, currently updated by the FIMR Ice Service, seem to be the best and most extensive of that kind of data. This data, which well illustrate distinctive annual variations (Figure 2) suggest the long-term ice extent to have decreased from the early 19th century, whereas from the early 20th century up to 1980s a decreasing trend cannot be found; one may even see an increasing one. After that, the time series nicely shows the period of the mild last 15 years of low sea ice extent.

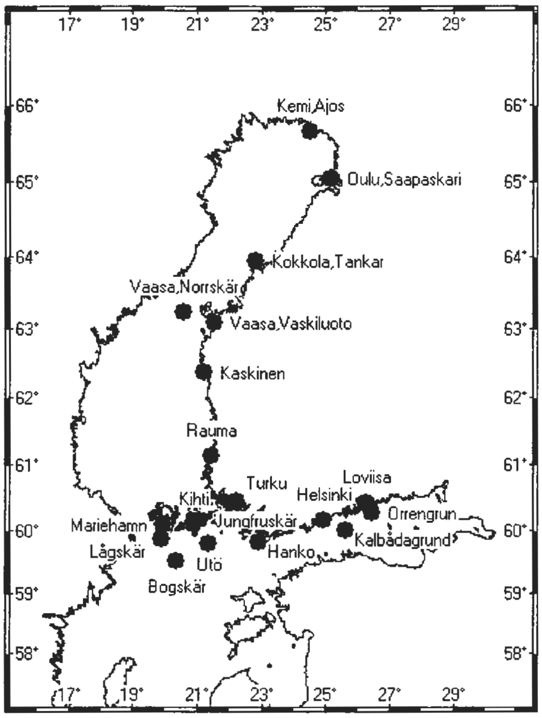

Figure 1: Finnish stations of observations of date of freezing, ice break-up, number of ice days, and maximum ice thickness in the northern Baltic Sea.

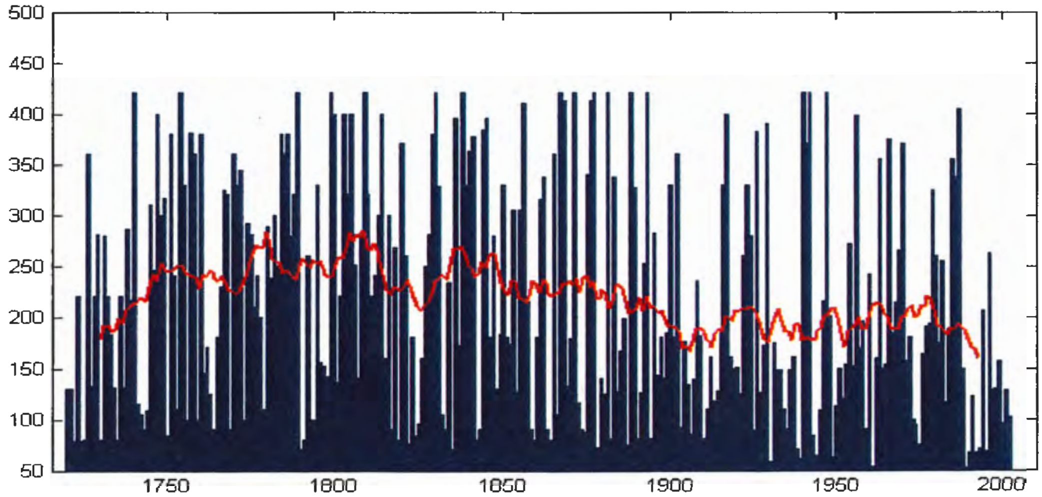

Figure 2: Maximum annual sea ice extent (in 1000 km^2) in the Baltic Sea in 1720 – 2002. Continuous line gives the 20-year running average.

Assessing the time series above we have to keep in mind that accuracy of the older data may not be of the quality of the recent data. The observation sources for the old data were few and proxy. Therefore, for strict evaluation of the time series we know that the data from the mid-

1960s onwards are most reliable. Sea ice reconnaissance from aircrafts was begun in that time and some satellite data were available from late 1960s. Another stage to mention, assuring an improvement to data quality, was the early 1927 when the Finnish government ordered the merchant vessels to keep record (hourly) about the sea ice conditions, to report those further to FIMR.

2.2 Trends during the 20th century

In the northern part of the Baltic Sea, in the Bay of Bothnia especially, the (maximum annual) ice thickness indicated increase during the 20th century up to 1980s, which may be seen in Figure 3. This was most evident in the northernmost station Ajos, off the city of Kemi. The length of the annual ice season, given in Figure 4, shows a physically logical parallel behaviour i.e. increase of duration of ice winter, onwards from 1930s at least. It is interesting to note that even the Bogskär (Figure 4) data in south shows slight lengthening of the ice season from 1930s to 1980s. Except the length of the ice season in Kemi, both the thickness and the length of the ice winter show a distinct decrease during the mild winters of the last fifteen years.

As to the Gulf of Finland, we didn't have long-term accurate time series for disposal yet, and no final general conclusion can be made, except that the ice winters were becoming distinctly milder after 1980s. From Helsinki, for example, we got a long-term time series (since 1861), but the ice thickness versus sea ice days suggest to an urbanization effect to the time series. The data has to be studied strictly and corrected, if possible.

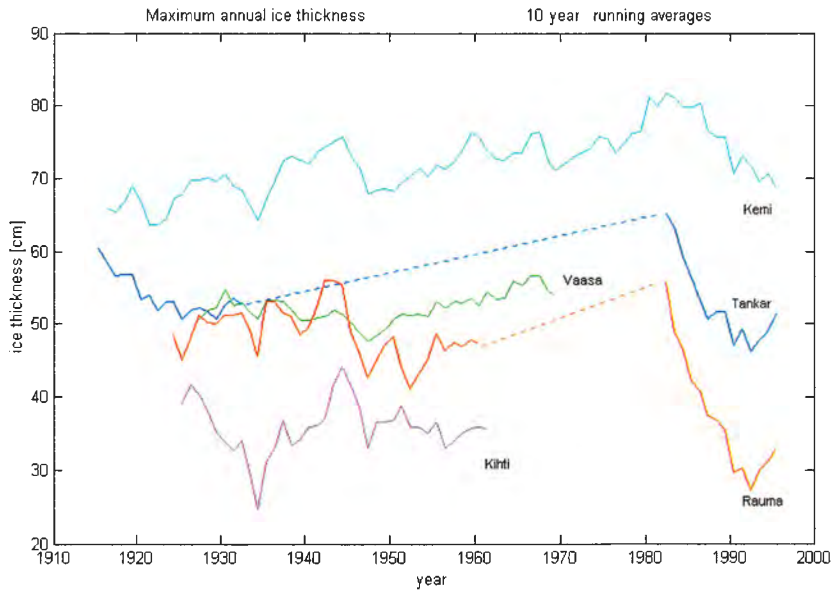

Figure 3: Time series of the maximum sea ice thickness at various stations in the Gulf of Bothnia. 10-year running averages.

As to the exceptional behaviour of Kemi, we know from before that the ice conditions there are often not analogous to those in the other regions. For example, the ice winter and ice thickness are not correlated with (forced by) the air temperature in such a degree than in the other stations, cf. discussion below. Several candidates can be speculated for the reason, e.g.

sea ice dynamics and hydrological and/or meteorological characteristics in the northernmost end of the bay, but those have not yet been investigated, specifically.

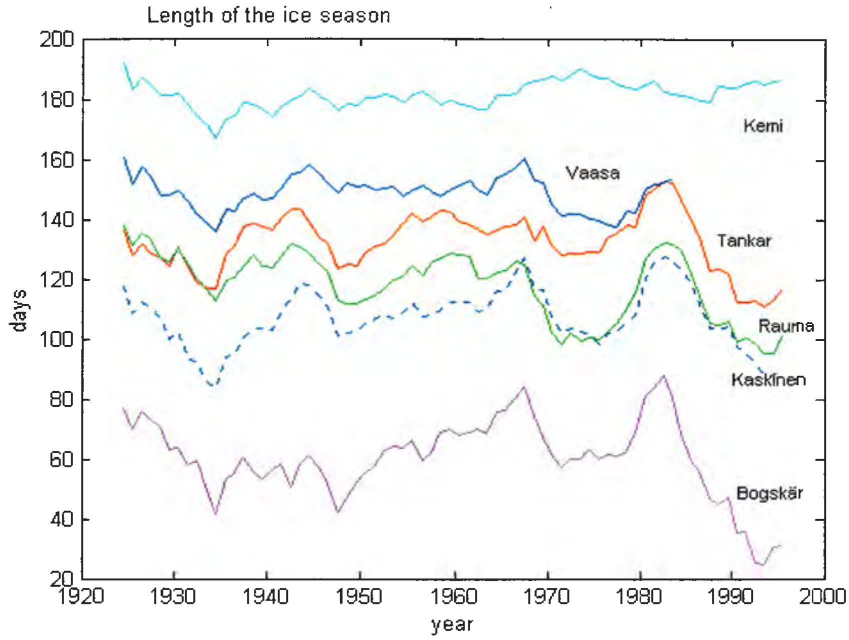

Figure 4: Time series of the length of the annual sea ice season. 10-year running averages.

The above results of time series of ice thickness and length of the ice season do not, up to 1980s, support locally and regionally a warming winter climate. That may even be seen as contradictory to the general Climate Change and Northern Hemisphere warming during the 20th century. The latter is to be seen e.g. in http://www.cru.uea.ac.uk/cru/climon/data/themi/.

2.3 Sea ice and air temperature

In several efforts, the Baltic sea ice has been found to show a close relationship with air temperature, which is physically rather relevant. Using the long time series, Makkonen et al. (1984), Tinz (1996) and Tinz (1999) have correlated the maximum annual Baltic Sea ice extent with local or regional wintertime air temperature. Using the approach, in Figure 5 are given the time series of the observed and by air temperature based regression estimated annual maximum ice extents, for data from 1910s onwards. The result shows that a simple air temperature based approximation may work rather well. However, the regression depends on the period we use (cf. Figure 6). A regression for the recent "best quality" ice data should be the most accurate and approximate the last decades of mild ice winters better than the one which is fitted for the whole longer period and given in Figure 5. Accordingly, the linear regression fit giving area $A(1000\ km^2) = -42.2 \times T + 85.2$, where T is the wintertime (Dec-Feb) mean air temperature from Stockholm and Helsinki, gives the highest correlation (0.96) and should best reflect the current mild climate winters also physically.

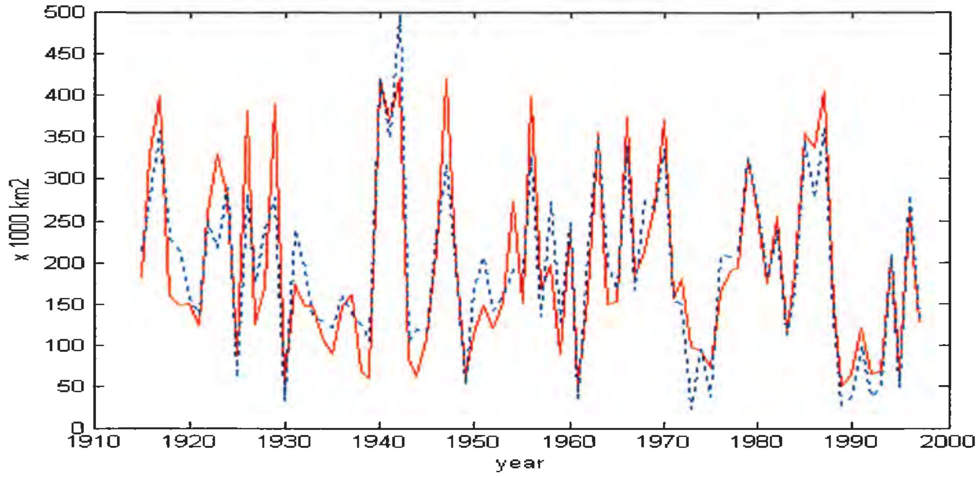

Figure 5: Annual maximum sea ice extent in the Baltic Sea. Continuous line shows the observed variation, and the broken line gives the diagnostic estimate, based on the found relationship between the air temperature and sea ice extent given in Figure 6. As the air temperature, the mean of Stockholm and Helsinki, from December to February, was used. (Temperature data from SMHI, Sweden, and from the Finnish Meteorological Institute).

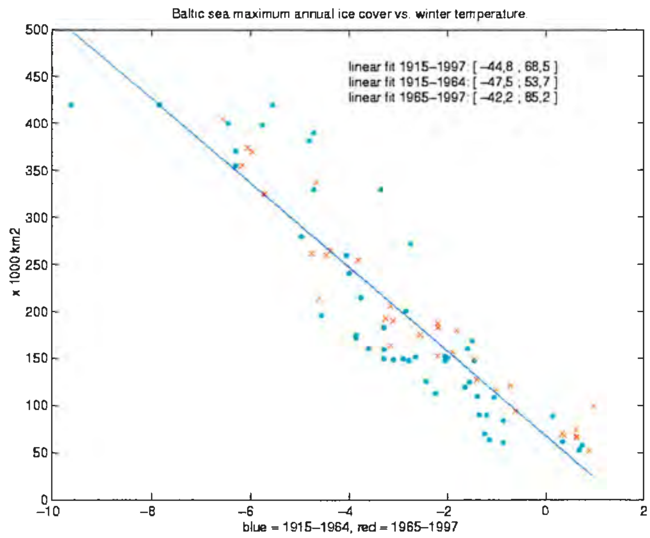

Figure 6: Annual maximum sea ice extent versus wintertime air temperature (Stockholm-Helsinki mean from December to February). The continuous line gives the regression fit for all the data of 1915-1997. Crosses give the data for 1965-1997. For numerical regression, see the text.

The close relationship of air temperature with sea ice thickness and the length of the ice season can be seen from Figures 7 and 8. The former figure gives the time series of the observed maximum ice thickness in station Kihti (Figure 1; data available up to 1966). In the same figure, an approximated ice thickness is given by the broken line. The approximation is based on a regression found between air temperature (mean of Stockholm-Helsinki) and annual observed maximum ice thickness. A similar observed to approximated comparison of the variation of the length of the ice season is given in Figure 8. In both cases, linear regressions were used. In some cases, a slightly nonlinear regression fit may even increase explainability. As an overall conclusion, we may see that the temperature based approximations well agree with the observed data.

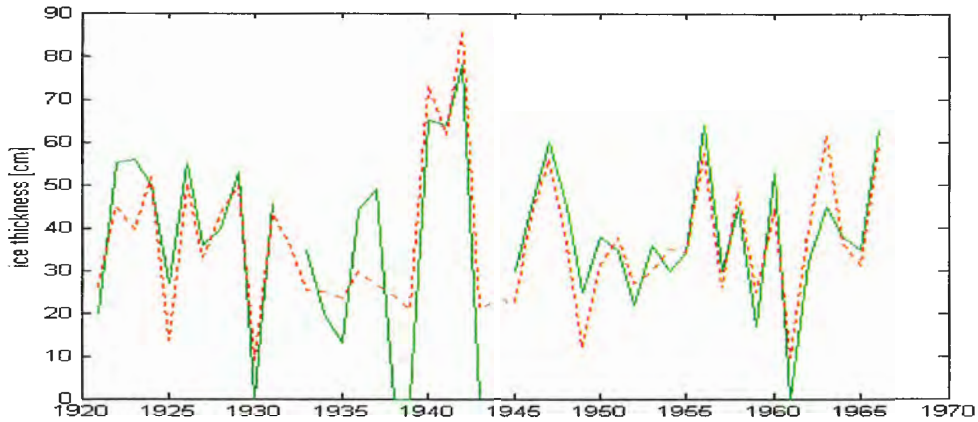

Figure 7: Annual maximum sea ice thickness at Kihti (see Figure 1). The continuous line shows the observed variation and the broken line gives an estimate based on the found relationship between the wintertime air temperature and sea ice thickness. As the air temperature, the wintertime mean of Stockholm and Helsinki (cf. above) was used.

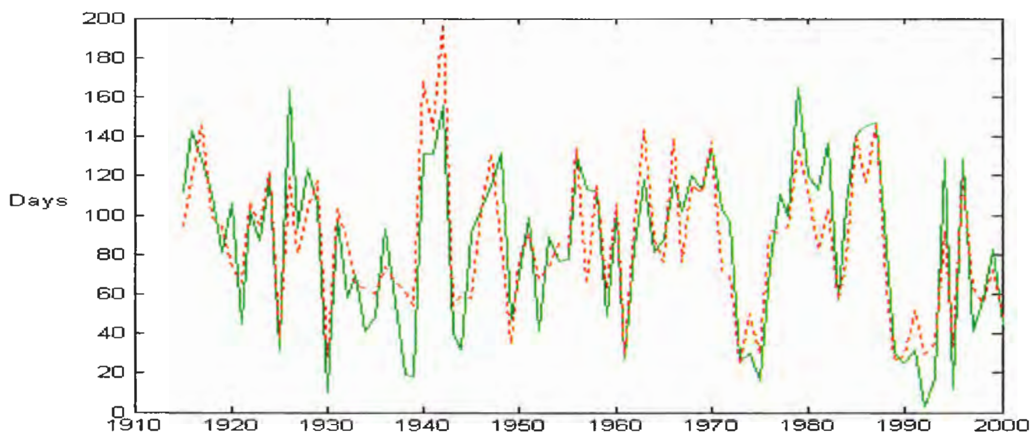

Figure 8: Annual length of the ice season at Norrskär. The continuous line shows the observed variation and the broken line gives an estimate based on the relationship between the wintertime air temperature and length of the ice season. As the air temperature, the wintertime mean of Stockholm and Helsinki was used.

One more example of air temperature based sea ice variation approximation (reconstruction) is given. Figure 9 gives the observed maximum distance, from off the harbour Hamina (in the eastern Gulf of Finland, 60° 31' N, 27° 09' E), to the zone where the sea ice thickness decreases to 10 cm. A temperature based regression estimate is given in the figure as well. A good comparability is to be seen. From the point of view and tools of winter navigation strategies, this kind of information should be of interest. A more comprehensive study for Finnish harbours is under progress.

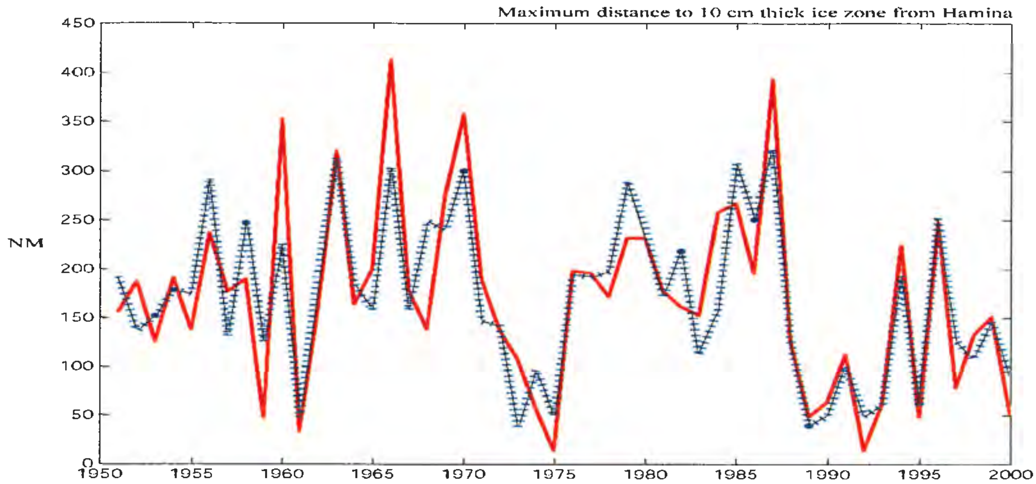

Figure 9: Annual maximum distance from the harbour of Hamina (eastern Gulf of Finland) down to a zone of sea ice less than 10 cm thick. Distance is given in nautical miles. Thick line shows the observed values and the crosswise marked line gives an estimate based on the air temperature.

The findings above show a nice and interesting relationship between the air temperature and the sea ice characteristics. Accordingly, a regional and even local temperature may be an interesting tool for diagnostic studies and hindcasting. As to forecasting, prediction and even to scenarios, we should make a "forewarning" of using local or regional air temperature (that of surface layer or lower ABL) for estimation of development of sea ice characteristics and ice winter in a too straightforward way. This is because the air temperature and sea ice have a strong physical coupling with various thermal interaction processes yielding to a dynamic thermal balance. Accordingly, the sea ice affects the air temperature, and the latter is not in this context a free external forcing quantity or a simple causal reason to sea ice variations. In terms of e.g. the Baltic Sea surface atmospheric fields and temperature this holds. Therefore, the models for prediction and scenarios of over-sea air temperature shall have a proper air-ice-(sea) coupling module. An example of a high resolution 1-D coupling module which includes the adaptation of an over-ice atmospheric temperature is given in Launiainen and Cheng (1998). Another approach to make ice characteristics estimation might be to use some larger region and/or upper ABL- atmospheric fields, but any quantitative analysis of their inter-relationship with the Baltic Sea ice climate has not been made.

2.4 Sea ice reflections of large scale forcing, NAO

The Northern Atlantic forcing modes exert a strong control on the climate in the northern hemisphere, especially in winter. The NAO Index (North Atlantic Oscillation Index) is a south-to-north index with respect to surface air pressure difference in the Atlantic, between the latitudes of cirka 35° N and 64° N. The NAO may be regarded as a discrete paradigm (Wallace, 2000) of the Arctic Oscillation (AO). The Arctic Oscillation (Thompson and Wallace, 1998) is the first mode of the spatial and temporal global northern polar pressure field, defined from observations by EOF (empirical orthogonal function) analysis. Positive phases of NAO signify high, mild and moist winds from west in the northern Europe in winter.

Related to the winter NAO index, the Baltic Sea annual maximum ice extent is given in Figure 10. Comparison is given for the recent (accurate) ice data and a rather good comparability is seen. The annual variations of the length of the ice season (in Norrskär, Bothnian Sea) are compared with the NAO in Figure 11, and Figure 12 shows variations of ice thickness (Kihti) compared with those of the winter NAO index. We can see from the results that variations in the NAO are rather comparable to the variations in the sea ice characteristics. If averaged and smoothed (cf. Figure 13), a similarity is especially evident.

Figure 13 indicates the importance of the NAO in controlling the winter climate in these regions.

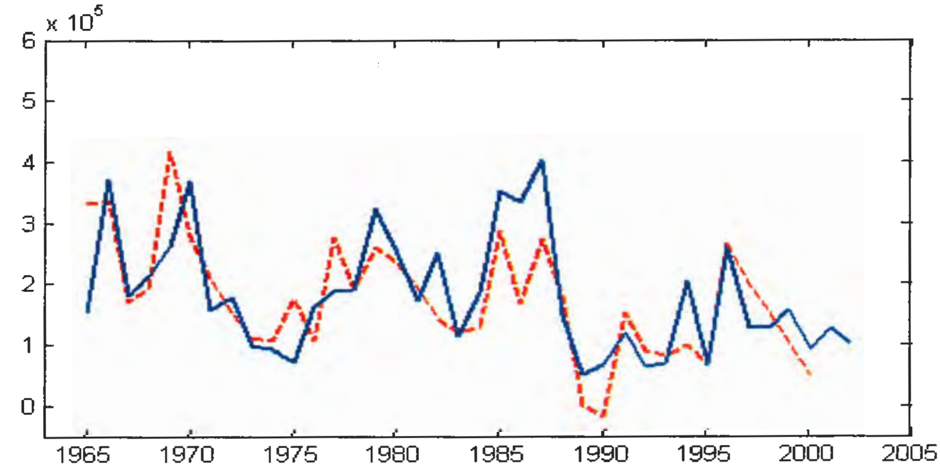

Figure 10: Maximum annual sea ice cover (in km^2) in the Baltic Sea (continuous) and the variations of the wintertime NAO (broken) in 1965-2002. (The NAO index is given as negative compared to the common notation, in relative normalized units; see the text.)

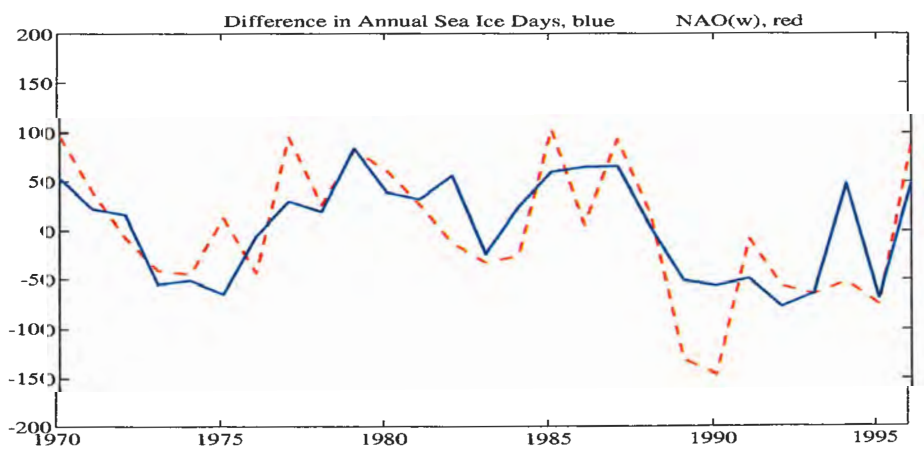

Figure 11: Variation of the annual sea ice days at Norrskär, (continuous) and the winter NAO (broken) in 1970-1997. Annual sea ice day variation is given as the difference from the long-term (1915-2000) mean length of the local ice season. (The NAO index is given as negative in relative normalized units; see the text.)

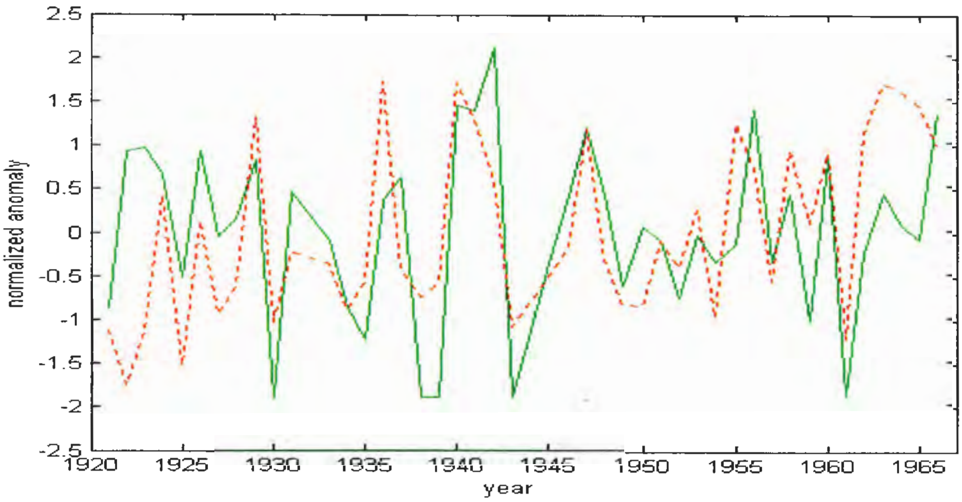

Figure 12: Variations of the sea ice thickness at Kihti (continuous) and the wintertime NAO (broken). Relative normalized anomalies. (The NAO index is given as negative compared to the common notation.)

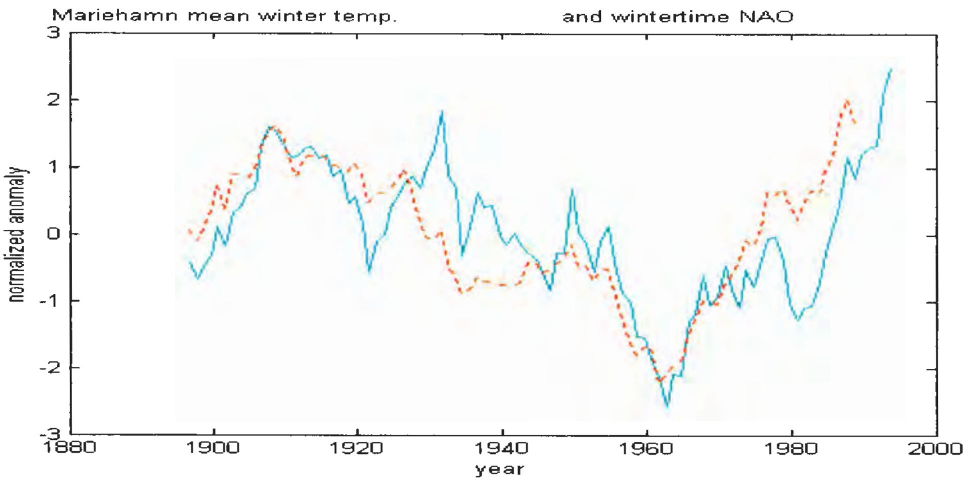

Figure 13: Variations of the air temperature at Mariehamn (continuous) and the wintertime NAO (broken). Relative normalized anomalies. 15-year running averages. (Temperature data from the Finnish Meteorological Institute.)

We further may note that in the literature there exist currently at least four discrete definitions of NAO, the various candidates having minor differences in observation sites or primary observation data smoothing. As to the winter NAO, the various indexes do not differ very much from each other. We frequently use the one taken from www.cru.uea.ac.uk/cru/data/. In the figures shown, for comparison with the physical quantities in question, the mutual variations have been calculated as normalized anomalies (na), by the mean (mean) and standard deviation (sd), defined as na(x) = (x - mean(x)) / sd(x).

Physically, the NAO index signifies a forcing which is an external one, for the Baltic Sea region. Therefore, this independent forcing, having no interdependence, such as the one between the sea and regional air temperature, may serve as a valuable tool for causal and diagnostic studies, and as a prognostic tool for forecasting and scenarios. In addition to sea ice characteristics we have studied reflections of the Northern Atlantic forcing to hydrological conditions (http://www2.fimr.fi/en/tutkimus/tutkimusalueet/fysikaalinen-tutkimus/naoposter.html).

So far, unfortunately, the current large-scale circulation models (GCMs) cannot detect and solve the NAO. Even for control runs and hindcasting they do errors in both time scale and amplitude of the NAO index compared with the observed one, as can be seen from Figure 14.

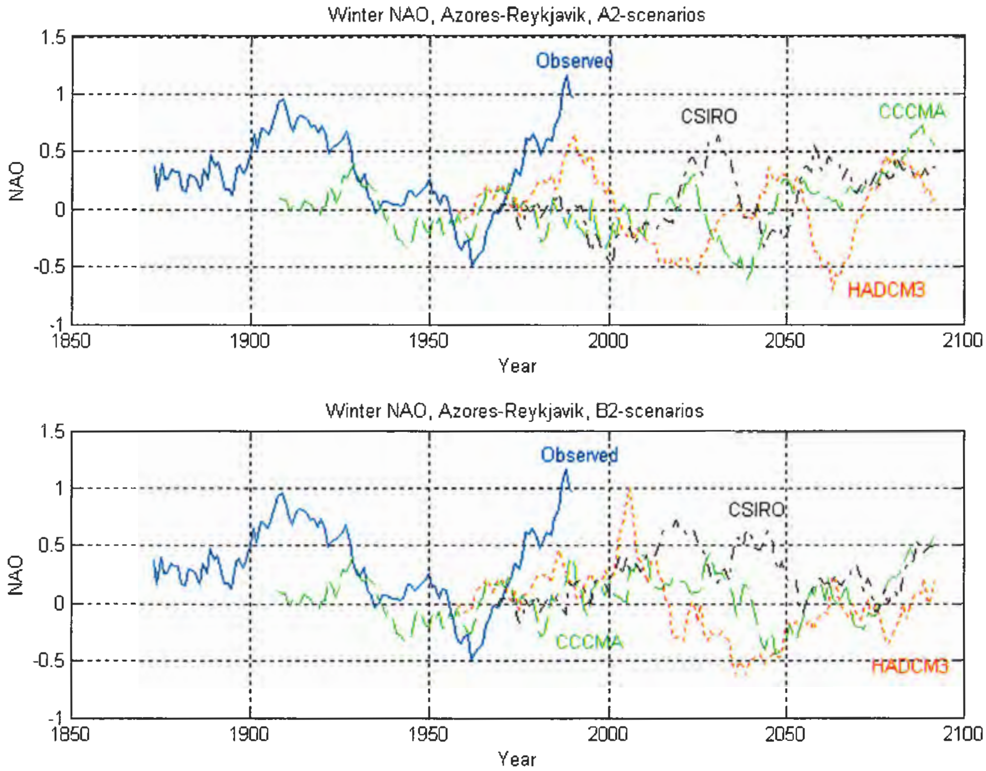

Figure 14: The observed NAO index (based on Azores and Reykjavik) and that given by various well-known CGCM's (Coupled General Circulation Models), 15-year running averages. The model results up to the period of observations correspond to control runs with observed input meteorological and marine data. The input data for future prognoses correspond to so-called A2 and B2 scenarios (IPPC-TAR, 2001) of estimated greenhouse gas releases in the future. (The model data: HADCM3, Hadley Centre, U.K; CSIRO-Mk2, CSIRO, Australia; CGCM2, CCCMA, Canada. Web home pages.)

3. Concluding remark

The most essential findings in the study may be summarized as follows

From the early 20th century up to 1980s the extent of the Baltic sea ice, ice thickness and length of ice season in the Northern Baltic and the Gulf of Bothnia do not show a trend of ice winters getting milder. This is in a regional contradiction to the general warming of the Northern Hemisphere in the period.

The various sea ice characteristics indicate a distinct and quantitative interdependence (correlation) with the air temperature, except in Kemi (northernmost end of the Bay of Bothnia). The reason for the latter seems to be physical, and, as to the easternmost end of the

Gulf of Finland, a scientific speculation might suggest similar weaker air temperature interdependence there also.

For diagnostic studies and hindcasting, observation based relationship between ice characteristics and the air temperature can be used, but for prognostic purposes special concern should be given. Sensitivity tests and effects of relative changes might be studied.

As the primary wintertime forcing, NAO affects the weather and climate, and sea ice characteristics in a high degree. The causal effects and dependencies found can be used as a prognostic tool for estimation of major variations and general trends. However, the NAO index cannot yet be estimated by the GCMs.

Sea ice observations and studies of sea ice variations and climatology give, beside the daily sea ice services, useful and practical information for winter navigation. This should be especially the case in the stage we can give proper longer-term prognoses and forecasts for tactic and strategic planning, e.g. in terms of forecasting such things as those given in Figure 9.

Acknowledgement

The colleagues at SMHI, and Professor Anders Omstedt especially, are kindly acknowledged having discussions and co-operation within the studies of sea ice climate. Dr. Kirsti Jylhä, Finnish Meteorological Institute, is acknowledged for helping to get the CGCM model data.

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Time series analysis of synthetic aperture radar data of sea ice in the Bothnian Bay, Baltic Sea

Maria Lundin and Bertil Håkansson

Swedish Meteorological and Hydrological Institute, Nya Varvet 31, SE-426 71 Västra Frölunda, Sweden

1. Introduction

Synthetic Aperture Radar (SAR) is a satellite sensor widely used within sea ice applications, but encounters difficulties due to the variable characteristics of the sea ice system. The snow cover on ice has an effect on both the thermodynamics in the air-sea-ice system and the dielectric characteristics vital for the interaction within microwave remote sensing of sea ice. SAR data are used within ice services. The Swedish, Finnish and German ice-breaking services use Radarsat SAR images operationally for navigating.

The aim is to increase our knowledge of snow covered first-year brackish water sea ice and its interaction with SAR signals. The overall objective of the work is to increase the usefulness of SAR images by developing the interpretation of the images. Future use of SAR data includes modelling input data, climate studies and sea ice monitoring.

Since SAR is an active sensor, i.e. both transmits and receives its own signal, it is independent of daylight in its acquisition of data. Furthermore, SAR can measure through clouds due to the long wavelength used and is hence suited to winter and cloudy conditions. However, the SAR signal is not weather independent, since the backscattered signal is affected by the wetness in the scattering layer. The snow cover has a large effect on the ice, in terms of both roughness and its dielectric properties, which are vital for the behaviour of the backscattered signal in SAR and microwave applications.

In the following two projects are briefly described. The first shows how the temperature dependency of SAR data has been investigated for a time series of 17 ERS-1 SAR images from the Baltic Sea and an empirical relationship between the backscatter coefficient and the air temperature has been determined. Furthermore, an algorithm for determining sea ice concentration in Baltic Sea from Radarsat SAR data is described.

2. Temperature dependency in SAR data

Our interest is to explain temporal variability of first year sea ice backscatter coefficient and the influence from weather parameters. For this, a time series of 17 SAR images, measured by the satellite ERS-1, from the northern most part of the Bothnian Bay has been studied. Basically the air temperature, which is strongly correlated with air water content in this area, determine the snow moisture working as a filter for SAR sea ice backscatter. Wet snow can totally blank out the underlying sea ice in SAR images. This is illustrated in figure 1 where the decrease in backscatter is clearly seen. There are 12 days between the images and the ice situation has not changed between the two dates according to the ice charts while the air temperature changed from -8°C in the left image to 1°C in the right image. This means that the decrease in backscatter must be due to surface changes.

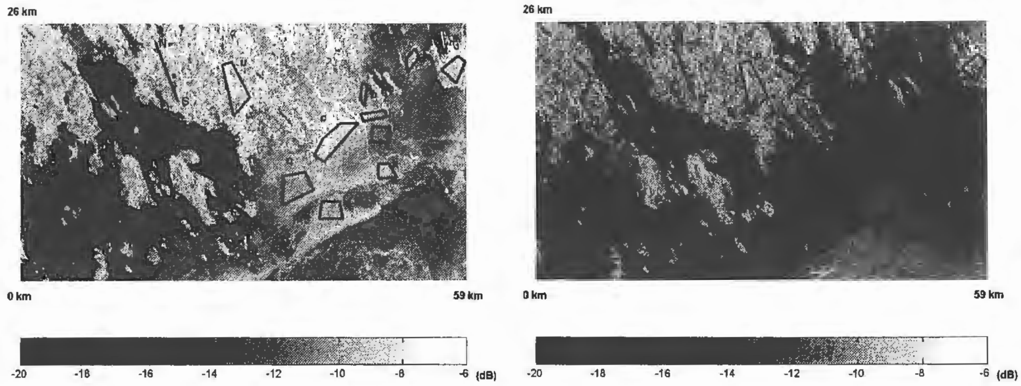

Figure 1: The temperature dependency in SAR data is illustrated in the two scenes above. Left) The SAR signal penetrates the dry snow on the ice (air temperature -8°C) and scatters from the ice surface. Right) The air temperature is 1°C and the wet snow on the ice absorbs the SAR signal (right).

The backscatter coefficient in figure1 has mainly decreased between the two images in areas with rough ice, while smooth ice is more or less unchanged. Under cold conditions when the snow on the ice is dry, the microwave signal penetrates through the snow and interacts with the ice surface underneath. On the other hand, when the snow is wet the penetration depth of the radar signal decreases and the signal is scattered from the snow cover. The snow becomes visible to the radar. At the same time the backscattered signal decreases due to absorption in the wet snow layer. There is less snow on plane surfaces due to wind, which could be a reason for the small changes in backscatter on smooth ice.

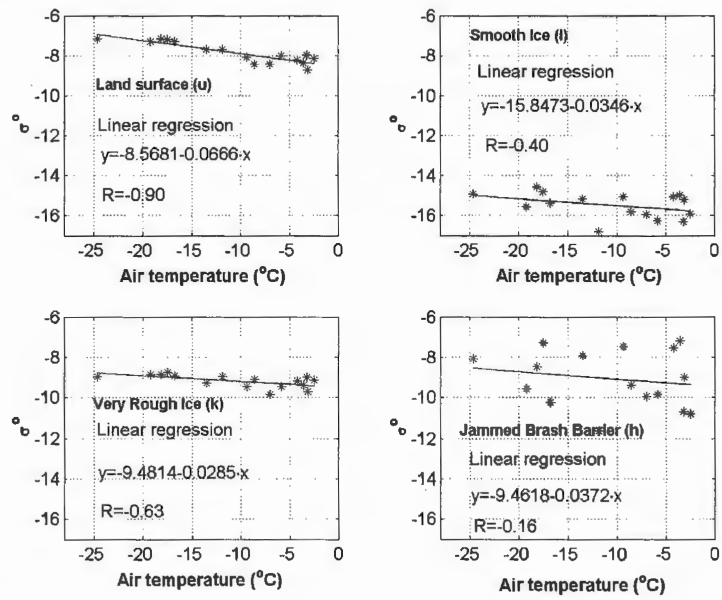

Figure 2: Backscatter coefficient versus air temperature for different surface types in the SAR scene. The regression lines and the correlation coefficients (R) are stated.

In this study the backscatter perturbations governed by air temperature are investigated. Spatial mean backscatter values from 21 selected test sites are correlated against the air temperature. In addition, linear functions are fitted to the data sets. The relation between the SAR backscatter value, σ^0 and the air temperature is shown in figure 2 for four different surface types. The SAR backscatter shows a weak but distinct decreases with increasing air temperature for all surfaces. The decreasing trend of the backscatter coefficient for increasing temperature is contradictory to results from Arctic sea ice *Barber et al. (1999)*. The conflict is probably due to differences in salinity between the two sea areas, which influences the backscatter mechanism.

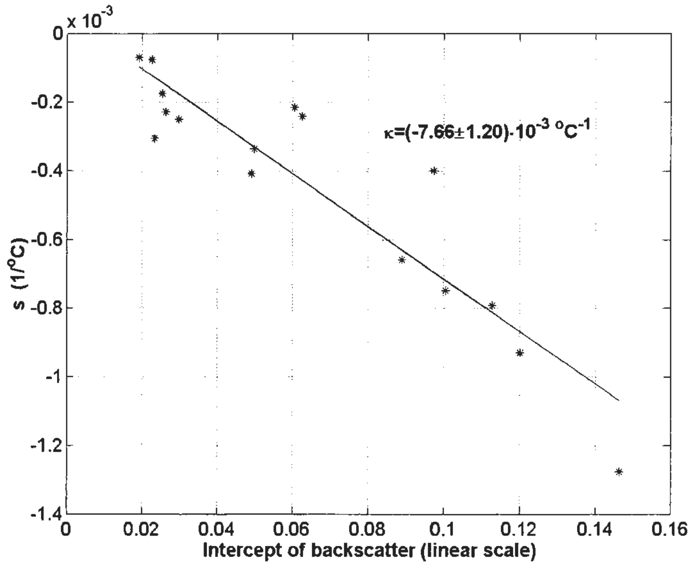

Figure 3: The slopes from the regression lines in figure 2 and from the other test sites versus the intercept of the same regression lines.

The slope parameter s, which is shown four example of in figure 2, is strongly correlated with the intercept of the backscatter coefficient, σ^0 for all test sites in the study, see figure 3. The linear relation in figure 3 implies that rough ice is more sensitive than smooth ice to air temperature changes. The linear relationship between slope and intercept gives us the following temperature dependency of σ^0:

$$\sigma^0 = \sigma^0_{T_0}(1-\kappa T) \text{ for } T_{air} < -1^\circ C,$$

where $\sigma^0_{T_0}$ is the intercept of σ^0 and κ describes the slope in figure 3 and is calculated as (-7.66±1.20)·10^{-3} $(°C)^{-1}$.

It can be concluded that snow-covered sea ice backscatter is weakly but distinctly linearly dependent on air temperature below –1 °C, which can be compensated for by reducing each pixel value to its local intercept $\sigma^0_{T_0}$, taking into account the empirically determined equation above. Backscatter sensitivity increases with the magnitude of the backscatter coefficient, characterising the ice type, when air temperature decreases. The hypothesis of the scattering mechanism needs further investigation.

For air temperatures above -1 °C, the backscatter coefficient decreases dramatically and most ice surfaces are merging towards the same level of backscatter, which leads to loss of image contrast. The fact that the Baltic Sea plays an important role, economically, for the shipping industry and climatologically for the region, stresses the importance of further studies in the area.

3. Sea ice concentration derived from Radarsat data

A sea ice concentration algorithm determining sea ice concentration from SAR data have been developed and applied on Radarsat SAR scenes from the BALTEX/BASIS winter experiment period carried out in the Northern Quark 1998. The algorithm is based on local threshold, developed in *Dokken et al. (2000)*, where the thresholds are partly manually extracted. Radarsat scenes of the type ScanSAR Narrow have been used in the study. Each image covers an area of 300×300 km^2 with a resolution of 50 m.

The sea ice concentration algorithm is based on local threshold in order to work on non-calibrated SAR data. The thresholds are determined from manually extracted water and ice values typical for the area each threshold is working on. Since the SAR sensor looks sideways there is a range dependency in the SAR data. Influence from the range dependency is avoided when several thresholds are defined along the range direction in the image.

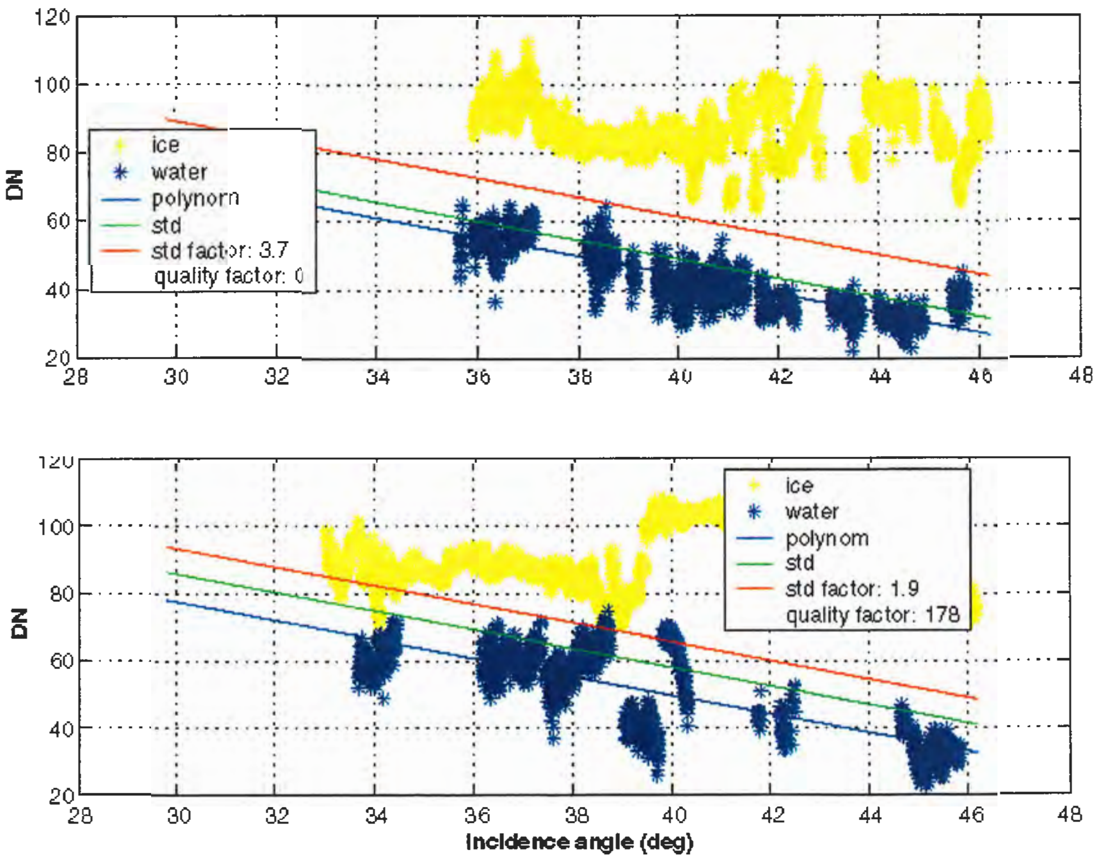

Figure 4: Two examples of threshold extraction from Radarsat scenes from February 18 and 25, 1998.

The diagrams in figure 4 show backscatter values of open water and ice for different incidence angles from two Radarsat scenes from February 18 and 25, 1998. The values have been extracted manually from typical water and ice areas. In order to reduce the influence of speckle, each point represents a mean value of several pixels. The blue and green line represent water mean backscatter and standard deviation from mean, respectively. The red line represents the chosen threshold between water and ice. In order to achieve as true separation as possible between water and ice the threshold is optimised at 1.9 times the standard deviation. Least number of the manually chosen pixels is miss-classified at that level.

The range dependency in the SAR data in figure 4 is clearly seen among the water pixel values, which increases with decreased incidence angle. The range dependency is not that clear in the ice data due to many different ice types that conceals the range effect. In the upper diagram there is a clear separation between open water and ice backscatter values which is due to favourable weather condition with very low wind and low air temperature that increases the contrast in the image. That kind of weather condition is not only an advantage since the production of new ice increases on large areas, which is difficult to distinguish from open water by a threshold. In the same way as the new ice, level fast ice is sometimes miss-classified into water. In order to prevent that the land fast ice is masked by the 10-metre bathymetry data that is assumed to cover the main part of land fast ice areas. Furthermore large open water areas are manually masked. Such areas have a higher backscatter value than smaller water areas due to wind influences.

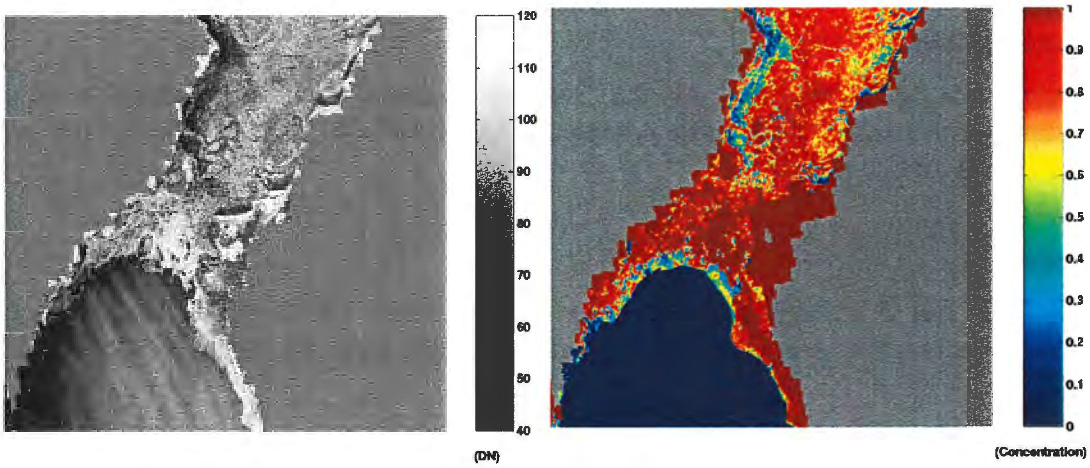

Figure 5: Left) Radarsat ScanSAR Narrow scene from February 18, 1998. Right) Sea ice concentration algorithm applied.

In figure 5 and 6, the sea ice concentration algorithm has been applied on Radarsat scenes, which covers the northern part of Gulf of Bothnia. The thresholds in figure 4 have been used. When applying the threshold each pixel get the value ice or water with a resolution of 50 metres. In Figure 5 and 6 the data have been averaged into ice concentration between 0-1.

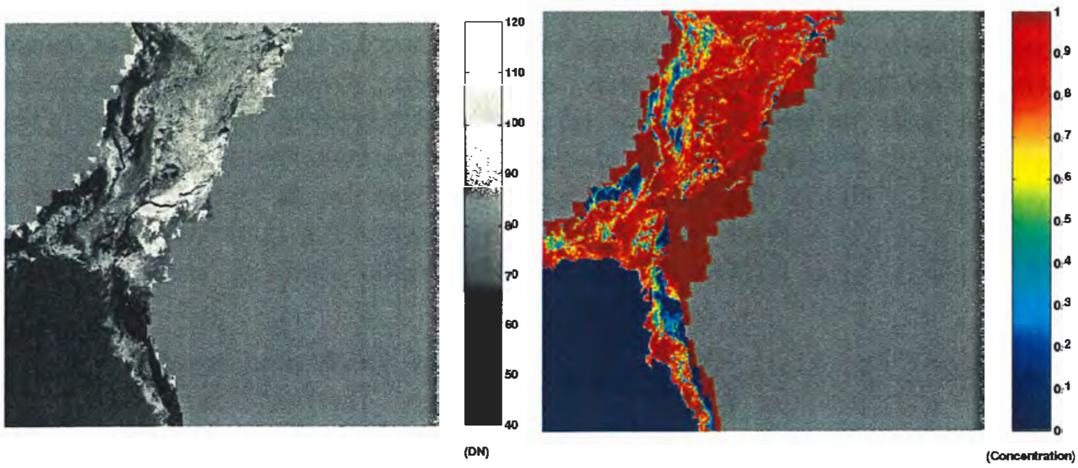

Figure 6: Left) Radarsat ScanSAR Narrow scene from February 25, 1998. Right) Sea ice concentration algorithm applied.

The thresholds determined in figure 4 have been used on the Radarsat scenes that cover southern part of Bothnian Bay and northern part of Bothnian Sea. Open water south of the ice edge in Bothnian Sea has been classified manually. Large open water areas are more affected by the wind and can not be separated from ice by simply a threshold. Land fast ice has been masked by 10-metre bathymetry data.

Acknowledgements

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The development of the Swedish Ice Service during last 40 years

Jan-Eric Lundqvist

Swedish Meteorological and Hydrological Institute, SE-601 76 Norrköping, Sweden

The development of ice observations methods and ice mapping have been rapid during the last 40 years. But also ice forecast methods and ice service have developed as well as the navigation.

During the 60th observations from the archipelagoes and off the coasts were most common. The observations were reported in the Baltic Sea Ice Code. Observations at sea were made 4 times a day by the ice breakers when operating at sea. Also reports by vessels in clear text. Air reconnaissance from helicopter or small air crafts occurred. Development of weather satellites became a chance to a limited overview of the ice extension when clear sky. Then all ice information were collected and manual drawn on an ice chart. The symbols were special agreed by the Baltic countries except USSR. See ice chart below. Weather- and ice forecasts were twice a week made to the Ice Breaking Service.

The ice chart was transmitted on radiofacsimile twice a day. A printed version was made and sent to customers by postal mail twice a week. Also ice reports in clear Swedish and English were broadcasted or transmitted to the navigation by coastal radio.

A real step forwards started at a Sea Ice Conference in Stockholm 3-4 October 1972. Participants from the Swedish and Finnish meteorological and oceanographical institutes, the navigation administrations, navigation companies and the industry were represented.

Board of Winter Navigation Research report No 1 The conference resulted in a research program and a task to start an all year around traffic to the Bay of Bothnia. A demand was focused on an increase of ice strengthened vessels, new ice breakers and improving ice observations and ice forecasts.

A very active period followed during the 70th and 80th. In the beginning the resources were focused on ice drift modelling, ridging of ice but also on the ice physics. Expeditions to the ice field in Bay of Bothnia were organized. During this period the ice winters were easy.(See fig 4) To find ice we had to go to Bay of Bothnia where the "real" ice occurred but also due to the interest of more "brackish water" ice. Bay of Bothnia became a popular ice research laboratory. Comfortable accommodation on board the ice breakers in the ice field made it easier and more effective to handle the equipment. International reseach program were also involved.

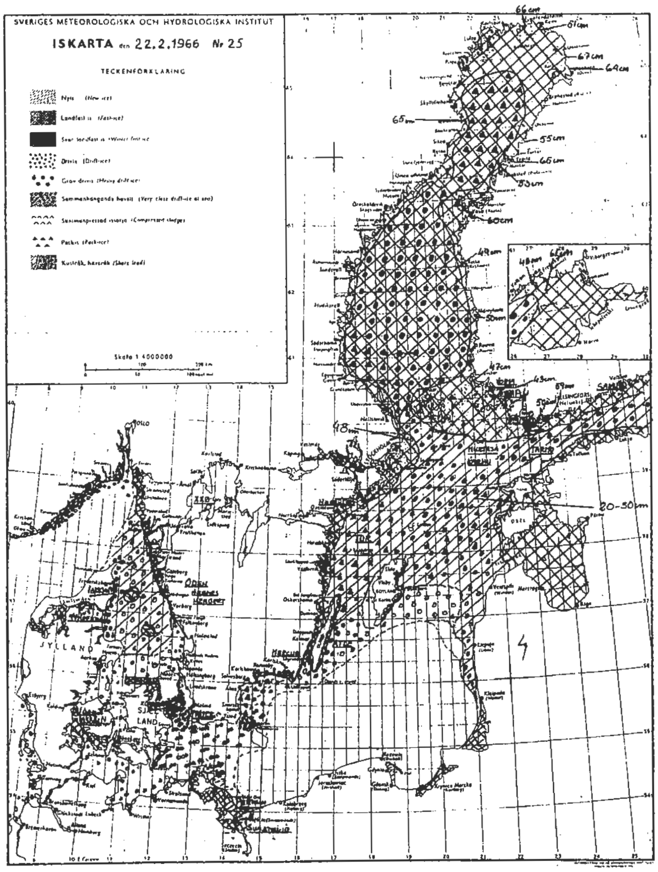

Figure 1:. Ice chart for 22 February, 1966.

An international remote sensing program, Sea Ice–75 (*Winter Navigation Research Bord, report No 16:1-9 1976*), made tests of SLAR (Side Looking Airborne Radar), NOAA visual and infrared images compared with air photos from 1500m high and ground trough.

Another big research program was BEPERS–88 (Bothnian Experiment in Preparation for ERS-1). (See *Winter navigation Research Bord, reports No 45 – 48*).

Development of computer models for cooling and freezing of water together with currents resulted in the PROBE-Baltic model and later on the BOBA-model which is used today together with HIROMB (High-Resolution Operational Model for the Baltic Sea).

The co-operation between the Baltic countries ice services was increased. The BSIM (Baltic Sea Ice Meeting) was from 1977 arranged every second year. It resulted 1981 to a revised Baltic Sea Ice Code in four figures instead of three. The ice symbols on the ice charts became international, named "the egg code". But also the exchange of ice information was intensified. An international ice nomenclature was established and published. (*The Baltic Sea Ice Code, description with illustrations of the code valid from October 1981. SMHI 1981).*

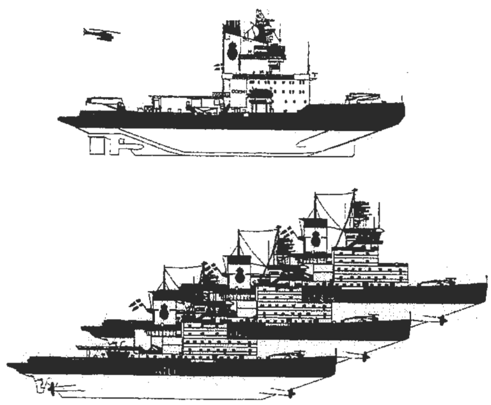

Figure 2: New Swedish ice breakers during the 70th and 80th.

New more powerful ice breaker were built both in Finland and Sweden. Development of new thechnical communication system and transmissinon improved the change of information between the icebreakers, the merchant vessels and the ice services. Today the computer system called IBNET (IceBreaker Network)and IBPLOTT (IceBreaker Plotting program) made the change of information of clear text and charts very rapid.

In co-operation between Finland and Sweden an Ice Atlas was published 1979: *Climatological Ice Atlas for the Baltic Sea, Kattegat, Skagerrak and lake Vänern (*1963-

1979.)

After all these reseach the technical development improved the use of the ice knowledge. The satellite images became better and the use of SAR improved the ice analysis. Some images from ERS 1 1992 were used but more operational ERS 2 from 1997. The first RADAR-SAT images was used 1998. Due to the easy ice winters since 1988 (except normal ice winters 1994 and 1996) the use of ERS and RADARSAT has been concentrated to the Bay of Bothnia and Gulf of Finland. The technical development of drawing program resulted in ICEMAP-system for digital chart construction. (See fig 3).

The tranmission of ice charts to the ice breakers is made in the ICEMAP–system. To other users E-mail, Internet and fax have increased the ice information and been more effective. The navigation to ice fasted waters have also increased.

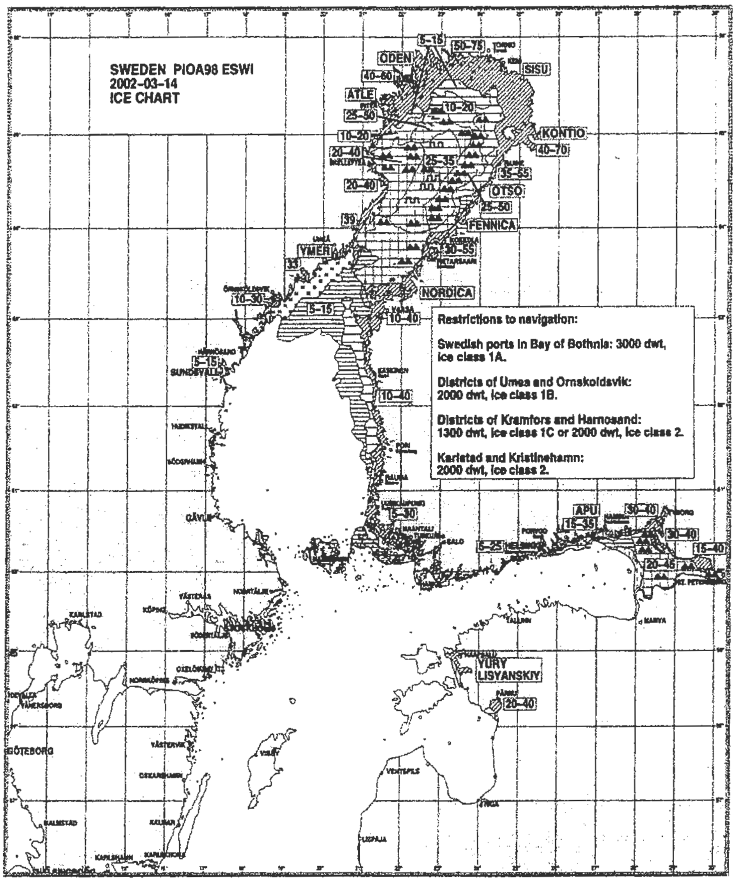

Figure 3: Ice chart 14th March 2002 showing one period with max ice extention.

As you see this 30-40 years have been a very exciting period in the ice development. We know more of the ice behavior but we worry about the lost of real ice winters. Hopefully, all this ice reseach will not be in vain. We are waiting for next severe ice winter. See fig 4 next page.

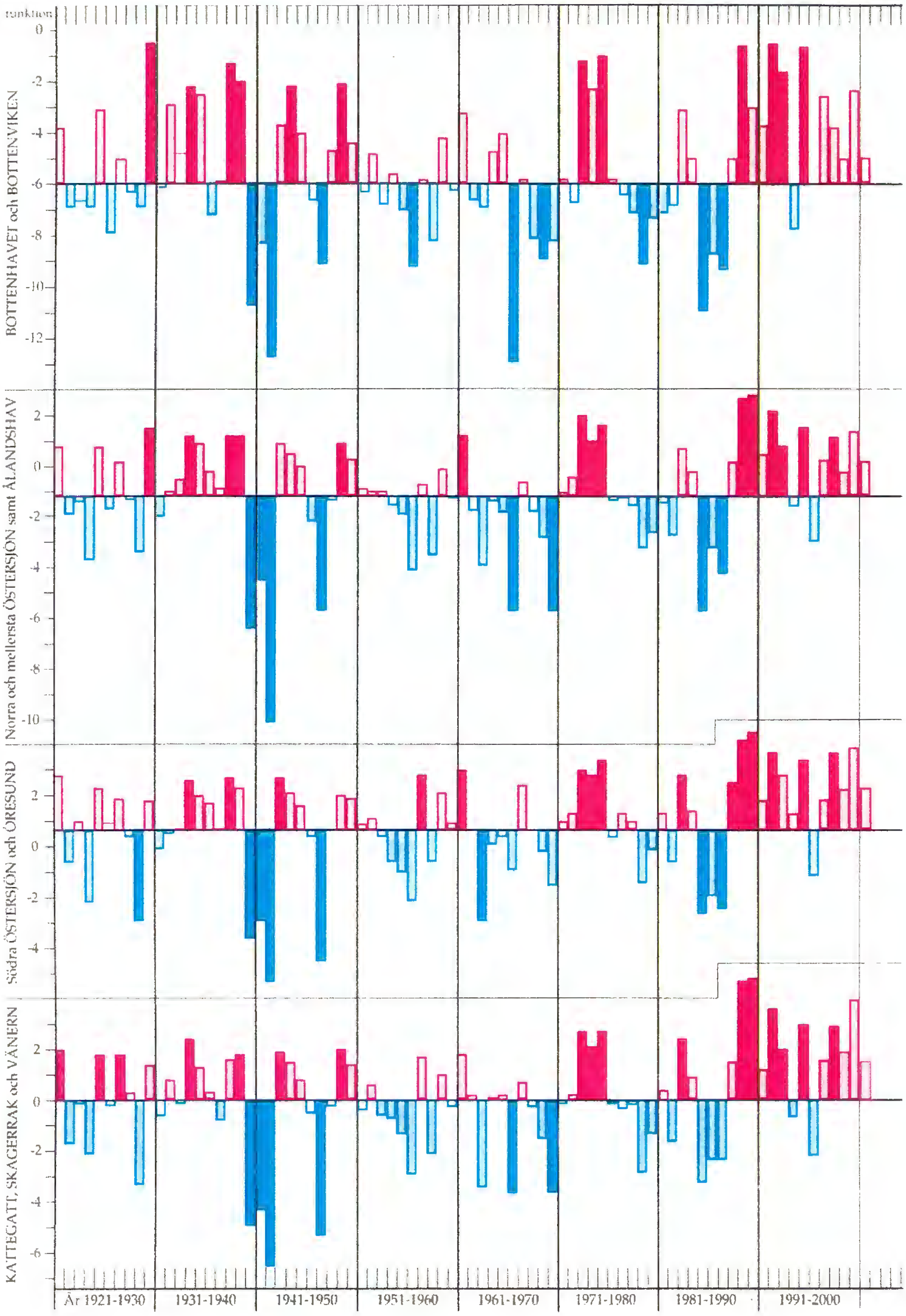

Figure 4: Degree of diffculty for the winters 1920/21 – 2000/01 as a funtion of the air temperature. Red table show easy icewinter, blue severe icewinters, unfilled normal. 1st diagram show Gulf of Bothnia, 2nd northern Baltic, 3rd southern Baltic and the 4th Kattegat and Skagerrak.

Some aspects of the Baltic Sea ocean climate system

Anders Omstedt

Earth Sciences Centre, Department of Oceanography, Göteborg University, Sweden

1. Introduction

The objective of the presentation is to highlight the Baltic Sea ocean climate system. The climate system in this connection is defined as the statistical properties of salinity, ice, temperature, sea levels, in- and out-flows to and from the Baltic Sea. Calculations of these parameters should include seasonal and inter-annual means as well as extremes. The number of relevant publications in the area is large and only references to some recent studies will be given.

2. Salinity

The present climate of the Baltic Sea with regard to the salinity and the freshwater budget was analysed by Winsor et al. (2001, 2002). In Figure 1, the Baltic Sea mean salinity is shown as 5-year running mean together with the surface salinity in the Bornholm Basin. We notice that the mean salinity of the Baltic Sea has varied between about 7.1 and 8.2‰ during the 20th century, with a typical time scale of thirty years. The surface salinity in the southern part of the Baltic Sea is well correlated with the mean salinity of the Baltic Sea (calculated using data from the Gotland Deep). There is no long-term trend found during the century. The figure illustrates that climate control runs must cover several decades, probably up to 100 years, to catch the natural variability of today's climate.

3. Ice and temperature

Some interesting long-term sea ice and temperature time series are available in the Baltic Sea. Jevrejva (2001) has recently presented an analysis of the severity of winter seasons in the northern Baltic Sea based on data from 1529 to 1990. Koslowski and Glaser (1999) presented results from the western Baltic Sea based on a time series from 1501 to 1995. Annual maximum ice extent data for the Baltic Sea are collected by the Finnish Institute of Marine Research and is available from 1720 to present. The influence of atmospheric circulation on the maximum ice extent in the Baltic Sea was recently analysed by Omstedt and Chen (2001). Figure 2 shows the anomaly from the long-term mean, which indicates that the significant trend earlier identified may be a result of a sudden change in the means. This change can be indicated by a "change point" in the mean of the ice extent series. The change point divides the total series into two periods of approximately equal length, with the transition corresponding to the end of little ice age and the beginning of industrialisation. Any studies of the long-term change need to consider the little ice period, a period which also can be found in other parameters as for example the in the Stockholm sea level time series (Ekman, 1999).

The variation of the maximal ice extent during the 20^{th} century is illustrated in Figure 3. The slight negative trend indicates a reduction of sea ice extent of less than 10% during the century. By using the close relation between winter temperature and ice extent (Omstedt and Chen, 2001, Figure 3a) we can estimate the needed temperature increase for observed ice extent reduction during the 20th century to 0.4-0.6 (^{0}C). This is close to the observed change in the Stockholm winter temperatures and we can thus conclude that the observed temperature increase can explain the reduction in ice extent during the last 100 years.

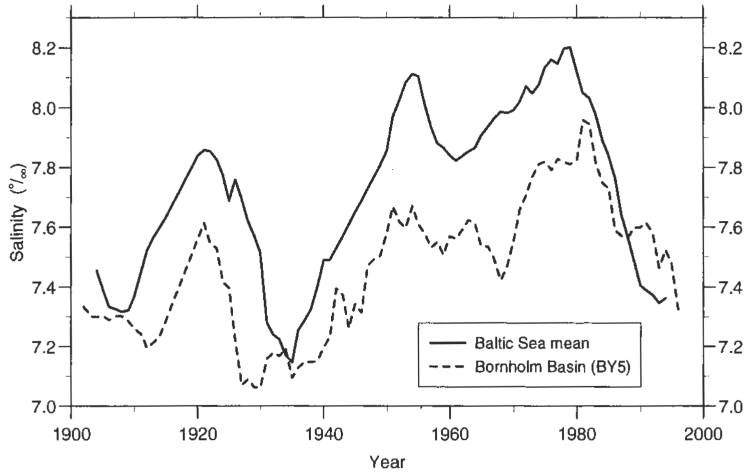

Figure 1: Surface salinity in the Bornholm Basin (BY5) together with the mean salinity of the Baltic Sea calculated from the freshwater content. Both series are 5-year running means. From Winsor et al (2002)

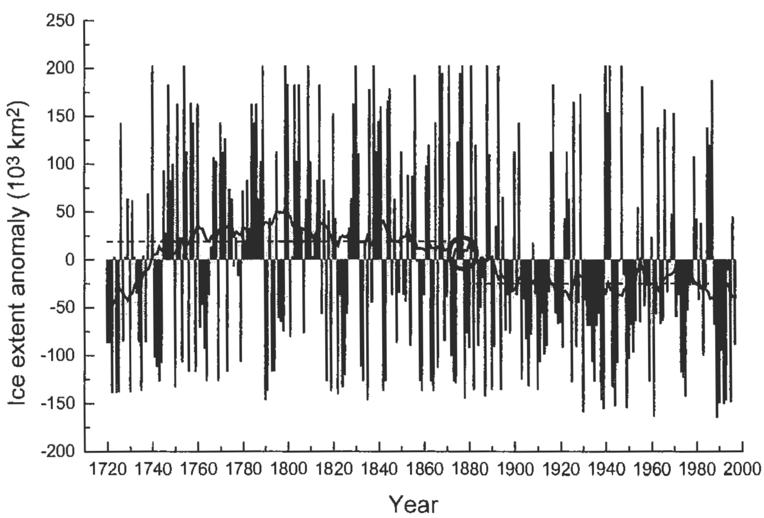

Figure 2: The anomaly (A_i-A_{mean}) of the maximum ice extent, with the change point (circle), 30-years running mean (thick line), and the means of the two subintervals divided by the change point (dashed lines). From Omstedt and Chen (2001).

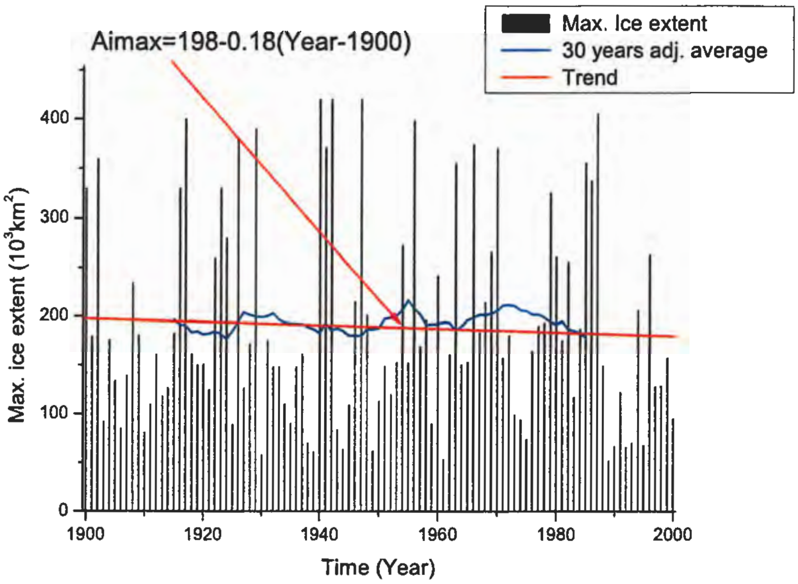

Figure 3: The maximum ice extent during the 20th century.

4. Sea levels

The countries around the Baltic Sea are still adjusting to the latest glaciations, which ended about 10 000 years ago. The postglacial uplift from the southern to the northern Baltic varies today between -1 to 8 mm/year (Ekman, 1996).Due to the salinity distribution in the Baltic Sea the mean sea level drops from the Bothnian Bay to the Skagerrak by about 35-40 cm (Ekman and Mäkinen, 1996 and Carlsson, 1998). Added on these mean sea level states large regional, seasonal and inter-annual variations are observed.

The water exchange through the Baltic Sea entrance area is mainly forced by the sea level differences between the Kattegat and the Baltic Sea and is strongly reduced due to friction. For time scales of months and larger the zonal wind and the basin mean sea level of the North Sea are the driving mechanisms for the Baltic Sea mean level (Wroblewski, 1998, Gustafsson and Andersson, 2001). The strong coupling between large scale atmospheric circulation and Baltic Sea levels has recently been analysed by Andersson (2001) and is illustrated in Figure 4.

5. In- and out-flows

From sea level, runoff and net-precipitation data one can calculate the instantaneous barotropic transports through the Danish Straits. Other methods exists such as direct measurements of the flows but for longer time series one need to use sea level variations across the Baltic entrance area to calculate the through flows. This method has been applied by Winsor et al (2001) when studying the in and out-flows during the last century. In Figure 5 the estimated yearly means of the outflow from the Baltic Sea together with a 5-year running mean are shown. The mean value of this flow, 80×10^3 m^{3}s^{-1}, is about 5 times larger than the river runoff, which is 14×10^3 m^{3}s^{-1}. The standard deviation is 3500 m^{3}s^{-1}, which is about twice that for the river runoff. Variations over a few years dominate but there are also variations over several decades. There is no significant trend, when looking at the whole period, though there is a general decrease from the mid 1940s to the mid 1970s.

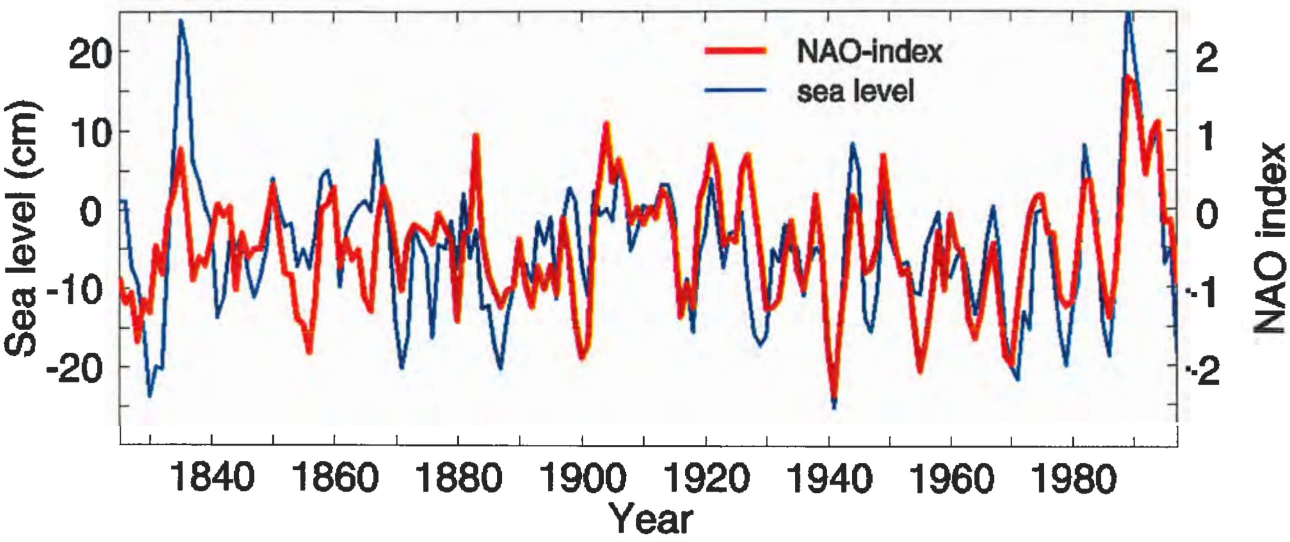

Figure 4: The winter (JFM) mean of the Baltic sea level and the NAO index for the period 1825-1997, smoothed with a 3-year running mean. From Andersson (2001).

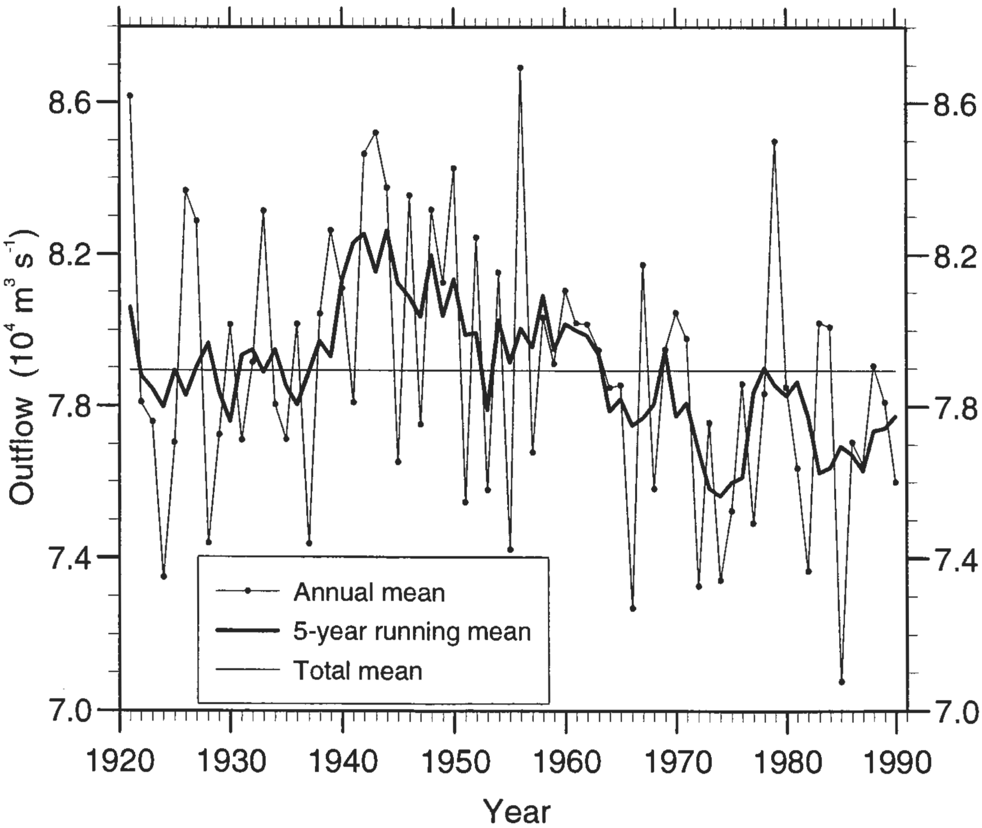

Figure 5: Calculated annual mean outflow from the Baltic Sea. From Winsor et al.(2001).

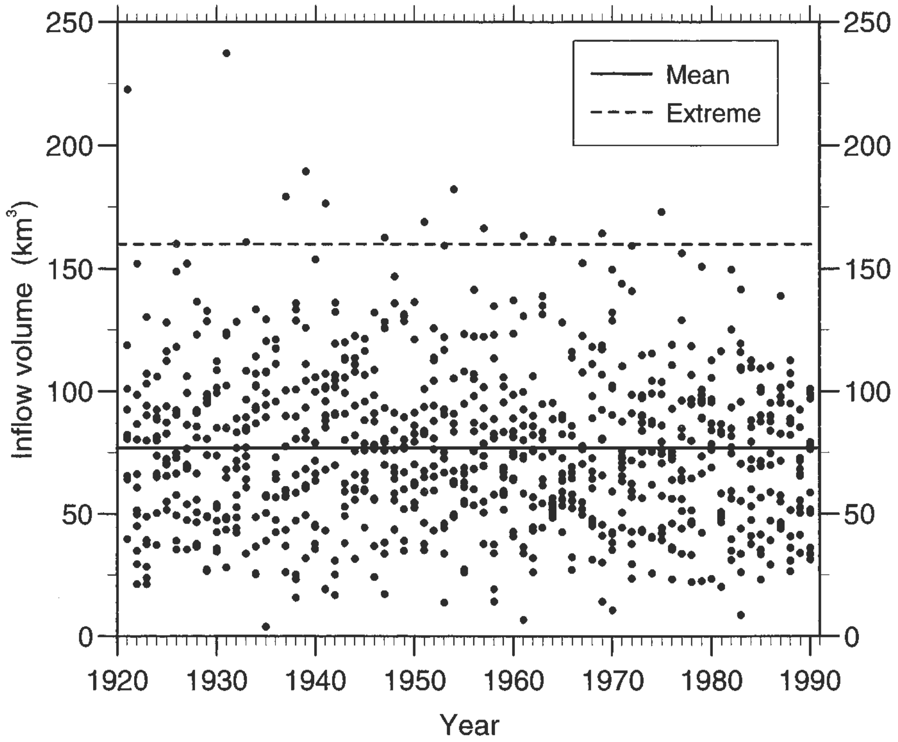

Figure 6: Scatter plot of all modelled consecutive inflow events. From Winsor et al. (2001).

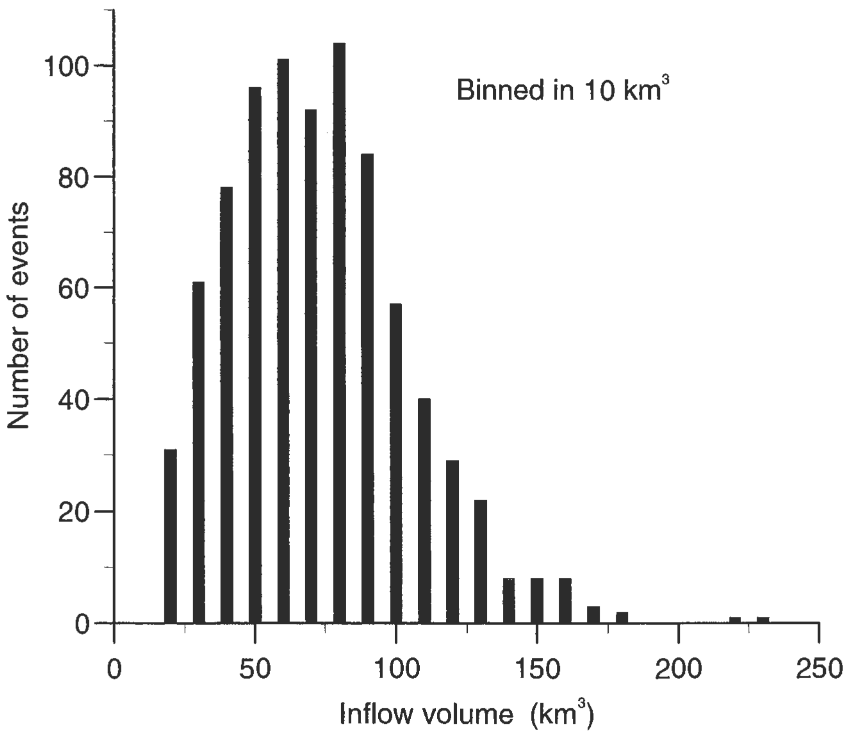

Figure 7: Distribution of inflow events. From Winsor et al. (2001).

Figure 6 shows the estimated volume transport during all inflow events. The average inflow-event transport is indicated. We see a rather even distribution with time. The frequency distribution related to this is shown in Figure 7. The events with the largest inflow volumes can be expected to have carried extra ordinary high salinity and thus have been responsible for renewal of the deepest basin water. An, at the moment, arbitrary chosen limit of 160 km^3 defining extreme inflows is inserted in Figure 6 (dashed line). Matthaus and Franck(1992) presented other ways to characterise major Baltic Sea inflows.

Acknowledgements

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Decadal variability in Baltic Sea ice development analysis of model results and observations

Corinna Schrum[1] and Frank Janssen[2]

[1]Institute of Oceanography, Center of Marine and Climate Research, University of Hamburg, Troplowitzstr. 7, D-22529 Hamburg, Germany, schrum@dkrz.de

[2]Baltic Sea Research Institute Warnemünde, Seestr. 15, D-18119 Rostock, Germany,

frank.janssen@io-warnemuende.de

1. Introduction

The Baltic Sea ice extend has been investigated regularly already for a long time. The Swedish Meteorological and Hydrographic Institute (SMHI) provided ½ weekly maps showing the ice boarder, compactness, different ice classes and the observed ice thickness since 1960. Only from 1960 to 1979 the maps are available as digital data sets. Although this is a valuable data base its length is quite short for climatic investigations. Furthermore the observational schemes and the number of available observations have been changed with time, creating problems in the homogenity of the data common to many observational based analysis of climatic variability. This was the motivation to carry out a more complex analysis of decadal variability of the Baltic Sea sea ice, based not only on observations but on results of a dynamic coupled ice ocean model, forced by atmospheric re-analysis to ensure consistent atmospheric forcing conditions.

As the dynamic modeling creates its own uncertainties and drawbacks, a careful analysis and validation of the model data set is necessary to learn about the statistical behavior of the model results set in comparison to observations and different model hindcast realizations. In the following, results of a 40-years decadal model simulation with a coupled ice/ocean model will be used for the investigation of climatic induced variability. This data set will be validated against observations and compared to another shorter model realization using the European Centre of Middlefrist Weather Forecast (ECMWF) atmospheric forcing data. After detailed validation using observational data provided by the SMHI and SSMR/SSMI based data compiled by the Arctic and Antarctic Research Institute in Russia (AARI), this data set is statistically analyzed to investigate variability on decadal time scales and to identify the correlation between sea ice variability in the Baltic Sea and North Atlantic Oscillation Index.

2. Data bases

2.1 Observational data

One data set which has been used for the present investigation is the gridded BASIS data set (Udin et al., 1981), which is a cmpilations of data from ground based observational systems like shipborne and aircraft measurements and coastal stations, and completed by additional satellite data (AVHRR), so far available. These data have been compiled, analyzed and published with a 1/2 weekly resolution by the SMHI operational ice service. The conducted maps have been digitized for the period 1960-1979 in a joint effort of SMHI and FMR (Finnish Marine Research Institute, Helsinki, Finland), using an approximate 28 km grid. Unfortunately digitized maps of the same quality are not available from 1979 onwards. To fill this gap remote sensing data were used for this period. The AARI provided a data set with a comparable resolution based only on SSMR/SSMI microwave data, compiled in the frame of the

WMO project 'Global Digital Sea Ice Data Bank' (National Ice Center, 1996), in the following named as NIC data. As the microwave sensor shows problems in detecting new ice and has strong problems to distinguish between land and sea ice, the uncorrected raw satellite data show a different behavior concerning the average ice conditions as well as for the observed variability. This is illustrated by a comparison of the average monthly ice conditions estimated from BASIS data and NIC data (Fig. 1). Especially the near coastal ice distribution is considerably underestimated by the NIC data. Furthermore the pattern of ice compactness show a different structure, direction of gradients are shifted up to 90 degree compared to BASIS data.

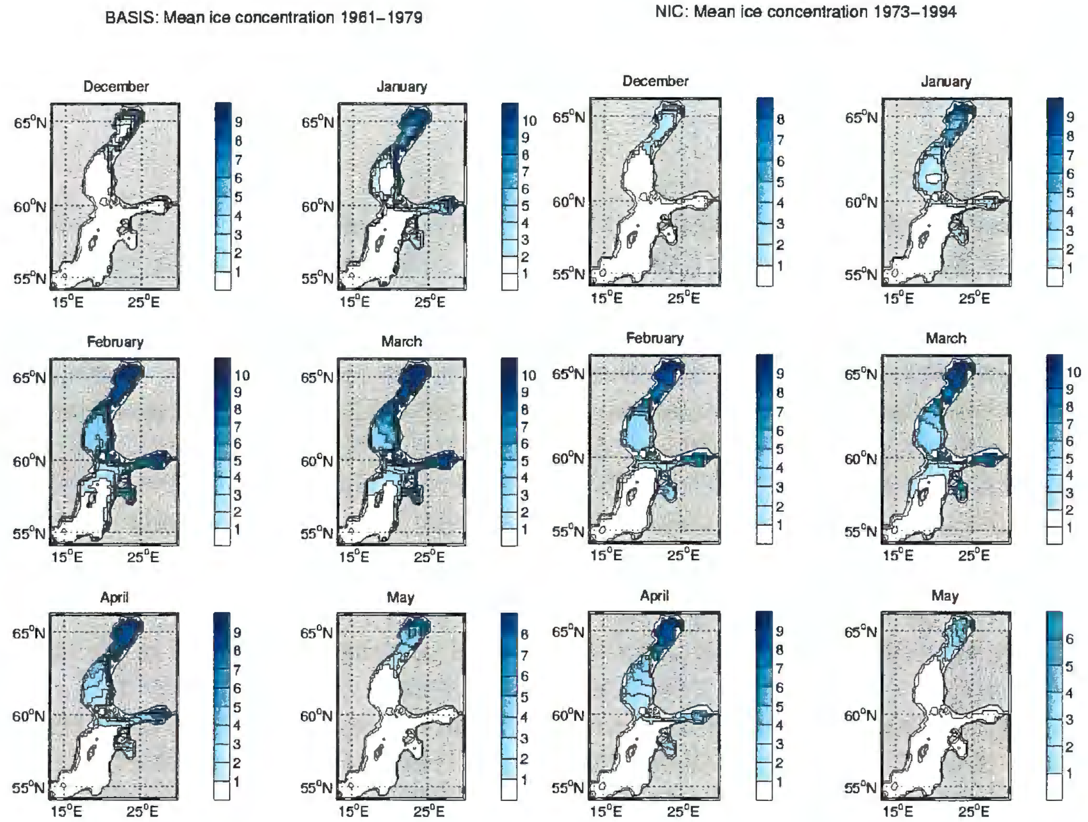

Figure 1: Mean ice compactness 1973-1979 from BASIS data (left) and NIC data (right).

It can be assumed that the BASIS data are more reliable than the raw satellite based estimates, which still needs to be calibrated for the Baltic Sea. Therefore an attempt was made to calibrate the total ice area time series estimated from NIC data by using the independent BASIS weekly ice area time series. The overlapping period for which both data were available, i.e. the period 1972-1979, was used to calibrate the NIC data. By means of a regression analysis, an approximate linear relationship was found which was used to calibrate the entire weekly sea ice time series from NIC (Fig. 2). In Fig. 2 (upper) , the two ice time series are compared, in the middle of Fig. 2 BASIS area estimates are plotted vs. NIC ice area estimates and a linear regression was applied. The regression line was found to be given by the linear relationship $y=ax+b$ with $y=$ *BASIS data*, $x=$ *NIC data*, a=1.2069 and b=1.6 10^4 km^2. The lower plot in Fig. 2 shows the calibrated NIC time series in comparison to the BASIS time series. After calibration both time series show a good agreement, exceptions are found in the beginning and ending of the ice weeks.

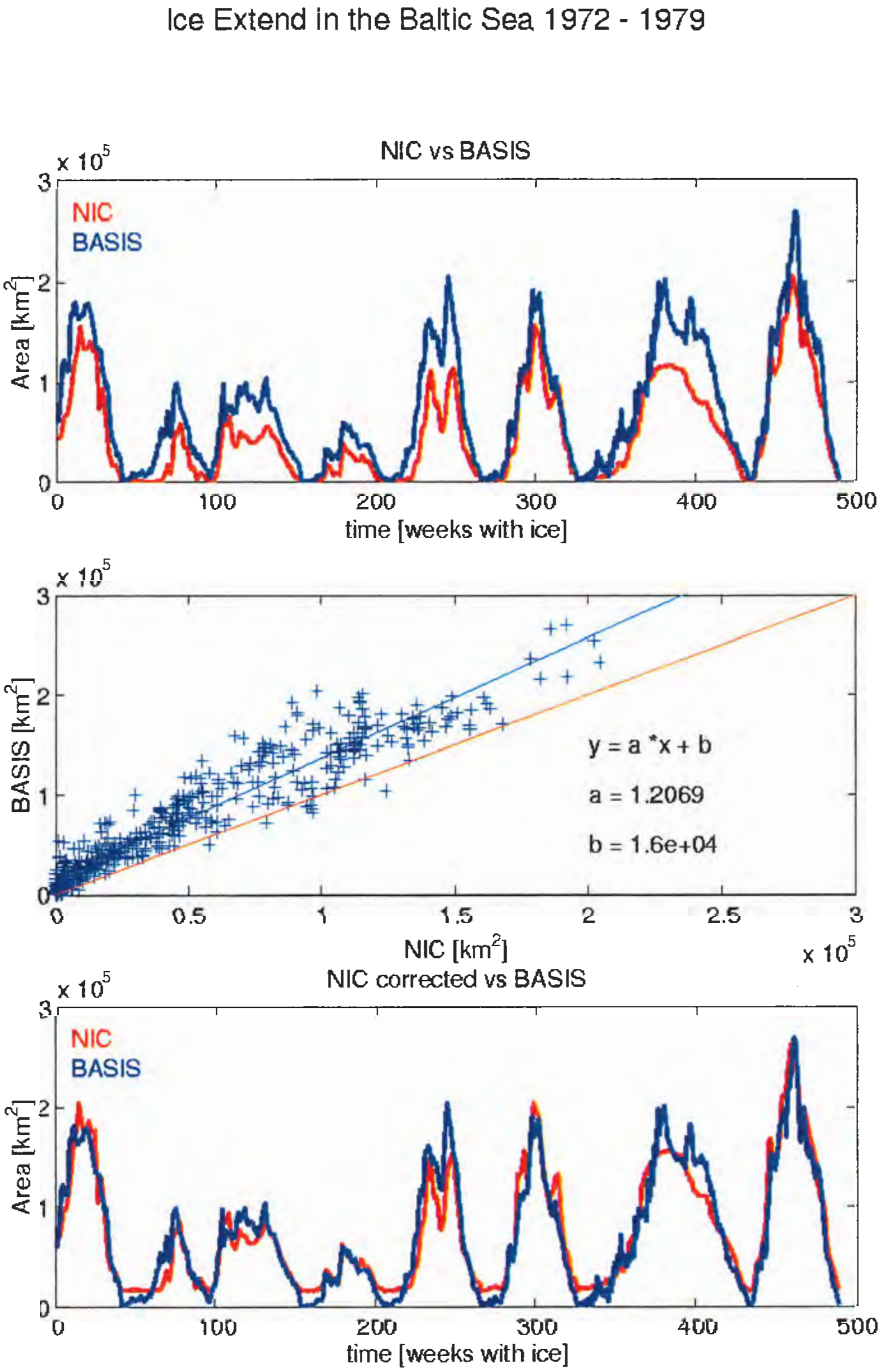

Figure 2: Calibration of the NIC against BASIS data. Upper: Time series of uncalibrated NIC data (thick line) and BASIS data (thin line), weekly resolution. Middle: Scatter plot of NIC ice area data vs BASIS ice area data. The corresponding regression line is given. Lower: Calibrated NIC ice area data and BASIS ice area data. The units are km^2.

2.2 Modeled data

The modeled data sets which were used in addition to the observational data are results of a coupled ice/ocean model with an approximate resolution of 10 km. The model has been introduced by Schrum (1997) and was in detail described by Schrum and Backhaus (1999). In the present configuration the model is forced by the atmospheric boundary conditions for mean sea level pressure, 10m winds, 2m air temperature, 2m dew-point temperature, precipitation and radiation (short wave and long wave).

Turbulent fluxes are estimated using an atmospheric boundary layer approach, based on Monin-Obukhov similarity theory (1954), applying an iterative scheme similar to that one firstly given by Launiainen and Vihma (1990).

Initial and boundary conditions for temperature and salinity were taken from Janssen et al. (1999). Additionally an annual correction for temperature and salinity was applied at the open boundaries, taken from available observations compiled by Janssen et al. (1999) from various data bases. At the open boundaries the model is forced by daily sea surface elevations calculated by a diagnostic shelf-break model (see results presented by Smith et al., 1996) and additional tidal elevations. River runoff for the Baltic Sea is taken from a data base created by Bergström and Carlsson (1994). For the North Sea the run off data were kindly provided by Peter Damm and Johannes Pätsch (Institute of Oceanography, University Hamburg, Germany), who compiled data from various sources (for details see Damm, 1997). Missing data are replaced by the monthly climatology for the runoff of respective rivers and additional variability was reconstructed by application of statistical relationships between neighboring correlated runoff-regions.

Two model simulations have been used for the following investigations: The first one was carried out for the period 1979-1993 by using the atmospheric forcing provided by the ECMWF (Gibson et al., 1996), in the following referenced as ERA-15 run. This run has been validated in detail, using a number of different observational data (Schrum et al., 2000; Janssen et al., 2001; Janssen, 2002). The second run which has been used in the frame of this contribution was forced by the NCEP re-analysis data (Kalnay et al., 1996). The latter are meanwhile available from 1949 onwards, the model run presented has been carried out for the period 1958-1997.

3. Validation of modeled data

The calculated monthly mean ice compactness estimated from ERA-15 forcing and from NCEP-40 forcing show distinct differences, caused by the differences in the atmospheric forcing. Main problems in the NCEP re-analysis are to be found in the short-wave radiation (see as well Semmler, 2002). This results in under-estimation of ice production in winter time and under-estimation of ice melting in spring and summer. The latter results in sea ice occurrence in the northern Baltic up to the late summer. This is in contrast to natural Baltic Sea ice conditions which typically show vanishing ice latest in the beginning of June (see Climatological Ice Atlas for the Baltic Sea, Kattegat, Skagerrak and Lake Vänern 1963-1979; Anonymous, 1982). As well under-estimated are the calculated monthly mean ice compactness (Fig. 3). The calculated values are below 0.5, whereby the observed ice compactness from BASIS data base reaches values up to 1 in monthly mean, i.e. a closed ice surface occurs typically at least in the near coastal and most northern region of the Baltic Sea.

In contradiction to the NCEP-40 run, the climatological ice conditions from the ERA-data show strong similarities to observed ice conditions. The extend as well as the regional pattern of the ice compactness show similar structures to observations and the seasonal cycle is well reproduced. Maximum calculated ice compactness is up to 0.9 and thus close to observations. Slight differences between BASIS pattern and calculated ERA-15 pattern are in the range of inter-annual variability caused by the different integration periods (1973-1979 for the BASIS data and 1979-1994 for the ERA-15 calculations).

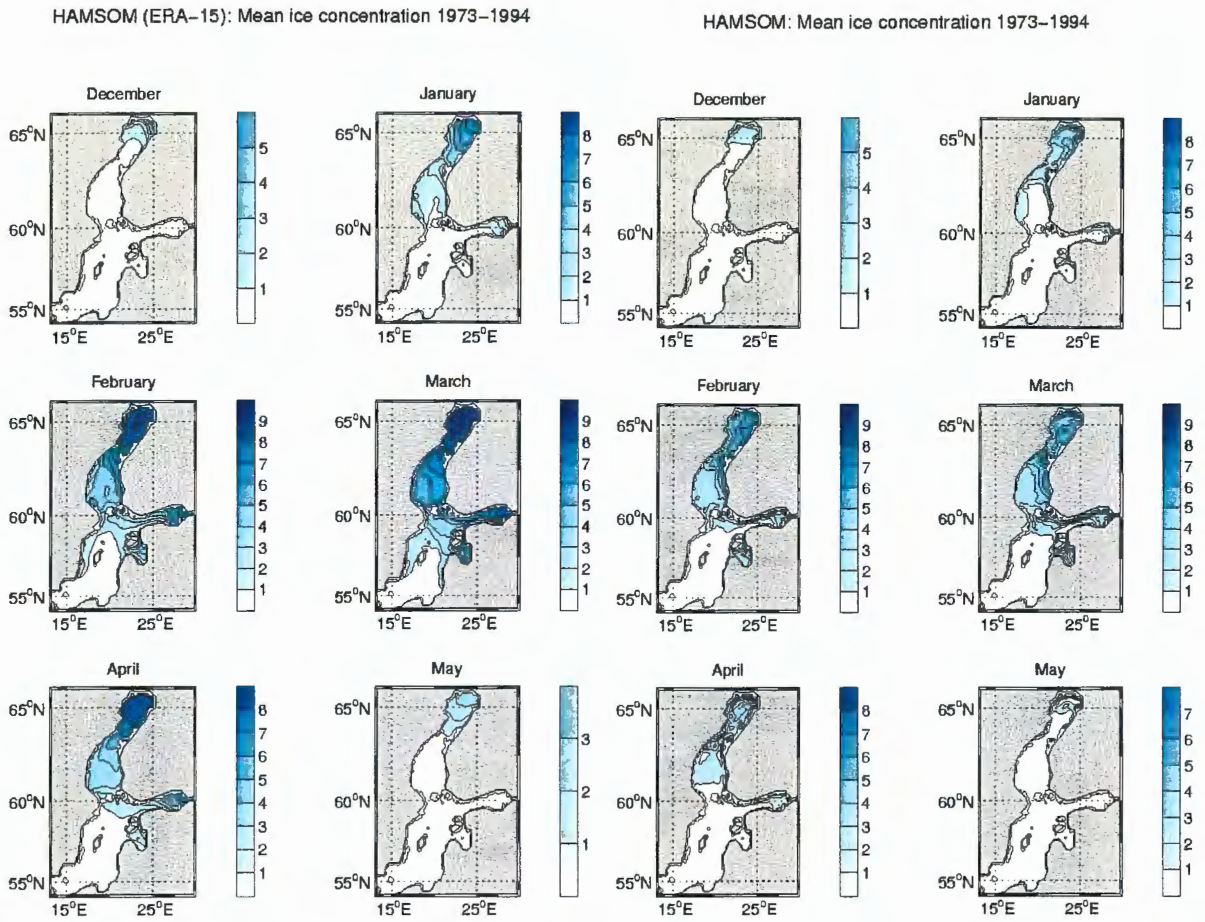

Figure 3: Calculated monthly mean ice compactness from the ERA-15 run for the period 1979-1994 (left) and NCEP-40 run 1973-1979 (right).

In Figure 4, the monthly anomalies of ice covered area for the months December, January, February, March, April and May are plotted for the different observational and modeled data sets. The observational time series is combined from the BASIS time series and the calibrated NIC time series (from 1979 onwards). It is obvious that the estimated variability shows apart from the generally good agreement some differences: Although the correlation between observations and model results from the NCEP-40 run are quite high (r=0.9 for 1979-1993; r=0.85 for 1961-1994), the modeled variability is significantly under-estimated compared to observations (explained variance EV=68.58 % for 1979-1993 and EV=63.14 % for 1961-1994). This is not the case for the ERA-15 forced run: The correlation is slightly higher (r=0.94) and the explained variance is significantly higher compared to the NCEP-forcing (EV=86.31 %). These results indicate that even though the NCEP-40 run is not able to reproduce well the typical seasonal cycle, the results of the NCEP-40 run can be regarded as valuable for correlation analysis of the climatically induced variability in sea ice, due to the high correlation to observations. This of course is not the case for estimates of the strength of variability, which is significantly under-estimated compared to observations.

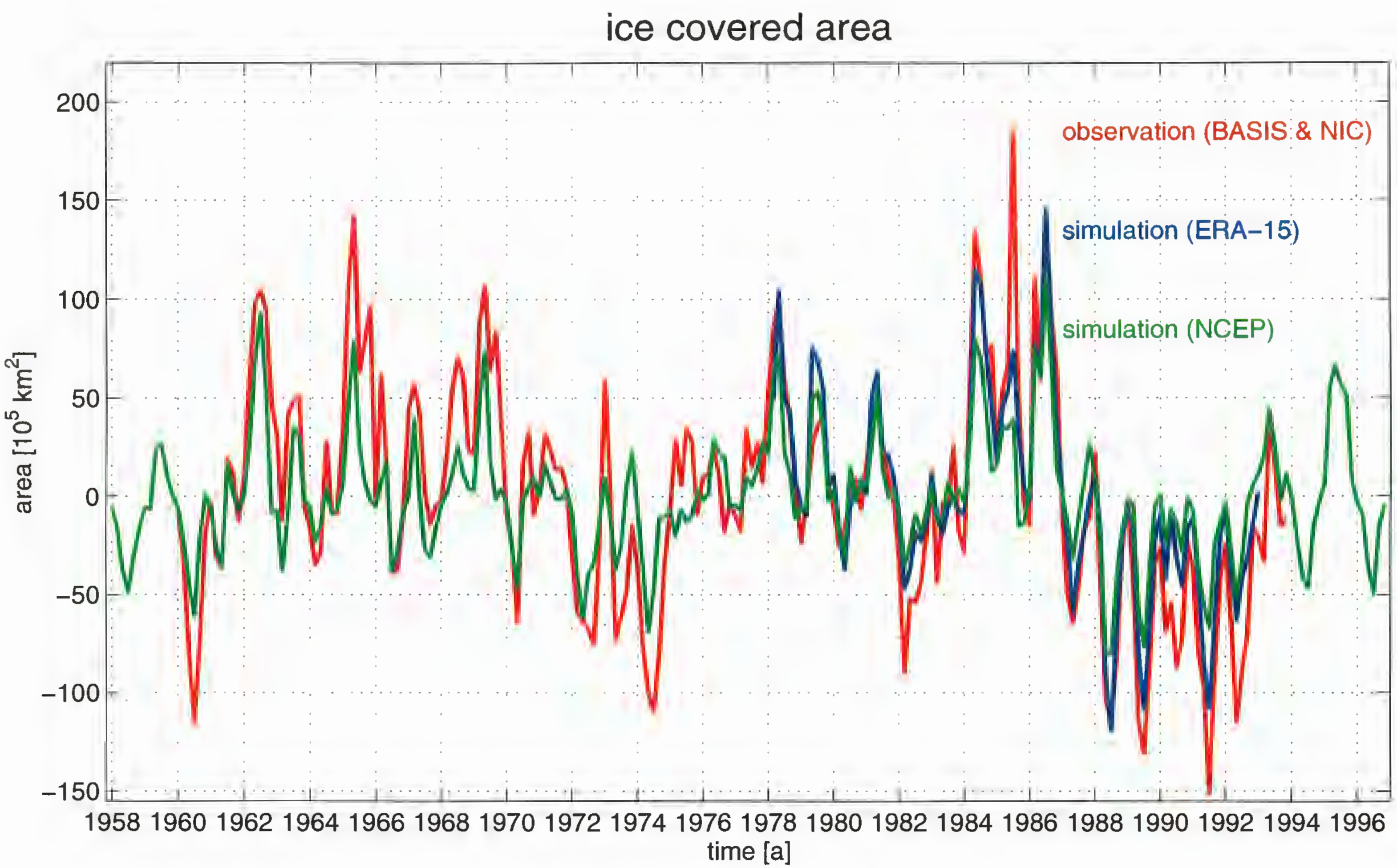

Figure 4: Calculated anomalies of ice covered area for the BASIS/NIC time series and the NCEP40, and ERA-15 runs.

4. Results

4.1 Correlation to NAOI

As the North Atlantic Oscillation Index (NAOI) is known to be an important climatic index for Northern Europe, and previous authors have shown that the maximum ice extend in the Baltic Sea is correlated to NAOI (Omstedt and Chen, 2001; Tinz, 1996) the correlation to NAOI will be investigated in the frame of this contribution. Former analysis of e.g. Omstedt and Chen showed that the NAOI is of varying significance for the North European Climate in time. Thus, the temporal development of the correlation will be analyzed additionally using the moving correlation in time. The length and consistence of the modeled NCEP-40 run time series of the sea ice anomalies thereby is an advantage compared to former analysis based only on observations which have been collected from various sources. E.g. the time series of maximum ice extend presented by Omstedt and Chen (2001) and Tinz (1996) has been compiled from

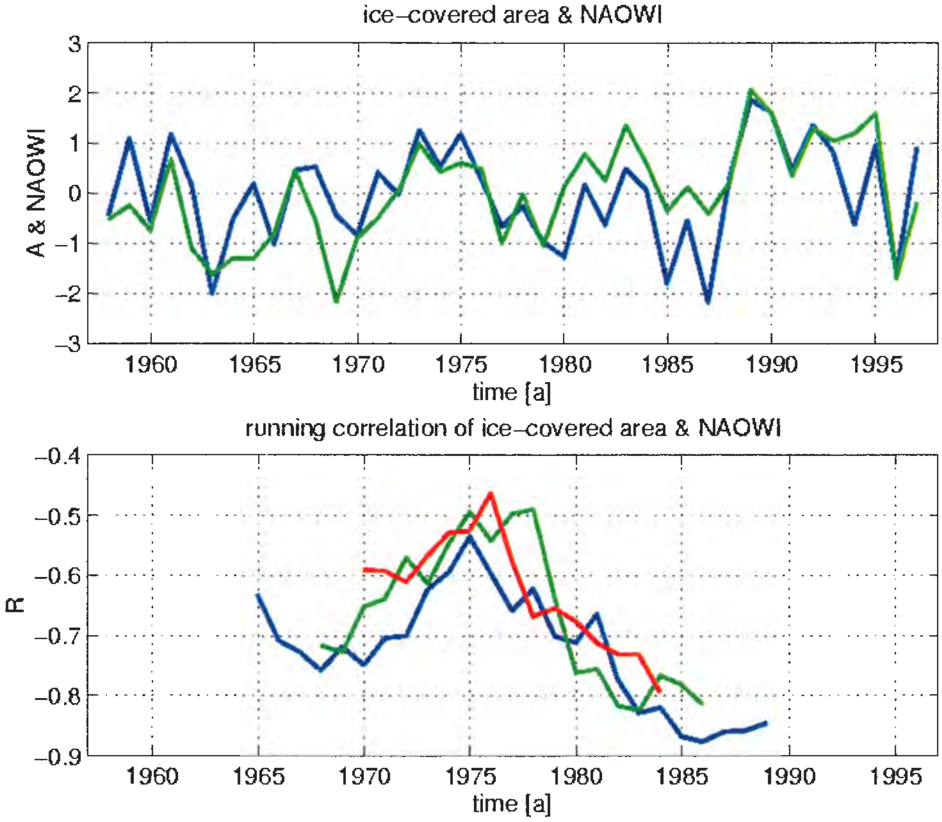

Figure 5: Upper: Standarized sea ice time series based on the NCEP model results multiplied by minus one (blue) and NAOWI (green). Lower: The moving correlation between both time series for different temporal windows are shown. The windows are selected to be equal to 15, 20 and 25 years respectively.

archive material like lighthouse diaries, ship reports and newspapers for the period earlier than 1920s. From the 20s century onwards observations from FMR and later SMHI have been used to compile a time series from 1756 to 1997. Omstedt and Chens analysis already indicates strong variations of correlations of ice conditions with NAOI in time. The range of the calculated correlations lasts from 0.3 to 0.7. However, as the quality and density of observations have been changed strongly in time, the moving correlation analysis which were shown by Omstedt and Chen, might be explained partly by unknown and known inconsistencies in the observational data and thus a similar analysis using the modeled time series could provide additional arguments.

In the following, the moving correlation in time is calculated based on the modeled time series of standardized sea ice anomalies and the NAOI, calculated after Hurrell (1996). For the NAOI time series winter means for the period December to March are used which is the typical definition of the NAO winter index (NAOWI). The ice time series is calculated from means of the month February to April. Both time series are standardized by the subtraction of their mean and devision by their standard deviation. In Figure 6 upper, the NAOWI is shown together with the ice time series multiplied by minus one . The visual comparison indicates already the correlation between both time series (the correlation is R=-0.65). Furthermore, in Figure 5 lower, the moving correlation for different time windows are shown. The windows are selected to be equal to 15, 20 and 25 years respectively. The wide of the window has only little influence on the general results. The strongest (negative) correlations up to about –0.9 were found for the eigthies. Lowest correlations were found for the seventies with minimum values below –0.5, intermediate correlations around -0.7 were found for the end of the sixties. These results are in agreement to Omstedt and Chen (2001). The correlations calculated here are slightly higher compared to the correlation of NAOI and maximum ice extend presented by Omstedt and Chen. This might be explained by the different nature of the investigated data bases.

5. Conclusions

By the previous analysis and detailed investigation of the modeled data, it was possible to answer the question about the usefulness of model data and to develop ideas about how do deal with uncertainties in the model results. The here presented investigations were able to illustrate the advantages of dynamical modelling. Even though the detailed validation of model results clearly indicated the under-estimation of observed variability and problems in reproducing the seasonal cycle in dependence of atmospheric forcing data, the correlations between model results and observations are quite high, higher than typically reached by statistical models (see e.g. Omstedt and Chen, 2001). Thus correlation based analysis could be carried out on the base of model results and might give some indications about driving or connected forcing mechanisms. Further improvements might be reached by climatic corrections of the atmospheric forcing data.

Concerning the state of the art in dynamical modelling, it is clear that there is a need of new high quality observational data. To improve dynamic models and their results sufficiently, gridded observational data of higher quality, consistent in time, are necessary. New efforts are necessary to digitalize the information which has been collected by the ice services over the last decades into high quality gridded data sets, about the type of the ice and the thickness of the ice. The needs for new observational data are a very good resolution in time and space and a detailed classification about the ice type, roughness and its salinity. Consistency of the data set in time and space is as well an important requirement for new observational data.

Apart from the general remarks to be made about the quality and ability of the data sets, the previous analysis had provided valuable hints towards possible predictors to be used for the Baltic Sea sea ice state. In detail the relevance and usefulness of the NAOI as a predictor for the regional sea ice development during the recent climate has been studied. It turned out that the NAOI shows strong limitations as predictor for the regional sea ice conditions in the Baltic already on the deacdal time scale. Although the NAOI is in general correlated to the regional sea ice cover of the Baltic, the negative correlations vary from below 0.5 (in the seventies) to almost 0.9 for the middle of the eigthies. This is in line with earlier analysis carried out by Omstedt and Chen (2001).

Acknowledgments

We have to thank our colleague Frank Siegismund, who carried out the long NCEP-40 forced model runs and our colleague Udo Hübner, for his help in carrying out the ERA-15 forced model run. Further thanks are given to a number of colleagues who contributed by providing forcing, initial and boundary conditions for the long model runs. Some names which should be given are Thomas Pohlmann, Peter Damm, Johannes Pätsch, Sten Bergström and Bengt Carlsson. Further thanks have to be given to Vassily Smolanitsky who provided the NIC data and forwarded the BASIS data provided by Jan-Erik Lundquist to us. The study has been funded by the University of Hamburg. External funding for the creation of model data were provided by the German Research Foundation (DFG) in the frame of the SFB 512, B3 and by the German Ministry of Research and Education (BMBF) in the frame of the project KLINO (grant number: 03 F01185B). Funding from the WMO (project: 'Global Digital Sea Ice Data Bank') was provided to create the digital satellite sea ice data (NIC data). Furthermore the efforts and funds provided by SMHI and FMR to carry out the regular sea ice observations and to create digital maps of ice compactness are to be mentioned.

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Measurements of under-ice oceanic heat flux in the Baltic Sea during the BALTEX/BASIS and HANKO experiments

Kunio Shirasawa[1], Jouko Launiainen[2] and Matti Leppäranta[3]

[1]Sea Ice Research Laboratory, Hokkaido University, 6-4-10 Minamigaoka, Mombetsu, Hokkaido 094-0013 Japan

[2]Finnish Institute of Marine Research, P.O. Box 33, FIN-00931 Helsinki, Finland

[3]Division of Geophysics, Department of Physical Sciences, University of Helsinki, P.O. Box 64 (Gustaf Hällströminkatu 2), FIN-00014 Helsinki, Finland

Abstract

The objective of the present paper is to evaluate the under-ice oceanic heat flux and bulk heat transfer coefficient in the Baltic Sea. Field experiments were carried out to measure turbulent fluxes of heat and momentum in the oceanic boundary layer under the landfast sea ice and to study the oceanic boundary layer structure, ice-sea and air-sea interaction processes near the ice edge region in the Bothnian Bay during the BALTEX/BASIS-98 and -99 and in the Gulf of Finland during the HANKO-99, -00 and -01, in the north and south of the Baltic Sea, respectively. Mean oceanic heat fluxes of 0.5 and 3 Wm^{-2} were estimated in the Bothnian Bay, while 22 to 62 Wm^{-2} in the Gulf of Finland. The mean bulk heat transfer coefficient of $3.9x10^{-4}$ was estimated by using the measured value of the oceanic heat flux during the BASIS-98.

1. Introduction

The Baltic Sea is one of the key components in the North-European climate system and in the physical and ecological environments in the area. The Baltic Sea is connected with the North Sea by a narrow and shallow strait and is therefore characterized as a semi-enclosed brackish water basin located in the seasonal sea ice zone with an ice cover forming and melting each year. The ice season lasts from some weeks in the south, to about 6 months in the north. The interannual variability in the ice extent is rather large. The observed maximum thickness of undeformed fast ice is 1.2 m in the north, while in general the thickness of landfast ice is 30 to 50 cm in the south.

The salinity of the Baltic Sea is controlled by the balance between the inflow of saline water from the North Sea and of fresh water from riverine input and precipitation.

By acting as a thermal insulator and a mechanical cover, the sea ice strongly influences the air-sea exchange of energy, water and momentum, and prominently affects to weather and meteorological conditions. Since the sea ice is typically less than 1 m thick, its presence and extent are highly sensitive indicators to a climate change. Considering the winter navigation, sea ice is of practical importance to various countries, and therefore has major economical influences.

Does the Baltic Sea gain or lose fresh water from the atmosphere ? Does the Baltic Sea gain or lose heat from the atmosphere ? How much water and heat leave the Baltic Sea through the entrance area? These are questions essential for the BALTEX (Baltic Sea Experiment) program (*BALTEX*, 1995).

The Baltic Air-Sea-Ice Study (BASIS) was a sub-project of the BALTEX, which is a program of GEWEX/WCRP, and explores, models and quantifies the main physical processes that control the energy and water exchange within the Baltic Sea and its drainage area. The project BASIS aimed at an improved understanding of the energy and water cycles during winter conditions by conducting a versatile air-ice-sea experiment in the Baltic Sea. BASIS was carried out in 1997-2000, during which the main field experiment was performed in the Bothnian Bay in February-March, 1998 (*BALTEX*, 1999, 2001).

One of the specific objectives of the BALTEX/BASIS field experiments was to investigate the physical structure of the oceanic boundary layer under the sea ice, especially close to the sea ice margin. Field experiments were carried out to measure turbulent fluxes of heat and momentum in the oceanic boundary layer under the landfast sea ice and to study the oceanic boundary layer structure, ice-sea and air-sea interaction processes in the Bothnian Bay, in the north of the Baltic Sea in February-March, 1998 and in March, 1999 (*BALTEX*, 1999, 2001). In this study the oceanic heat flux and heat transfer coefficient obtained from those field experiments are discussed.

A Finnish-Japanese cooperative research programme entitled "Ice Climatology of the Okhotsk and Baltic Seas" provided an opportunity to study evolving properties and thermodynamic processes of landfast sea ice along the coast of Hanko Peninsula in the Gulf of Finland, in the south of the Baltic Sea in winters 1999, 2000 and 2001 (HANKO-99, HANKO-00 and HANKO-01, respectively) (*Shirasawa and Leppäranta*, 2002a, 2002b; *Ishikawa et al.*, 2002). Hydrometeorological observations and ice core sampling programs were carried out throughout the whole winter from an ice cover forming to melting in Santala Bay at the entrance of the Gulf of Finland. In this study, similar to the BASIS field experiments, the under-ice oceanic heat fluxes obtained from the HANKO experiments are also discussed.

2. Methods

The turbulent fluxes of oceanic heat, momentum and salt are to be calculated from the fluctuations of 3-D currents, temperature and salt by the eddy correlation method (e.g., *Shirasawa and Ingram*, 1991). The velocity data are used to calculate the mean vector and covariance (i.e., Reynolds stress/momentum flux) tensor in an east-north-vertical reference frame in which the mean vertical velocity component vanishes. The covariances are to be used to calculate the Reynolds stress ($\tau = \langle u'w'\rangle + i\langle v'w'\rangle$), where u', v' and w' are the downflow, cross-flow, and vertical flow fluctuations, respectively, and $\langle\ \rangle$ denotes time averaging. Similar techniques are used for processing the fast response temperature data to get mean temperature and turbulent heat flux ($F_w = \rho C_p \langle w'T'\rangle$), where T' is the temperature fluctuation, ρ is density, and C_p is the specific heat.

A considerably more simplified method is so-called bulk formulation, in which the detailed physics of the thermal ice-ocean interaction is parameterized in terms of a heat transfer coefficient, C_h (*Omstedt and Wettlaufer*, 1992). The oceanic heat flux then reads,

$$F_w = \rho\, C_p C_h \Delta U (T_\infty - T_f(S_0)) \tag{1}$$

or the heat transfer coefficient is defined as,

$$C_h = F_w / \rho C_p \Delta U(T_\infty - T_f(S_0)) \quad (2)$$

where ΔU is the relative velocity between the ice drift and the current at a reference level, T_∞ is the far field temperature, and $T_f(S_0)$ is the interfacial temperature. In the present model the reference level is assumed to be 0.5 m below the ice-ocean interface, and the value of T_∞ is also taken at 0.5 m below the ice-ocean interface.

3. Experiments

Shown in Fig. 1 are ice stations established in the landfast sea ice region during February-March 1998 for the BALTEX/BASIS-98, March 1999 for the BASIS-99 and the 3-winter field experiments in 1999, 2000 and 2001 for the HANKO-901. The position and mean ice thickness of each station are listed in Table 1.

The BASIS-98 station was established in the landfast sea ice region westward from Vaasa in the southern part of the Bothnian Bay (Fig. 1). The study site was located about 280 m northwestward from *R/V Aranda*. The ice was about 48-cm thick level ice at the study site during the BASIS-98 (Table 1).

The fast response current meters attached with temperature and conductivity sensors were deployed from the level ice at the depths of 0.5 m and 5 m below the ice-ocean interface during the period from 19 February to 6 March 1998. The current meters provide time series of fluctuations of 3-D currents, temperature and conductivity.

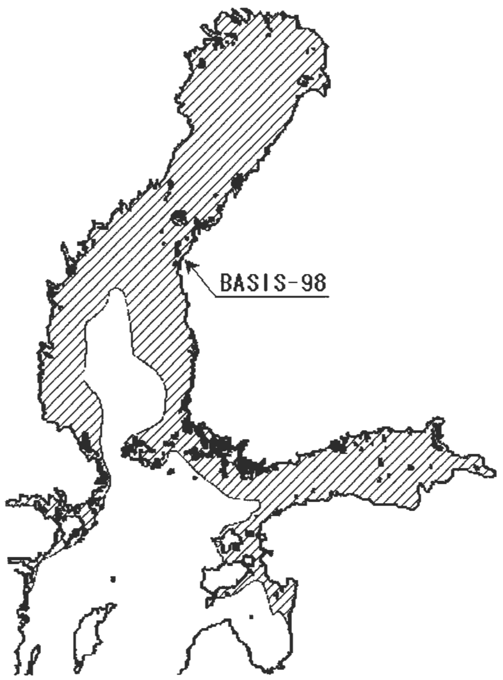
During winter 1998/1999 two ice stations were established; one was in the Bothnian Bay and the other was in the Santala Bay at the entrance of the Gulf of Finland (Fig. 1). Similar to the BASIS-98, the ice station was established near *R/V Aranda* during the BASIS-99. The current meter was deployed from the 43-cm level ice at the depth of 0.5 m below the ice-ocean interface during the period from 21-26 March 1999 in the southern Bothnian Bay (Table 1). The current meter was also deployed from the 53-cm level ice at the depth of 0.5 m below the ice-ocean interface during the period from 10-31 March 1999 in the Santala Bay for HANKO-99 (Table 1).

During the HANKO-00 and -01 in winters 1999/2000 and 2000/2001, respectively, the meteorological platform attached with current meters and temperature and conductivity sensors was deployed in the Santala Bay before the ice season to understand thermodynamic processes throughout the whole winter (Fig. 1 and Table 1).

Table 1: Summary of the measured and estimated oceanic heat fluxes and heat transfer coefficient in the Baltic Sea

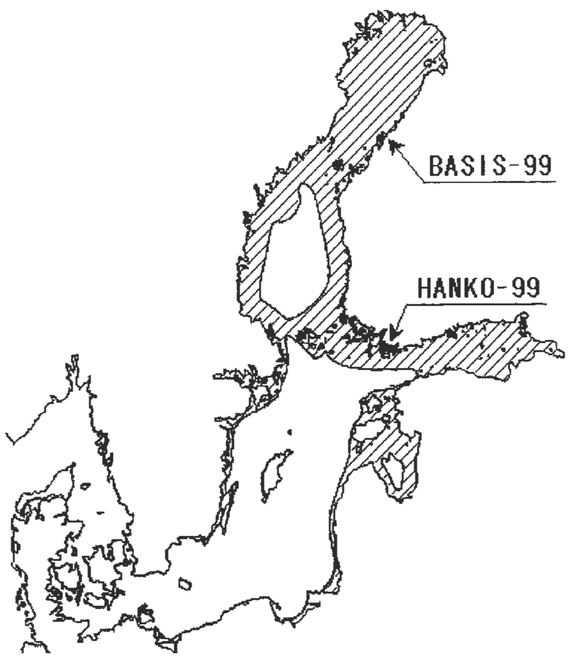
Program/ Area	Position	h_{ice} (cm)	Period	Sal. (psu)	$\Delta T = T - T_f$ (°C)	ΔU (cm/s)	F_w (W/m^2)	C_h	Method
BASIS-98/ Bothnian Bay	63°08.12' N 21°14.67' E	48	19 Feb.- 6 Mar. 1998	5	0.0003	4.6	0.5	3.9 x10^{-4}	Bulk & Eddy Correl
BASIS-99/ Bothnian Bay	63°55.487' N 22°56.942' E	43	21-26 Mar. 1999	3.4	0.11	1.7	3	3.9 x10^{-4}	Bulk
HANKO-99/ Santala Bay	59°53.292' N 23°05.662' E	53	10-31 Mar. 1999	5.5	0.79	1.7	22	3.9 x10^{-4}	Bulk
HANKO-00/ Santala Bay	59°53.431' N 23°06.299' E	28	30 Dec. 1999- 12 Mar. 2000	5.56	0.64	4.5	46.8	3.9 x10^{-4}	Bulk
			12-27 Mar. 2000	5.68	1.57	2.4	61.7	3.9 x10^{-4}	Bulk
HANKO-01/ Santala Bay	59°53.431' N 23°06.299' E	48	14 Jan.- 18 Mar. 2001	5.35	0.82	2.8	37.6	3.9 x10^{-4}	Bulk
			18 Mar.- 7 Apr. 2001	5.42	1.53	2.2	54	3.9 x10^{-4}	Bulk

Winter 1997 – 1998



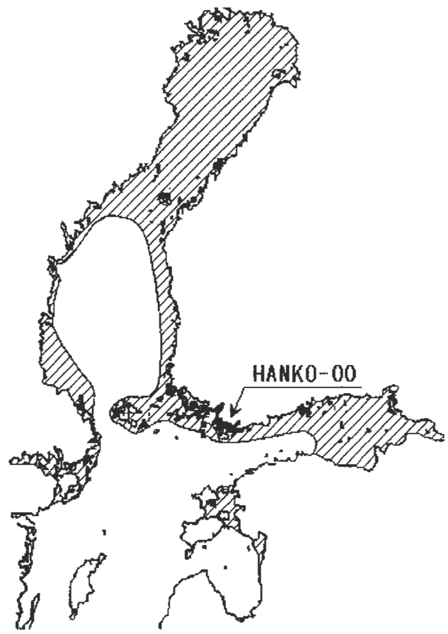
Largest Ice Extent on 11 March 1998

Winter 1998 – 1999



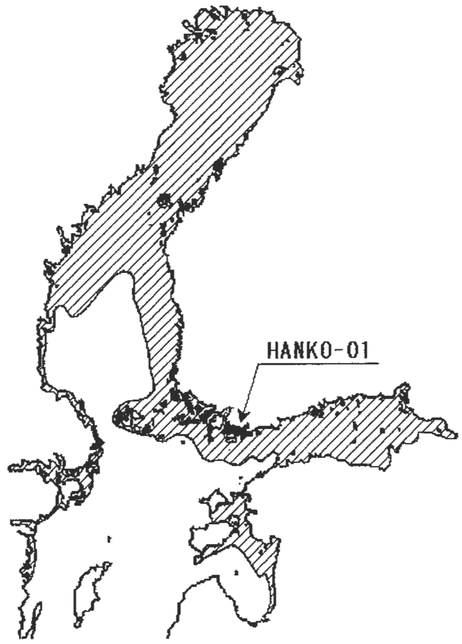
Largest Ice Extent on 11 February 1999

Winter 1999 – 2000



Largest Ice Extent on 24 February 2000

Winter 2000 - 2001



Largest Ice Extent on 26 March 2001

Figure 1: Study sites and largest ice extents in winters 1997/1998, 1998/1999, 1999/2000 and 2000/2001. Largest ice extents were obtained from the Ice Service, Finnish Institute of Marine Research (http://www2.fimr.fi/).

4. Ice conditions

Ice conditions can be provided by the Ice Service, Finnish Institute of Marine Research (http://www2.fimr.fi/) and are summarized below: The ice season 1997/1998 was mild. In early January the weather became mild and windy. The freezing process was slow until the end of January when the ice began to form in the Bothnian Bay, the Bothnian Sea, the Archipelago Sea and the Gulf of Finland. The Bothnian Bay was covered entirely on 1 February, two weeks later than the average. After mid-February the weather was mild again and the ice began to decrease. In early March there was a cold spell, during which the ice cover reached its largest extent on 11 March (Fig. 1). The ice then started slowly to decrease.

The maximum thickness of fast sea ice was 70-90 cm in the northern and 50-70 cm in the southern Bothnian Bay, respectively, and 25-30 cm in the western and 55-60 cm in the eastern Gulf of Finland, respectively.

The ice season was of medium length in the northern part but shorter than the average in the southern part of the Bothnian Bay.

The ice season 1998/1999 was on the average. The freezing process, as usual, started in early November in the northern Bothnian Bay. The ice expanded normally during November and in early December. In mid-December the weather became milder and the freezing process came to a halt. In January the weather was varied. In mid-January the mild and windy weather led to a break-up of the thin new ice, and the ice floes in the northernmost Bothnian Bay and in the Gulf of Finland drifted against the fast ice forming ridges. The weather changed cold again at the end of January and the Bothnian Bay became entirely covered with ice on 26 January, over a week later than the average. The ice reached its largest extent on 11 February (Fig. 1). April was warmer than the average and the ice started to deteriorate and melt. The Bothnian Bay was melted out only in early June, about a week later than the average.

The maximum thickness of the fast ice was 70-80 cm in the northern and 50-60 cm in the southern Bothnian Bay, and 40-60 cm in the Gulf of Finland.

The length of the ice season was on the average in the Bothnian Bay. The ice season in the Gulf of Finland was about a week and about four weeks longer than the average in the western and eastern part, respectively.

The ice season 1999/2000 was mild. During the first half of December a lot of new ice was formed in the northernmost Bothnian Bay. In the Gulf of Finland, in early January new ice was formed, two weeks later than the normal, and in mid-January there was a cold spell and new ice was formed. On 24 February the ice cover reached its largest extent, comprising the whole surface of the Bothnian Bay and the Archipelago (Fig. 1). At the end of February the ice situation was eased rapidly, especially in the Bothnian Sea and in the Gulf of Finland, where winds broke up the thin ice forming a brash barrier along the Bothnian Sea coast as well as in the Archipelago of the western Gulf of Finland. By mid-March the weather got milder again and the ice started to deteriorate and melt both in the Bothnian Sea and the Gulf of Finland. April was warmer than the average and the ice continued to deteriorate and melt. The western Gulf of Finland, as usual, became ice-free in the second part of April.

The maximum thickness of the fast ice was 50-85 cm in the northern Bothnian Bay, 10-25 cm in the Archipelago and western Gulf of Finland and 20-45 cm in the eastern Gulf of Finland.

The ice season was about a week shorter than the average in the northern Bothnian Bay and more than four weeks shorter in the western Gulf of Finland.

The ice season 2000/2001 was mild and shorter than the average. In the northernmost Bothnian Bay the freeze-up did not start until the end of November, approximately three weeks later than the average. In the Archipelago of the Gulf of Finland the freeze-up was delayed for more than a month until the end of January. In early February a cold spell set in and new ice formed along the entire Finnish coast. In early March the weather was varied with alternating short cold and mild spells. The ice extent diminished slightly. In mid-March a cold spell set in and during this spell the ice cover reached its largest extent on 26 March (Fig. 1), which is the latest date ever recorded. In April, as the weather was rather warmer, the thinner ice melted out faster, especially in the Bothnian Bay.

The maximum thickness of the fast ice was 50-60 cm in the Bothnian Bay, 30 cm in the western and 35-50 cm in the eastern Gulf of Finland, respectively.

The ice season was very much shorter than the average in all sea areas. In the Bothnian Bay it was about four weeks shorter and in the Gulf of Finland more than four weeks shorter than the average.

5. Under-ice oceanic heat fluxes

The oceanic heat flux and heat transfer coefficient are listed in Table 1. The mean oceanic heat flux (F_w) of 0.5 Wm^{-2} was obtained for the period from 19 February to 6 March 1998 during the BASIS-98 by the eddy correlation method (Table 1). The corresponding bulk heat transfer coefficient (C_h) estimated with Eq. (2) was 3.9×10^{-4} for the BASIS-98. The comparison between the eddy correlation method and the bulk method was made for the data obtained under the neutral condition ($-0.1<z/L<0.05$, where z is the depth and L is the Obukhov stability length). The parameters used in Eq. (2) are also listed in Table 1. As seen in Table 1, the water temperature was approximately the freezing point; namely the temperature difference (ΔT) was very small. The oceanic heat flux, therefore, contributed very little to melting process at the ice-ocean interface during the period of the experiment.

During the winter 1998/1999 the two field experiments were performed; one was in the Bothnian Bay for the BASIS-99 and the other was in the Santala Bay at the entrance of the Gulf of Finland for the HANKO-99 (Fig. 1). During the BASIS-99 for the period from 21 to 26 March 1999 the mean oceanic heat flux of 3 Wm^{-2} was estimated using Eq. (1) with the mean heat transfer coefficient of 3.9×10^{-4} obtained at the BASIS-98 and the parameters listed in Table 1. Similar to the BASIS-99's estimation, the mean oceanic heat flux of 22 Wm^{-2} was obtained for the period from 10 to 31 March 1999 during the HANKO-99 (Table 1). The mean oceanic heat flux was seven times larger in the Santala Bay than in the Bothnian Bay during mid- to late March. It results from the temperature difference being seven times larger in the Santala Bay than in the Bothnian Bay (in referring to Eq. (1)). It therefore appears that the warmer under-ice water, thus the large oceanic heat might contribute effectively to melting process at the ice-ocean interface in the Santala Bay.

During the HANKO-00 and -01 the field experiments were carried out for the whole ice season covering the freeze-up through the ice breakup. The period for averaging was separated into the two terms; one from the freeze-up to the onset of melting and the other from the onset to the breakup. During the HANKO-00 the mean oceanic heat fluxes were 47 and 62 Wm^{-2} during the periods from 30 December 1999 through 12 March 2000 (for the ice growing term) and from 12 through 27 March 2000 (for the melting term), respectively (Table 1). The mean oceanic heat fluxes were 38 and 54 Wm^{-2} during the periods from 14 January 2000 through 18 March 2001 (for the ice growing term) and from 18 March through 7 April 2001 (for the melting term), respectively, during the HANKO-01 (Table 1). The onset of melting started at mid-March for both winters, and the temperature difference correspondingly started to increase since then. The resultant increase of the oceanic heat flux could obviously contribute to melting process at the ice-ocean interface. The winter 1999/2000 was rather mild and the ice thickness was 28 cm at maximum, while the winter 2000/2001 was also mild but the ice thickness was 48 cm at maximum (Table 1). It appears that the oceanic heat flux might contribute more to thermodynamic processes at the ice-ocean interface throughout the winter 1999/2000 than the winter 2000/2001.

6. Conclusions

The ice season was rather mild for the winters 1997/1998, 1999/2000 and 2000/2001, and on the average for the winter 1998/1999. In the southern Bothnian Bay the mean oceanic heat fluxes of 0.5 and 3 Wm^{-2} were estimated during late February to late March. In the Santala Bay at the entrance of the Gulf of Finland the mean oceanic heat fluxes of 38 and 47 Wm^{-2} were estimated for the ice growing period, while 54 and 62 Wm^{-2} were estimated for the ice melting period.

The mean bulk heat transfer coefficient of 3.9×10^{-4} was estimated by using the measured value of the oceanic heat flux obtained during the BASIS-98 experiment.

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Changes of sea ice climate during the XX century – Polish coastal waters

Marzenna Sztobryn, Ida Stanislawczyk

IMGW OM Gdynia, PL-81342 Gdynia, ul.Waszyngtona 42, Poland

1. Introduction

Ice conditions in the Southern Baltic Sea differ from those in the remaining parts of this sea. They are by far more gentle in this region. The sea-ice climate is particularly changeable on the Polish coastal waters: from quite iceless to totally packed with ice. The aim of the presentation was to detect the changes in sea-ice climate in XX century along the Polish coast. Observation from 3 Polish sea-ice observing sites were analyzed: from the eastern part of the coast- Gdansk (1922/23 to 1999), from the central part - Ustka (1900-1999) and from the western part - Swinoujscie (1900 -1999).

The data previous to 1945 have been gathered by the German Ice Service (German Hydrographic Institute) and the data since 1946 - by the Polish Institute of Meteorology and Water Management. Observations refer to the open coastal waters. The type of observations (visual only) and type of winter seasons met with in the Polish coast of the Baltic Sea allow for statistical consideration of following indicators of sea-ice climate :

- probability of sea-ice appearance,
- number of days with sea-ice,
- the date of first ice appearance (freezing),
- the date of ice decay (melting).

For calculations moving 30-years periods of decadal time-step were applied, beginning with 1900-1929 until 1970 – 1999 (in analogy to moving averages). It should be stressed, however that only data from the periods of 30-years step (1900-1929, 1930-1959 and 1960-1989) are independent.

Probability of sea-ice occurrence is here defined as the ratio of number of winters with sea-ice observed to number of winters with sea-ice information available.

2. Changes in sea-ice climate in Gulf of Gdansk (eastern part)

Characteristic for the XX-th century was a large diversity of changes in sea-ice conditions in the Gulf of Gdańsk. To analyse the variation and intensity of the sea-ice climate, the basic sea-ice indicators, as probability of sea-ice occurrence, number of winters with sea-ice, number of days with sea-ice per winter season, date of the first day with ice (freezing), date of the last day with ice (melting) – were considered and presented in Table 1.

The probability of sea-ice occurrence varied from 0,44 in the 30 years 1920-49, grew to 0,72 in 1940-69, to decrease to a rather low value 0,37 in the last 30 years of the century. In other words, in the first and final 30 years of the eighty years under consideration, the sea-ice climate in the Gulf of Gdańsk was more gentle, than in the middle of the century, when it was most severe.

Mean number of days with sea-ice was calculated using the data from all the winters considered. Mean values gained using the all-winters data confirm, that the most severe sea-ice conditions prevailed in the Gulf of Gdańsk in the 30 years 1940-1969.

Table 1: Sea-ice climate indicators in Gulf of Gdansk in XX century

	1920-1949	1930-1959	1940-1969	1950-1979	1960-1989	1970-1999
Number of winters with sea-ice observations lacking	3	1	1	0	0	0
Number of winters with sea-ice	12	15	21	19	17	11
Probability of sea-ice occurrence	0.44	0.52	0.72	0.63	0.57	0.37
Mean number of days with sea-ice (iceless winters included)	10	12	17	12	12	6
Mean freezing date	24 Jan.	28 Jan.	26 Jan.	28 Jan.	25 Jan.	28 Jan.
Mean melting date	20 Feb.	1 Mar.	3 Mar.	5 Mar.	3 Mar.	27 Feb.

According to the mean values the shortest sea-ice persistent time, i.e. the smallest mean number of days with ice was met with during 1970-99 and was as small as 6. This is the consequence of the drastic decrease of the number of winters with sea-ice in 1970-99 (especially in the last decade of these 30 years). As already said, the probability of sea-ice appearance decreased to 0,37 in 1970-99.

Mean dates of first ice appearance do not fluctuate much in successive 30-years periods – merely between 24 and 28 Jan. Mean dates if sea-ice decay (melting) however varied in wider limits: between 20 Feb. in 1922-49 and 5 Mar. in 1950-79. Thus the difference was as high as 13 days.

Local conditions along the coast determine the sea-ice appearance in particular winters to a high degree. Especially during mild or moderate winters sea-ice does not appear in sea areas as e.g. sea-exposed coasts, at all, while more sheltered waters may freeze in even very mild winters. Thus, any direct comparison of different coastal regions using only the sea-ice from the "local ice winters" there, would give vague results. To avoid this the calculations were made in respect to all the winters in the whole time series. Considered was frequency of winters with specific number of days with sea-ice, the iceless winters included as the "zero-days with sea-ice winters". The specific intervals of number of days with sea-ice were : 0 days, 1-10 days, 11-20 days, 21-30 days, and soon, by tens of days.

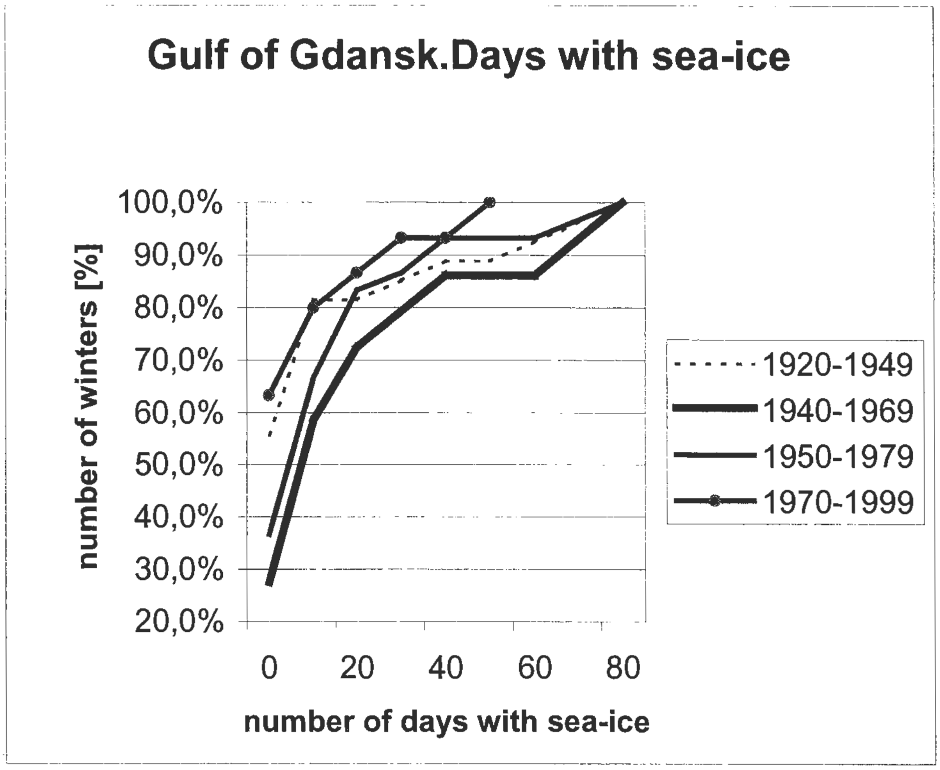

Figure 1: Cumulative distribution of days with sea-ice.Gulf of Gdansk.

Cumulative distribution of number of days with sea-ice (by these intervals) was calculated versus number of winters in particular 30-years periods. Respective points of winters (in the specified 30 years) had the number of days with sea-ice not higher than in particular interval. The point of intersection of this curve with the vertical axis (for value equal to 0) represents the number of iceless winters. The average shape of the curve can be taken as indicator of the mean winter severity : the more frequent the severe winters in a period the greater the inclination angle of the cumulation curve (the section of the "zero number of days" included). For instance, the winters in the middle of the century, 1940-69), are presented in Fig.1 by the curve of greatest inclination angle, while the curves for 1922-49 and 1970-99 representing much milder spells, run much sloped (their sections of the "zero number of days" included) and lie close to each other. This can confirm the former conclusion on the non-linearity and heterogeneity of sea-ice climate changes in the waters of Gulf of Gdansk..

3. Sea area off Ustka (central part)

In this sea basin sea-ice conditions were recorded during 97 winters in the XX century. Lacking are observations from 1903, 1914 and 1945. The values of some sea-ice climate indicators for this sea area are presented in Table 2.

The probability of winters with sea-ice varied from 0.76 in 1910-1939 and 1920-49 to only 0.43 in 1960-89 and 0.23 in 1970-99. In the first decades of the century, and especially in the 30 years 1910-1939 was encountered the greatest number of winters with sea-ice (the probability reached 0.71 and 0.76). In the successive decades the probability of winters with ice gradually, through uneven declined, to the lowest value 0.23 in 1970-99, as already mentioned.

Table 2: Sea-ice climate indicators sea off Ustka in XX century

	1900-1929	1910-1939	1920-1949	1930-1959	1940-1969	1950-1979	1960-1989	1970-1999
Number of winters with sea-ice observations lacking	2	1	1	1	1	0	0	0
Number of winters with sea-ice	20	22	22	19	20	16	13	7
Probability of sea-ice occurrence	0.71	0.76	0.76	0.66	0.69	0.53	0.43	0.23
Mean number of days with sea-ice (iceless winters included)	15	18	22	16	17	10	11	6
Mean freezing date	8 Jan.	11 Jan.	10 Jan.	29 Jan.	27 Jan.	1 Feb.	26 Jan.	25 Jan.
Mean melting date	13 Feb.	19 Feb.	23 Feb.	4 Mar.	27 Feb.	28 Feb.	28 Feb.	25 Feb.

The same tendencies appeared in the mean number of days with ice, which oscillated between 22 days in 1920-49 and only 6 in 1970-99. The very beginning of the century had fewer number of days with ice, and after the maximum in 1920-49 a steady though uneven began. Approximately in the first 4-5 decades the winter severity in the water off Ustka grew, to deadline considerably in the following 5-6 decades.

In comparison to the coast of Gulf of Gdańsk and the sea off Swinoujscie , where the sea-ice climate was most severe in 1930-59 and 1940-69, the most difficult ice conditions in sea off Ustka appeared earlier by two decades, namely in 1910-39 and 1920-49.

Mean freezing dates (first ice day) oscillated between 8 Jan. and 1 Feb., what makes as many as 23 days off much higher than in the both sea areas compared. Another difference concerning the dates of first sea-ice appearance between the first half of the century, in which the mean dates of first ice oscillated only between the 8 and 11 Jan., and the second half of the century, when the mean dates of first sea-ice were as late as the end of January and the beginning of February. Thus, the changes of the area freezing had somewhat different character in the sea off Ustka than freezing eastwards (Gulf of Gdańsk) and westwards (Swinoujscie) of it.

Mean dates of ice decay varied between 13 Feb. (1900-29) and 4 March (1930-59). The differences, however, between the first and the second halves of the century do not appear so distinctly, through these of the second half of century shift towards the later dates.

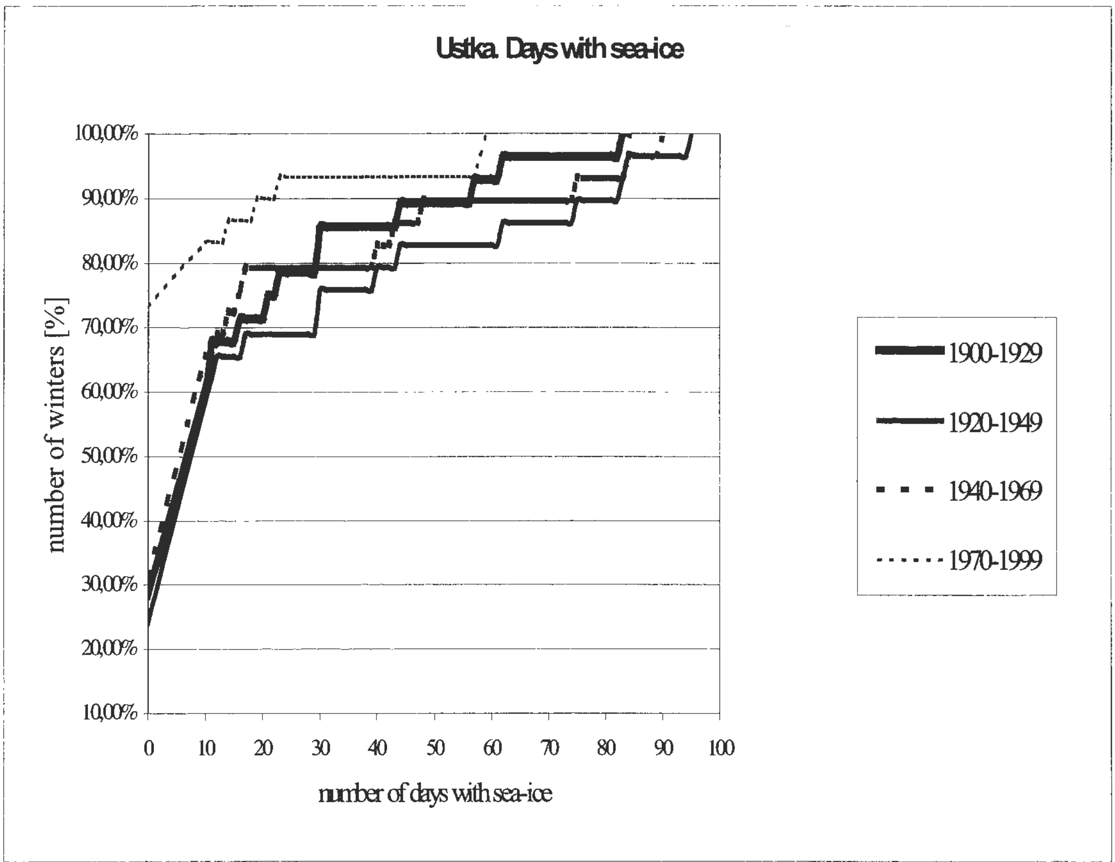

Figure 2: Cumulative distribution of days with sea-ice. Ustka.

Cumulative distribution of number of days with sea-ice (by the 10 days intervals) is shown on the Fig.2. The variation and inclination of distribution curves calculated for particular 30-years periods confirm different character of changes of sea-ice climate in sea area off Ustka in comparison with Gulf of Gdansk. The first 30-years period (e.g.1900-1929) wasn't very mild and the period 1940-1969 wasn't the most severe, where period 1920-49 was characterized by most difficult sea-ice conditions.

4. Sea area off Swinoujscie (western part)

Time of sea-ice observations in the XX-th century included 98 winter seasons (only in the years 1914 and 1945 the sea-ice observations didn't provided here) . The values of sea-ice indicators calculated for sea area off Swinoujscie are shown in table 3.

The probability of sea-ice occurrence n this sea area varied from 0.6 (1970-99) to 0.93 (1940-1969). The 30-years periods 1930-59 and 1950-79 only slightly declined from the most severe one, with the probabilities of sea-ice occurrence amounting to 0.87-0.9. In the remaining years the probability values were closed between 0.77 and 0.79.

Table 3: Sea-ice climate indicators for sea off Świnoujście in XX century

	1900-1929	1910-1939	1920-1949	1930-1959	1940-1969	1950-1979	1960-1989	1970-1999
Number of winters with sea-ice observations lacking	1	1	1	1	1	0	0	0
Number of winters with sea-ice	23	23	23	26	27	26	23	18
Probability of sea-ice occurrence	0,77	0,77	0,77	0,90	0,93	0,87	0,77	0,60
Mean number of days with sea-ice (iceless winters included)	32	17	22	26	34	26	24	14
Mean freezing date	13 Jan.	17 Jan.	16 Jan.	12 Jan.	10 Jan.	8 Jan.	9 Jan.	14 Jan.
Mean melting date	27 Feb.	25 Feb.	25 Feb.	1 Mar.	5 Mar.	2 Mar.	28 Feb.	23 Feb.

As in the eastern section of the coast the most severe sea-ice conditions were encountered in the central decades of the century and the mildest ones - between the years nineteen seventies and nineteen nineties.

These conclusions can confirmed by the mean number of the days with sea-ice, which reached the highest value, 34 days, in 1940-99.

Mean freezing dates (first ice) oscillated between 8 Jan. (1950-79) and 17 Jan. (1910-1939). The earliest first sea-ice was observed in 1940-89 (mean date between 8 and 10 Jan.), the latest first sea-ice - in 1910-49 (mean date between 16 and 17 Jan.). No significant discrepancies can be found also in the mean dates of sea-ice decay (melting), which vary between 23 Feb. (1970-99) and 5 Mar. (1940-69).

The cumulative distribution curves for 30-years periods are presented on the Fig.3. The most severe sea-ice conditions were observed in this area in the middle of century, especially in the 1940-1969 years. The last investigated period was characterized by the mildest sea-ice conditions. In the consequence a conclusion can be formulated, that the sea-ice climate in the sea area off Swinoujscie fluctuated from a more gentle in the first four decades of the century, especially in 1910-39, through the most severe winters in the central decades to the milder toward the end of the century. Especially declining in the severity were the winters in the last 30-years of the century (1970-99).

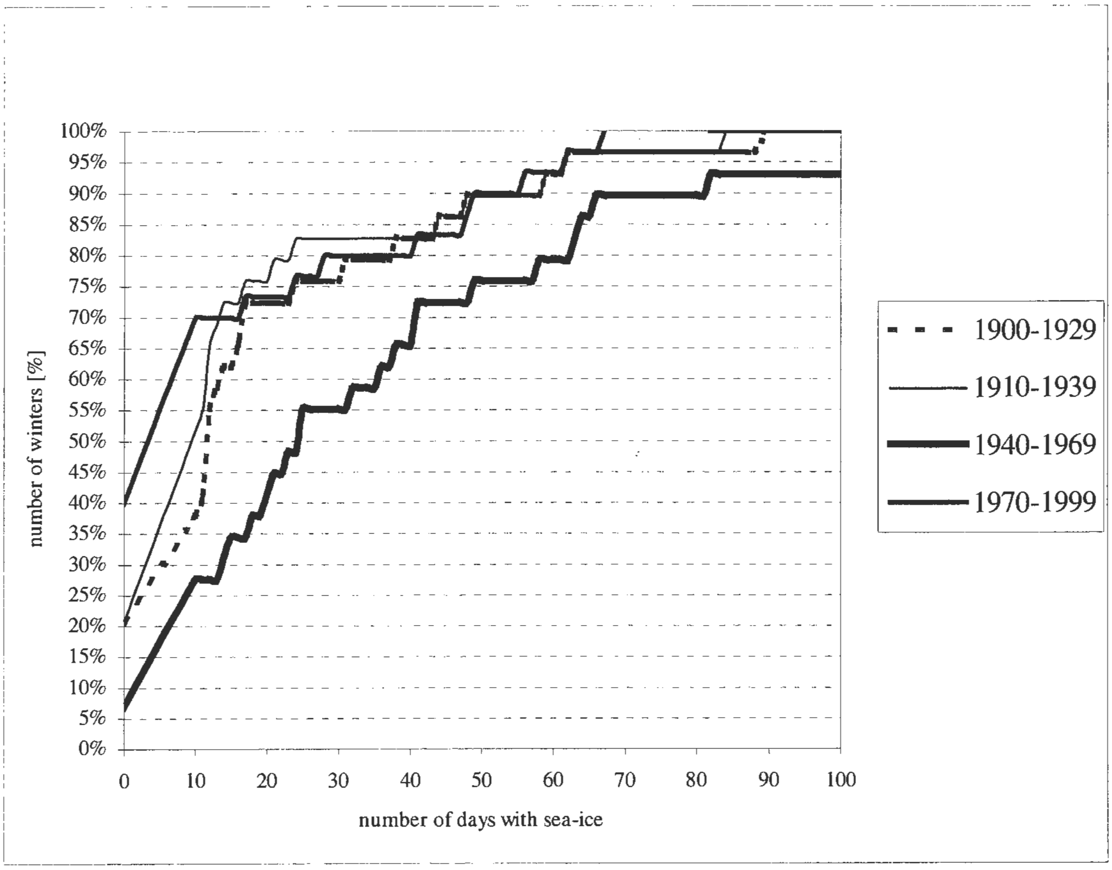

Figure 3 :Cumulative distribution of days with sea-ice. Swinoujscie.

5. Conclusions

Presented analysis permits for following conclusions:

- changes of sea-ice climate on the Polish coastal waters in XX century were heterogeneous and non-linear,
- the changes in the sea-ice climate in sea area off Ustka presented somewhat different tendencies that both those in the coastal waters of the Gulf of Gdansk and those in the area off Swinoujscie, where the appearance of the most severe winters occurs earlier (by two decades and significant dispersion of the freezing and melting dates is observed).
- most severe sea-ice conditions occurred in the middle of the century,
- towards the end of the century a considerable decrease of the number of winters with sea-ice was recorded.

Use of frequency analyses in sea-ice climate investigations allows for a comparison of sea basins, differing much in respect of frequency of occurrence and intensity of the sea-ice phenomena.

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Natural process of sea ice evolution in the Gulf of Riga

Keguang Wang[1], Matti Leppäranta[1], and Tarmo Kõuts[2]

[1]Department of Physical Sciences, University of Helsinki, Helsinki, Finland

[2]Department of Marine Physics, Estonia Marine Institute, Tallinn, Estonia

Abstract

The Gulf of Riga is a rather small semi-enclosed water basin in the eastern part of the Baltic Sea bordering on Estonia and Latvia. It only covers ~16400 km^2 with a volume of ~240 km^3 and a quite square shape. Compared with the whole Baltic Sea, the Gulf of Riga has even smaller memory, and the ice condition is dominated by the atmospheric circulation situations. The ice extent itself is no longer a valuable indicator for the ice climate conditions, and there is no independent ice condition classification system yet for the Gulf of Riga.

Referring to ice condition classification for the whole Baltic Sea, three categories of ice condition, namely mild, normal and severe winter, are employed to describe the natural process of sea ice evolution in the Gulf of Riga, respectively. In mild ice seasons, usually sea ice only appears in the Pärnu Bay, while in normal and severe ice seasons, sea ice often covers the all gulf. However, the durations are distinct. In severe ice seasons, sea ice covers the whole gulf in most of the time, while in normal ice seasons the gulf is covered by ice in merely a rather short time.

Because of the small area of the gulf, sea ice dynamics shows different properties from those of the entire Baltic Sea. The sea ice looks stronger in the Gulf of Riga than that of the Baltic Sea when they are the same thickness. And we also find that the demarcation of the fast ice and drift ice is almost constant in the normal and severe ice seasons. The mechanism is still waiting for answers.

Sveriges meteorologiska och hydrologiska institut
601 76 Norrköping
Tel 011-495 80 00 · Fax 011-495 80 01

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