BUNDESAMT FÜR
SEESCHIFFFAHRT
UND
HYDROGRAPHIE

Fifth Workshop on Baltic Sea Ice Climate
Hamburg, Germany
31 August – 2 September 2005

Herausgeber:
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Berichte des
Bundesamtes für Seeschifffahrt und Hydrographie
Nr. 42/2007

In der Reihe „Berichte des Bundesamtes für Seeschifffahrt und Hydrographie“
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Fifth Workshop on Baltic Sea Ice Climate im Internet:
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Hamburg und Rostock 2007
www.bsh.de

ISSN-Nr. 0946-6010

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PREFACE

The Fifth Workshop on Baltic Sea Ice Climate was arranged in Hamburg, Germany. The hosts of the workshop were the Centre of Marine and Atmospheric Sciences (ZMAW) at the University of Hamburg and the Bundesamt für Seeschifffahrt und Hydrographie (BSH), Germany. The workshop took place in the new building of ZMAW from 31, August-2, September, 2005.

The meeting reviewed research results related to the Baltic Sea ice in past, present and future climate conditions and, for the first time, built a link to other seasonally ice covered regions in the world. In contrast to the previous workshops, which were mainly devoted to Baltic Sea ice modelling and long-term time series, the fifth workshop represented a more wider spread of topics. The presentations addressed topics such as lake ice optics, sea ice remote sensing, ice dynamics, sea ice climate variations addressing several centuries, sea ice-snow interactions, sea ice microstructure and brine release, numerical modelling of sea ice and different aspects of sea ice related biology. Most of the presentations were related to the Baltic Sea, but a considerable number of presentations were dealing with sea ice problems in the Barents Sea.

Scientific advisory committee:
Prof. Anders Omstedt, Gothenburg University, Sweden.
Prof. Matti Leppäranta, University of Helsinki, Finland.
Dr. Johanna Ikävalko, Finnish Institute of Marine Research, Finland.
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Dr. Ingo Harms, ZMAW, University Hamburg, Germany [Barents Sea, Kara Sea]
Dr. Bin Cheng, Finnish Institute of Marine Research, Helsinki [Bohai Sea]

The proceedings from the 5th Workshop on Baltic Sea Ice Climate, containing contributions from oral and poster presentations, were edited by Dr. Natalija Schmelzer and Dr. Corinna Schrum.

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PROGRAM

Wednesday, 31 August

13:00-14:00: Welcome Coffee, Poster hang up	
14:00-14:15: Welcome	Corinna Schrum
14:15-14:30: Historic review on Baltic Sea Ice Workshops	Matti Leppäranta
14:30-15:00: Invited lecture: Sea ice regime in the Bohai Sea in comparison to the Baltic Sea ice regime	Bing Cheng, Wu Huiding
15:00-15:30: Invited Lecture: Arctic Shelves sea ice regimes	Ingo Harms
15:30-16:00: Coffee	
16:00-16:30: On climate variations in the Baltic Sea during the Little Ice Age (1300-1880)	Anders Omstedt, Christin Pettersen
16:30-17:00: Changes of Sea Ice Conditions in Poland and the Baltic Sea from 16 till 18 century	Marzenna Sztobryn
17:00-17:15: Short poster introductions:	Natalija Schmelzer, Lars Axell
17:15-18:30: Reception	

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9:00- 9:30: Lake ice spectral and integral optics: Finland and Estonia 2004-2005	Ants Erm, Jari Uusikivi Matti Leppäranta
9:30-10:00: Sea ice remote sensing at high resolution in the Baltic sea - a comparison of optical and microwave sensor data	Lars Kaleschke
10:00-10:30: Coffee	
10:30-11:00: Using AMSR-E 89 GHz Channels for Sea Ice Remote Sensing in Regional Seas	Gunnar Spreen
11:00-11:30: Sea ice station off Umeå, winter 2005	Matti Leppäranta
11:30-12:00: Ice dynamics in the Bothnian Bay as inferred from ADCP measurements	Christian Nohr, Göran Björk, Bo G. Gustafsson, Amund E.B. Lindberg
12:00-14:00 Lunch	
14:00-14:30: Land fast sea ice micro-organism succession, a 3-year time series from Santala Bay Hanko, SW coast of Finland	Karrell Kimmo

14:30-15:00: Some ideas on sea ice climate and navigation in the Baltic Sea	Klaus Strübing
15:00-15:30: Poster introductions:	Ove Pärn, Kimmo Karrell, Christian Nohr, Elise Reply, Stefan Kern, Iris Werner
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19:30 Conference Dinner	

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8:30- 9:00: Morning Coffee	
9:00- 9:30: Thermodynamic modeling of snow and land fast ice during spring melt-freezing period in the Baltic Sea	Bin Cheng
9:30-10:00: Brine release processes in melting sea ice. Results from an Arctic fjord, spring 2004	Karolina Widell
10:00-10:30: Predictability of sea ice salinity and microstructure from crystal growth theory	Sönke Maus
10:30-11:00: Coffee	
11:00-11:30: Sensitivity of Arctic Sea Ice in Rossby Centre Numerical Models	Ralf Döscher, Markus Meier,Klaus Wyser
11:30-12:00: Numerical Sensitivity Study of climate relevant processes in the Barents Sea	Ingo Harms, Kerstin Hatten, Corinna Schrum
12:00-12:30: Announcements, Closing	

Poster Program

1. Analysis of the ice model results for the Gulf of Finland. *Ove Pärn, Jari Haapala*
2. Ridged ice (Hailuoto, Gulf of Bothnia) as sympagic organism habitat. *Kimmo Karrell*
3. Spatial and temporal variability of ice growth and melting of waters of the region Oulu-Marjaniemi-Röyttä (Gulf of Bothnia). *Élise Lépy*
4. About polynia extents and sea ice compactness in the Kara sea obtained from Microwave radiometry. *Stefan Kern*
5. Ice winter strength in the western Baltic Sea in the period 1300-1500. *Natalija Schmelzer, G. Koslowski*
6. Under-ice zooplankton in the Baltic Sea. *Iris Werner*
7. Reconstruction of Annual Maximum Ice Extent in the Baltic Sea 1660-2005. *Lars Axell*
8. A Simplified Model of Sea Ice Deformation Based on the Formation Direction of Leads. *Christian Nohr, Göran Björk, Bo G. Gustafsson*

History of Baltic Sea Ice Climate Workshops

Matti Leppäranta

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Abstract

The first Baltic Sea Ice Climate Workshop was held in Tvärminne, Finland in 1993. The motivation was to collect sea ice scientists around the Baltic Sea together to exchange data, information and results, to start up a data base for sea ice modelling needs in the Baltic Sea. This workshop then grew into series at three-year time interval, the number of participants being in the range 20–40.

Introduction

Ice occurs in the Baltic Sea annually for seven months, from November to June. In normal winters the Gulf of Bothnia, Gulf of Finland, and Gulf of Riga are mostly ice covered, while further south only shallow bays and coastal areas freeze over. In cold winters the whole Baltic Sea is frozen; the most recent case is from 1947 but, however, in 1987 the coverage reached up to 96% of the total area of the Baltic Sea. The ice season has a major role in the annual cycle of the Baltic Sea via its influence on the air – sea momentum, heat and gas transfer, salinity budget of the sea, light conditions, and storage and transport of pollutants. The hydrographic and illumination conditions have further a strong influence on the ecological conditions in the basin.

In spite of the importance of the ice season in the Baltic Sea, many research programmes have overlooked the ice problems in the past. In particular this has led into serious biases in the research programmes in the northern and eastern large gulfs. Also it is well known that ice and ice-related presentations in the "Baltic Oceanographers" conference series has amounted to less than 5% of the total. Baltic Sea Ice Services have held meetings since early 20th century but these meetings have focused on practical questions such as ice codes, chart formats, and information exchange and transfer.

In the beginning of the 1990s, along with the increase of climate research in the Baltic Sea region, a workshop "Baltic Sea Ice Climate" was organised by the Department of Geophysics of the University of Helsinki. The objective was to collect sea ice scientists together on topics related to climate variability and Baltic Sea ice conditions. The workshop collected 36 participants, and in fact initiated a series of conferences on this topic, at three-year interval reaching to the 5th workshop in 2005.

The Five Workshops

First (1993, August): Tvärminne, Finland

The first workshop was held in the Tvärminne Zoological Station of the University of Helsinki. The organisers were Dr. Jari Haapala and the present author. Participants came from all Baltic Sea shoreline countries except Denmark, altogether 36: 5 from Estonia, 15 from Finland, 1 from Germany, 1 from Latvia, 1 from Lithuania, 4 from Poland, 6 from Russia, and 3 from Sweden. The presentations filled two and a half days, with one half-day reserved for an excursion to the town of Hanko (Fig. 1). This is a historical sea ice site since the first all-year ship route was opened between Hanko and Stockholm in 1877. Also the Russian tsar had built a railroad there from St. Petersburg because of the feasibility of Hanko as a winter harbour.

Fig. 1. The participants of the First Baltic Sea Ice Workshop, gathered at the Hanko Casino in the excursion.

In the first day mathematical modelling of sea ice in the Baltic Sea and the ice climate problem were discussed, and the second day was devoted to ice and related climatological time series. In the last day other ice related topics such as remote sensing of sea ice and the St. Petersburg dam ice problems were treated. Most of the presentations were collected in the workshop proceedings, together with the workshop recommendations and decisions (Leppäranta and Haapala, 1993).

As a practical result, a decision was made to establish a data base IDA for Baltic Sea ice climate investigations, open for all researchers to contribute and to utilize (Haapala et al., 1996). The focus was on three particular ice season to serve foe model calibration: normal (1983/1984), severe (1986/1987) and mild (1991/1992). Also an initiative was made to start joint climatological ice time series data collection and analysis, to produce result only almost ten years later (Jevrejeva et al., 2002; 2004). Finally, the participants agreed to have the second workshop in Estonia.

Second (1996, September): Otepää, Estonia

The second workshop was held in the Otepää, southern Estonia, in 2–5 September 1996. The organisers were Professor Heino Mardiste and Dr. Arvo Järvet from the Department of Geography of the University of Tartu. Participants came from all Baltic Sea shoreline countries except Latvia and Lithuania, altogether 28: 1 from Denmark, 6 from Estonia, 9 from Finland, 5 from Germany, 2 from Poland, 2 from Russia, and 3 from Sweden. The presentations filled two and a half days, with one half-day reserved for an excursion in the Estonian countryside.

Mathematical modelling and ice time series formed the main theme of the workshop (see Järvet, 1999). In addition, there were several papers about local ice conditions in different coastal regions of the Baltic Sea, such as Väinameer basin west from Estonia and the river Oder estuary. Snow conditions and freezing lakes in the Baltic Sea drainage basin were also covered in the presentations.

Third (September 1999): Stawiska, Poland

The third workshop was held in Stawiska, Kaszuby, Northern Poland, in 5–8 October 1999. The organisers were Dr. Marzenna Sztobryn and Ms. Ida Stanislawczyk from the Maritime Branch of the Institute of Meteorology and Water Management in Gdynia. The site was a small resort place in a picturesque lake district. Participants came altogether 23: 2 from Estonia, 8 from Finland, 3 from Germany, 9 from Poland, and in addition one representative from WMO (World Meteorological Organization), Geneva. The presentations filled two and a half days, with intensive discussions continuing until late hours.

Mathematical modelling and ice time series form the main theme of the workshop (see Sztobryn, 2002). In addition, there were several papers on environmental questions connected with sea ice.

Fourth (May 2002): Norrköping, Sweden

The fourth workshop was held in the Swedish Meteorological and Hydrological Institute (SMHI), Norrköping in 22–24 May 2002. The organisers were Professor Anders Omstedt from Göteborg University and Dr. Lars Axell from SMHI. Participants came altogether 35, containing scientists and end users: 4 from Estonia, 5 from Finland, 7 from Germany, 1 from Poland and 16 from Sweden, and additionally from outside the Baltic Sea 1 participant came from Canada and 1 from Japan. The presentations filled two and a half days, with one half-day reserved for an excursion in Norrköping.

It was clearly reflected in the presentations that the long-term modelling and time series analysis had greatly progressed since the first workshop nine years earlier (Omstedt and Axell, 2003). Now in 2002 there were several ice modelling groups around the Baltic Sea, and the picture of the ice season variability as seen by the time series had become much better understood. For future actions two important items were recognised: extension of IDA data base to include time series and calling modellers for a climatological prediction of the ice season 2049/2050. Also it was seen that the collaboration between sea ice geophysicists and sea ice biologists was rapidly expanding in the Baltic Sea region.

Fifth (September 2005): Hamburg, Germany

The fifth workshop was held in the University of Hamburg. The organiser was Dr. Corinna Schrum. Participants came altogether 23 (Fig. 2): 2 from Estonia, 3 from Finland, 8 from Germany, 1 from Poland and 3 from Sweden, and additionally from outside the Baltic Sea there were 2 participants from Canada, 1 from France and 2 from Norway. The presentations filled two and a half days, with oral and poster sessions included.

The Baltic Sea ice climate was strongly present in the workshop, but a changing was clearly seen toward a “Baltic Sea ice science workshop”, dealing with many different types of ice problems. Also there were invited talks representing other seas of the seasonal sea ice zone, namely Bohai Sea in China, a freezing sea at 37–40^{o}N (closest to the Equator for an annually freezing sea), and Arctic shelves. The proceedings of the workshop are presently in preparation, with Dr. Corinna Schrum as the editor.

Final remarks

Baltic Sea Ice Climate Workshops have been organized since 1993 at three-year intervals, the first one in Tvärminne, Finland and the fifth in 2005 in Hamburg (Fig. 3). It has been a very enjoyable and fruitful series, with significant openings into the sea ice research of the Baltic Sea. In particular, as results have come the following: IDA data bank for ice model calibration and validation has been set up, joint modelling studies have been performed, and ice time series have been jointly analysed. Also the topics discussed in the workshops have spread from geophysics into neighbouring disciplines, in particular sea ice ecology. The proceedings books of these workshops have come to a major literature source of the Baltic Sea ice research.

Fig. 2. The participants of the 5th Baltic Sea Ice Climate Workshop, campus are of the University of Hamburg.

In Hamburg it was agreed that the sixth workshop will come in 2008, the site still remaining open. Interestingly, year 2008 also fits into the period of the International Polar Year (IPY), and a new challenge will be to include also other seas from the seasonal sea ice zone into the workshop programme.

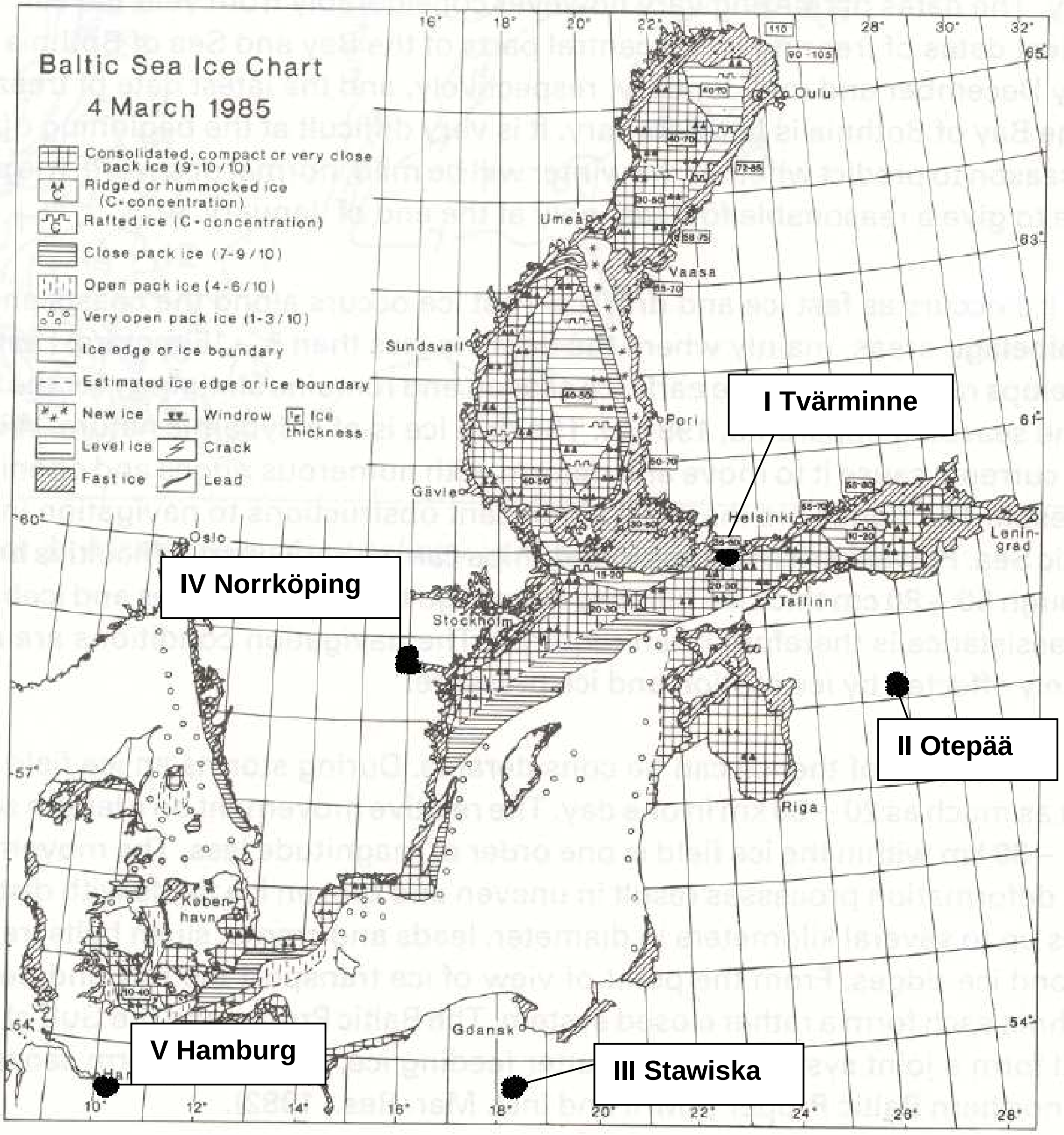

Fig. 3. The sites of the Baltic Sea Ice Workshops shown on an ice chart in a severe winter, 1985 (ice information by the Finnish Institute of Marine Research).

Acknowledgements

Dr. Jari Haapala is thanked for his efforts in the initiating the workshop series and in organising the first workshop. University of Helsinki, University of Tartu, Institute of Meteorology and Water Management, Gdynia, Swedish Meteorological and Hydrological Institute, Norrköping, and University of Hamburg are thanked for providing facilities for the ice workshops.

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Influence of the Temperature on Ice Conditions in the Bay of Bothnia (Baltic Sea)

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Abstract

Every winter, the ice sea is formed in the Bay of Bothnia (North of the Baltic Sea). The ice growth and melting processes of its waters are submitted to the northern climate with oceanic and continental influences. Temperature is an essential parameter to the formation of the ice pack, but is it the only element to have an influence on these processes? The statistical analysis of the correlation between temperature and ice conditions is necessary to understand the influence of other natural and anthropogenic elements on ice growth and melting in the Bay of Bothnia.

Key words: Ice growth, ice break-up, temperature, correlation, Bay of Bothnia

Introduction

Interior sea belonged to Europe, the Baltic Sea is the only one in which a state change process of its waters happens every year. In fact, waters of the Gulfs of Bothnia, Finland and Riga freeze every winter. Thus, seasonal processes of ice growth and melting can be observed each year and have an important role in the economic life - especially in the winter navigation- in all the countries close to these gulfs.

During the winter, “the maximum annual ice extent is 10 to 100% of the Baltic area, the length of ice season is 4 to 7 months, and the maximum annual thickness of landfast ice is 50 to 120 centimetres” (Jevrejeva, 2004). The ice pack is an important element in the climatology of the Baltic Sea (Haapala, Leppäranta, 1997). The ice growth of the sea has an influence on the climate which becomes more continental. The difference between the mean temperature of the warmest and coldest months of the year is an indicator of continentality (Autio, Heikkinen, 2002). In the Bay of Bothnia, the temperature difference is 21,3 to 37,1℃; the mean is 28,8℃ for the period 1957-2004 (mean monthly temperatures at Oulu airport station). Moreover, the sea ice “plays an important role in the North-European climate” (Haapala, Leppäranta, 1997).

Sea ice conditions are an indicator of the severity of the winter season (Haapala, Leppäranta, 1997). Nevertheless, the climatic parameter of temperature is it the only element which has an influence on the spatial and temporal variability of the ice growth and melting? The purpose of this paper is to analyse the interactions between climatic variables and cryomarine phenomena, and to discern others parameters to take care in the formation of the ice cover.

Data and methods

The ice growth and melting processes in the Bay of Bothnia is the main point of this paper. Temperature is an essential parameter for the ice to be formed. It seems interesting to establish an analysis of correlation between temperature and ice parameters in order to determinate how important the temperature influence is.

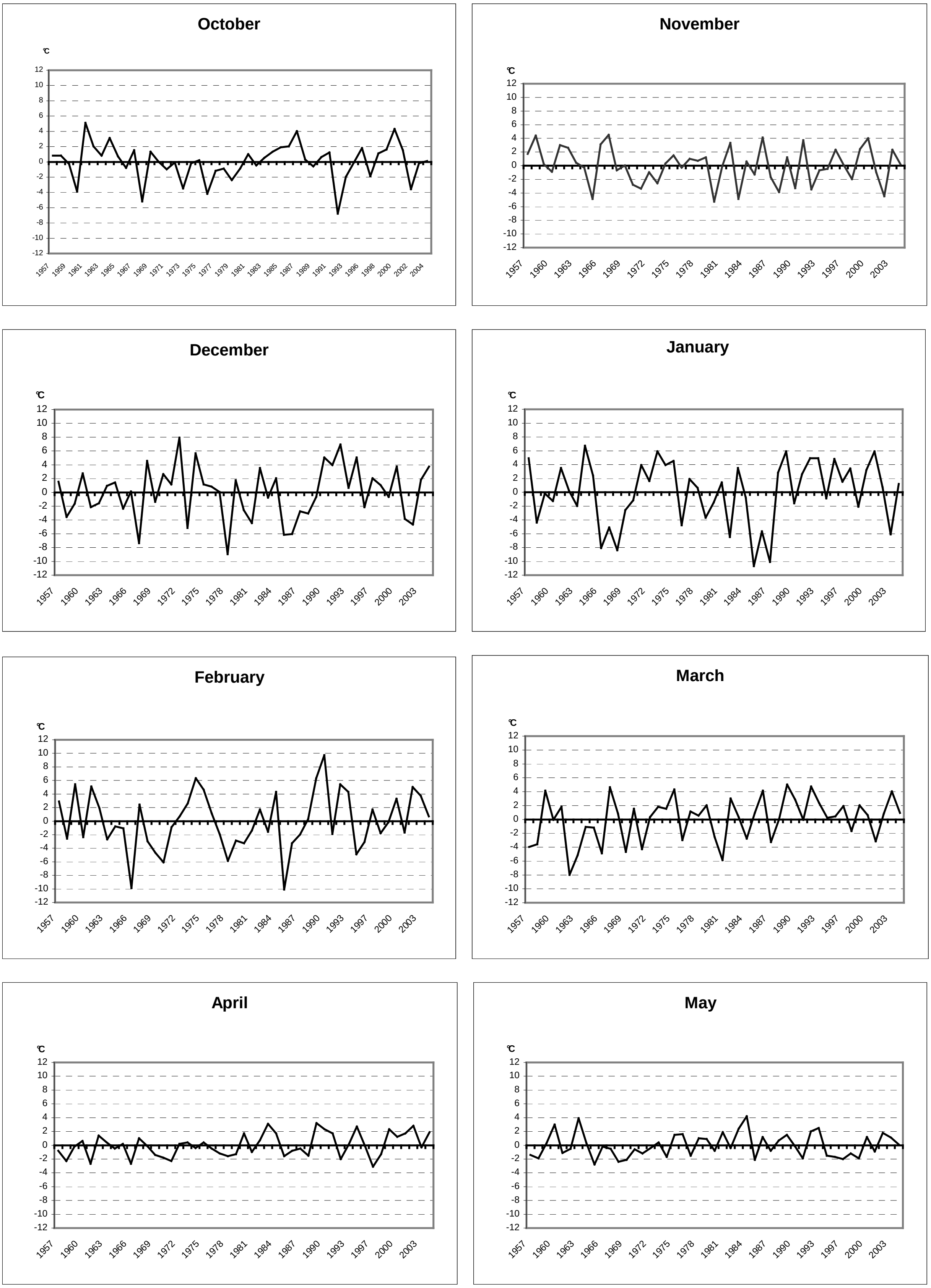

Fig. 1. Deviation from the average of the mean air temperature (period 1957-2004)
Sources : Ilmatieteellinen Keskuslaitos – Station of Oulu

Data series of temperature and ice thickness were fixed for the period 1988-2003. The main annual air temperature of each year of this period are from the meteorological station of Oulu airport. The observation spots were almost at the same place until 1995, and there was a relocation of them after that. Some homogeneity tests of the climatic series were realised by the FMI (Finnish Meteorological Institute). The monthly variability of the mean air temperature is important for this study. The most important variations of the temperature take place during the heart of the winter. It especially concerns the months of December, January and February (Fig. 1).

A succession of cold and warm winters can be noticed. Could it be possible to conclude to a significant trend? The mean air temperature of January 2003 was the coldest one recorded for the period 1988-2003, but January 2003 does not belong to the coldest winters of the end of the XXe century.

Temperature data can be in relation with ice data. The ice thickness data series presents measurements made for the period 1988-2003 by researchers from the station of Virpiniemi.

The analysis of a statistic relation between two quantitative variables – temperature and ice thickness – is for validating or not the hypothesis mentioned before. So the intensity of the relation of two variables can be measured by a correlation coefficient.

Results

The intensity of the relation temperature / ice thickness

In the Oulu region, the maximum annual thickness of ice is 40 to 90 centimetres, and the winter mean air temperatures is –3 to –7.5℃ from 1988 to 2003. The relationship between the winter air temperature and the Virpiniemi annual maximum ice thickness is shown for the period 1988-2003 in Figure 2. The Bravais-Pearson coefficient (r) is 0,607 and shows a good correlation between the winter mean temperature and the maximum annual ice thickness. Nevertheless some winters are some exceptions. For instance, the winter 1988/89 was warm, the mean air temperature (December 1998 – April 1989) about –3℃, but the maximum ice thickness was large, 77 cm.

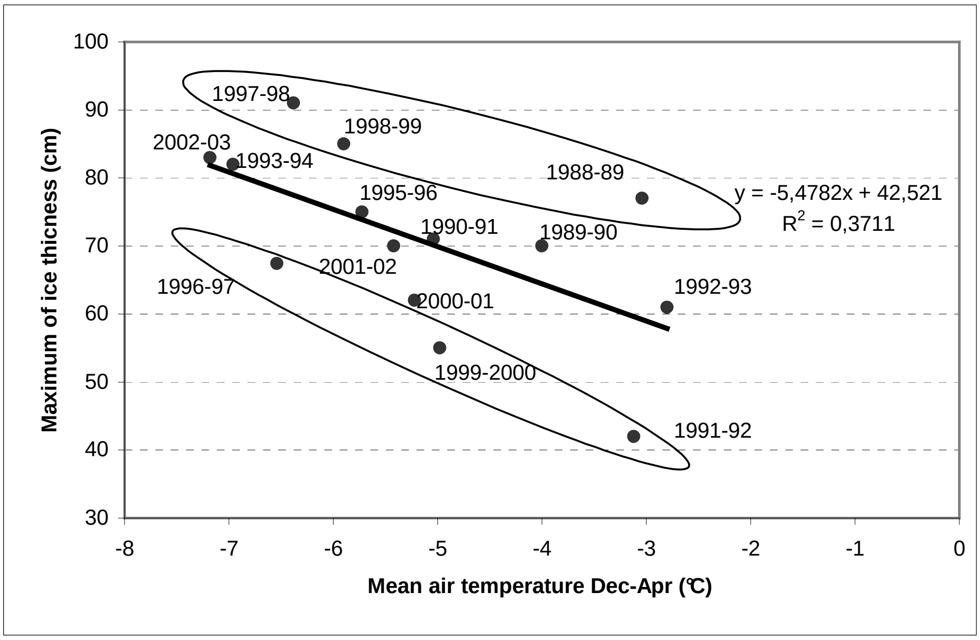

Fig. 2. The relationship between the mean winter season air temperature and maximum of ice thickness in Virpiniemi (1988-2003)

The ice thickness compared to the frequential distribution of the temperature

The analysis of the relationship between the winter mean air temperature and the maximum ice thickness gives some explanations to the exceptions. Some winters follow the hypothesis: more the temperature is low more the ice cover is large.

The winter 2002/03 confirms this hypothesis. The Virpiniemi ice thickness got larger and larger until March (80 cm). The high winter mean air temperature can be explained because the months from October to January were very cold (Fig. 3) even if March was one the warmest month of March of the 50 last years.

The winters 1988/89 and 1991/92 got mean temperatures near –3℃, but the maximum ice thickness, in March for both, evaluated differently, respectively 77 cm and 42 cm. The harshness of the winter and the weakness of snow precipitations are the reasons of an important thickness of the ice cover in 1988/89. The winter 1991/92 belongs to the 25% of warmest winters of the second part of the XXe century (Fig.3). The insulating effect of snow (Haapala, Lepparanta 1997) has also some consequences on ice layers. In 1999/2000, the thickness of ice cover was low compared to the temperatures because of the importance of the snow cover, about 35 cm. The winter 1996/97 was cold, but the ice thickness was only 67 cm and the snow cover was almost nonexistent. Thus, other reasons than the temperature and the snow cover could be explained the state of the ice thickness.

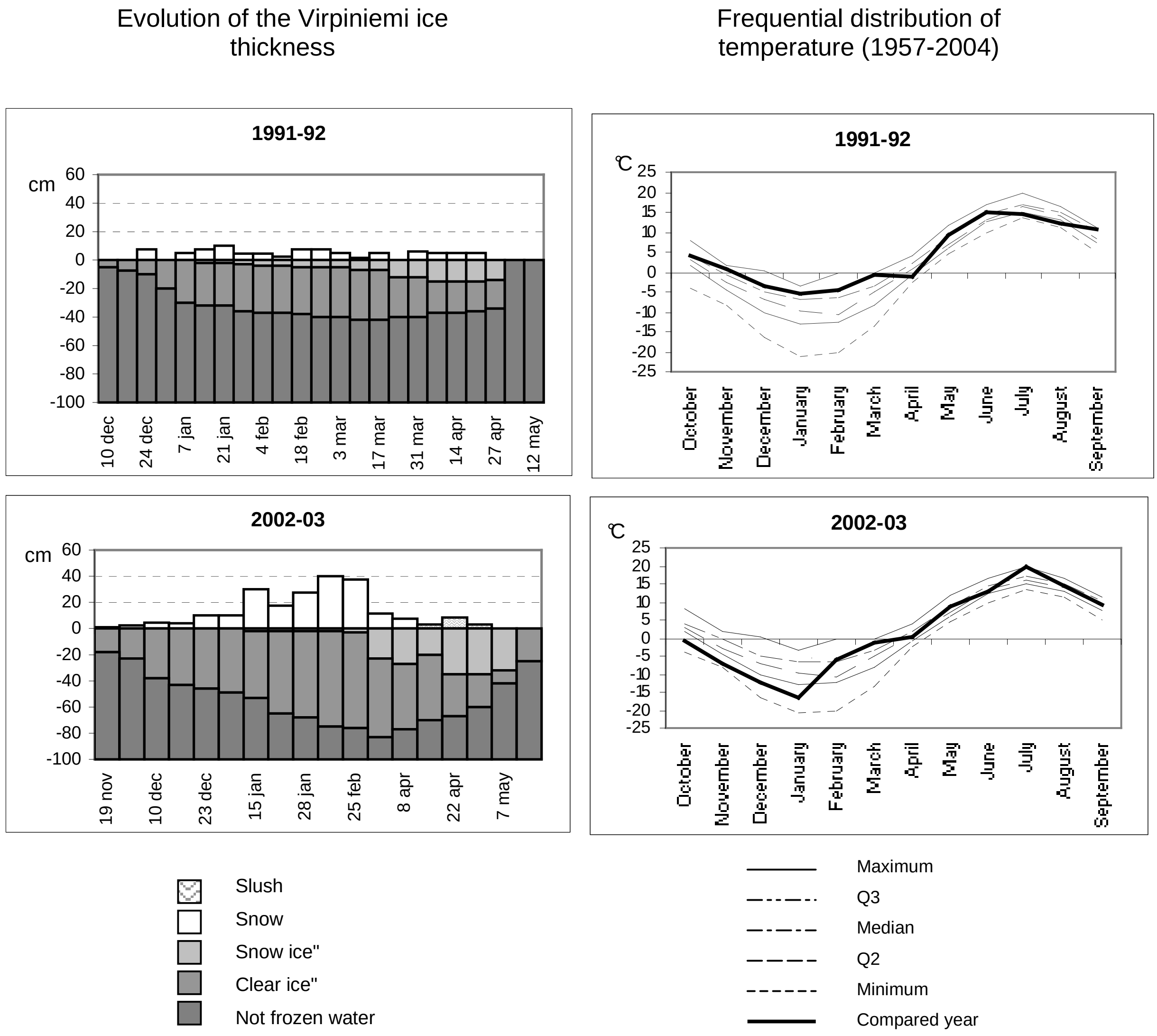

Fig. 3. Ice thickness compared to the frequential distribution of temperature
Sources : Station de Virpiniemi / Ilmatieteellinen Keskuslaitos – Station of Oulu

Explications

Low temperatures and small ice cover are responsible of the ice growth of the Bay of Bothnia. But other elements explain the formation and the evolution of the ice pack. The wind for example can induce important deformations of the ice cover. Boats which take channels made by ice breakers can have an influence on the deformation of the ice pack as well. So it seems important to take care about elements which can deform the ice cover or move the stations of measurement. The aquatic fauna can slow the ice growth.

Conclusions

The temperature is an essential element for the formation of the ice cover in the Baltic Sea where the salinity rate is really low. Even if the correlation between the temperature and the ice thickness is good, statistical analysis show that other climato-marine and anthropogenic factors have an influence on the spatial and temporal variability of ice growth and melting of sea waters, and on the movement of the ice pack. It is also necessary to take care of the climatic study of the past months of a studied moment in order to understand better the evolution of the ice thickness.

Nevertheless, climato-marine perspectives introduced by some authors show the importance of the relationship temperature / ice conditions. According to Haapala and Leppäranta (1997), ”small climatic changes will drastically influence ice conditions”. Some studies have shown that some parts of the Baltic Sea get less and less ice winters. Could it be a confirmation to a warming trend? Decrease of the probability of ice occurrence (Jevrejeva, 2004), diminution of the duration ice season in the Baltic Sea except in the Bay of Bothnia (Haapala, Leppäranta 1997), later date of freezing, earlier date of ice break-up… are previous phenomena for next winters.

The important role played by the climate on the ice pack is reinforced by other natural parameters and human activities. But the ice pack has also an influence on the climate (continentality…) and local ways of life.

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Sea Ice Station Umeå, Winter 2005

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Abstract

In winter 2005 ice investigations were performed in the Northern Quark, Gulf of Bothnia. A float was deployed at the Umeå Marine Sciences Centre in November 2004 for atmospheric surface layer, ice, and oceanographic measurements; this float then was destroyed in heavy storm in January 2005. In spring manual measurements were made at the station with ice sampling. The throughflow of ice in the Northern Quark was examined by mathematical modelling. The geometry of the strait, in particular the fast ice boundary, is critical for the dynamics of the ice there.

Introduction

In the Baltic Sea winter, near-coastal areas are covered by landfast ice while further out drift ice fields are found. The boundary between the fast ice and drift ice zone is on average at 10 m depth contour but if the ice is very thick the ice cover of a basin may become stationary (Leppäranta, 2004). The evolution of the location of the fast ice boundary is a challenging but very complicated question.

Coastal zone ice investigations have been ongoing in the recent years as part of our snow and ice research programme. This zone covers the fast ice zone and normally also a section of the drift ice field. The first main site was Santala Bay in the Gulf of Finland (e.g., Kawamura et al., 2001 ; Granskog et al., 2004) and the second one was at Perämeri Research Station on the western shore of Hailuoto island, Bay of Bothnia. In winter 2004/2005 the sea area off Umeå Marine Sceinces Centre was taken as the third main site. This paper presents the Umeå experimental campaign together with the first results.

Fast ice site 2004-2005

Umeå Marine Research Station is located on the shore of the Northern Quark in the village of Norrbyn, 40 km south of Umeå. A float was deployed at the station, about 0.5 km from the shore, on November 18, 2004 (Fig. 1). The sea was still open, surface temperature about 3^oC.

Fig. 1. Umeå float, deployed in November 18, 2004. The mast has meteorological instruments in two levels, and solar radiation sensors are in the arm.

The instrumentation of the float included the following quantities:

(i) *Surface layer meteorology:* wind speed and air temperature at two levels (1 m and 2 m), humidity and wind direction at 2 m level, and incoming and outgoing solar radiation at 1 m level.

(ii) *Ice:* thermistor chain and a line of PAR (Photosynthetically Active Radiation) sensors were lowered into the water for recording in the water first and later in the ice as the sensors were to be trapped by the ice.

(iii) *Temperature, salinity and currents in water:* A 3-dimensional sonic current meter was deployed at 5-m depth, anchored to the bottom. The instrument also recorded the temperature and salinity of the water.

The system started to work well, and ice started to form at about December 10th. The growth was rather slow, and in the end of December the ice thickness was 10 cm. Then a heavy storm

arose with southerly winds. As a consequence, the fast ice at the float broke and experienced a significant displacement. The float instrumentation was harmed and stopped functioning, and also part of the data was spoiled by penetration of seawater into the data logger box. Therefore, the data collected covers just a 40-day period; however, it is an interesting period since the surface water then cooled from 3°C to zero and ice grew from zero to 10 cm thickness.

At 5-m depth the water temperature fell from 4°C to 0.5°C in by the end of November (Fig. 2). Then the temperature was constant for two weeks. The water salinity was about 4.4‰. There was an inflow of warm water with temperatures of 1–2°C for one week, and then toward the end of December the water cooled down again. The salinity of the water varied between 4.0 and 4.6‰ and was not so clearly connected with the temperature evolution.

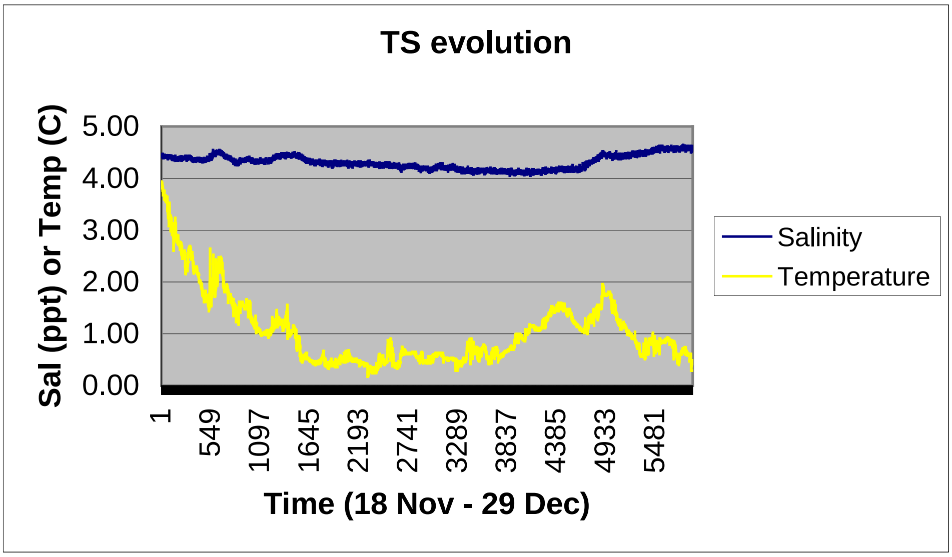

Fig. 2. Temperature and salinity of the water (5-m depth) at the Umeå float.

The breakage of fast ice was due to a combination of thin ice and strong wind. Since normally the ice grows faster than in the study winter, the period of potentially unstable ice cover was long. Landfast ice behaves as a plastic medium, with stationary state for

$$\tau_a L < P^* h$$

where τ_a is wind stress, L is basin size, P^* is ice compressive/tensile strength, and h is ice thickness (Leppäranta, 2004). Empirical data show that in the present case the thickness of 15–20 cm should have been enough for the ice sheet to resist the wind forcing.

At the end of March a short field trip was made to the landfast ice site. Ice sample was taken, and the springtime light transfer through ice and snow was determined. The fast ice thickness was then 30 cm at Umeå (Fig. 3). The Bay of Bothnia and Northern Quark were all ice-covered, but in the northern Sea of Bothnia there was a wide lead.

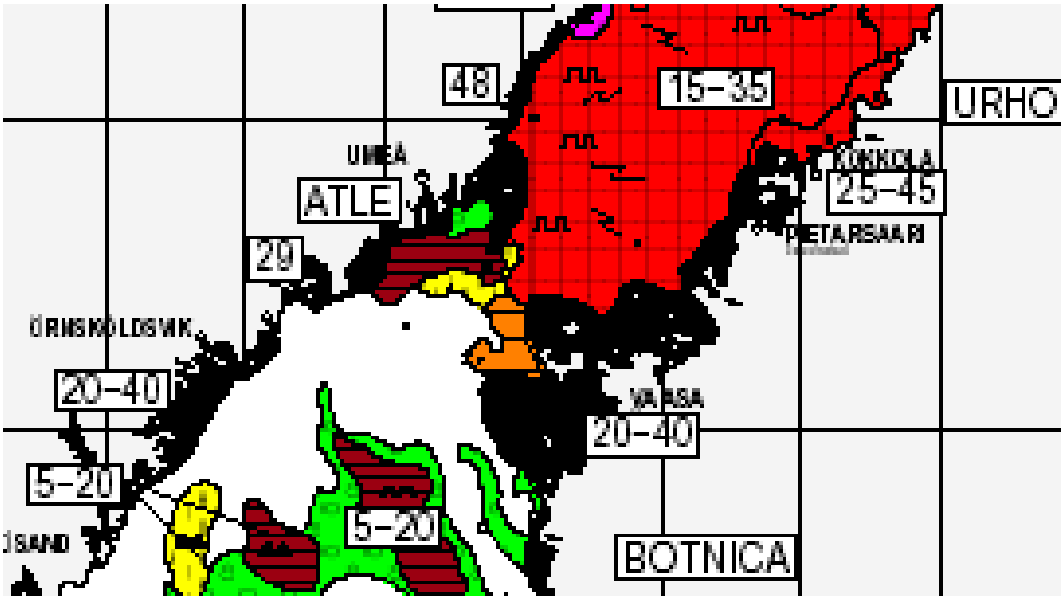

Fig. 3. The ice situation in the Northern Quark on 31 March 2005 according to the Swedish Meteorological Institute (http://www.smhi.se/).

At the site the ice was bare, and the thickness was 25 cm (Fig. 4). There was a thin snow-ice crust on top, and then 7 cm of clear congelation ice, and the lower part was porous congelation ice appearing opaque due to light scattering in the voids after the sample had been raised into the surface. The temperature of the inner ice was -0.2 – -0.4°C, approaching zero at the boundaries.

Fig. 5 shows the downwelling irradiance at ice surface and at the depths of 10 and 15 cm beneath the surface. The data are recorded in quanta irradiance/m^{2}s, which transforms into W/m^2 by division with 4.6 (Arst, 2003); consequently, the maximum daytime irradiance was about 500 W/m^2 (under clear sky conditions). The albedo was according to our measurements 0.3. Reducing the top irradiance by the influence of the albedo, it is seen that the irradiance level dropped by the factor of 0.25 in the first 10 cm and by the factor of 0.40 in the next 5 cm. Therefore, the resulting light penetration depths were 35 cm for the clear congelation ice and 10 cm in the porous ice (the penetration depth is here defined as the distance across which the irradiance level drops to 1/e ≈ 37% from the start level). In comparison, the light penetration depth in Santala Bay, Gulf of Finland, has been measured as 20–25 cm (Leppäranta et al., 2003).

Fig. 4. Ice sample, Umeå Marine Sciences Centre 31 March 2005.

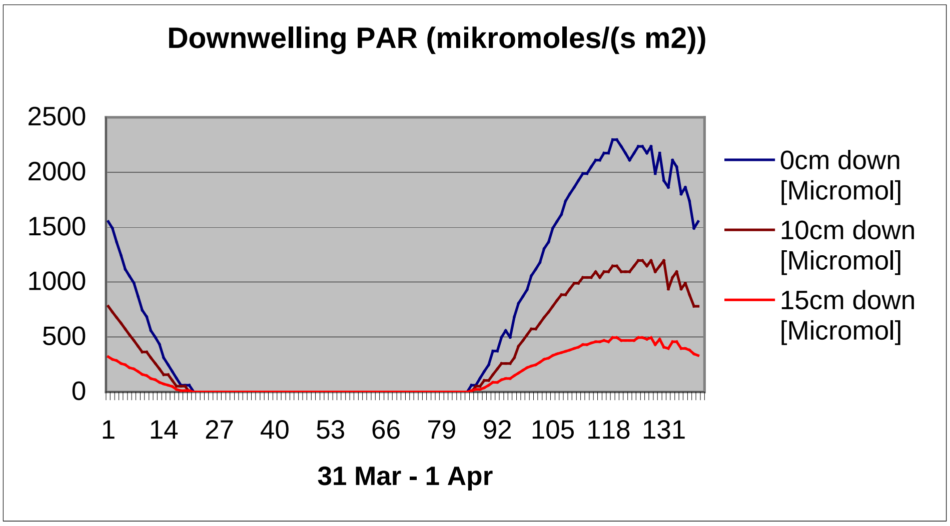

Fig. 5. Downwelling PAR irradiance in the ice sheet Umeå Marine Sciences Centre.

Modelling ice flow through Quark

The Northern Quark forms a narrow and shallow strait between the Bay and Sea of Bothnia. There is a wide archipelago in both sides of the strait, which make the drift ice channel still much more narrow than the strait itself. It is know that in mild winters of ice flows through the Northern Quark but in cold winters a fast ice bridge forms across between Finland and Sweden. This fast ice bridge was used in severe winters for on-ice traffic before 1970 when the northern part of the Gulf of Bothnia was closed for shipping. In principle the phenomenon known as arching could occur in the strait but such has not been reported in literature.

To examine the ice dynamics in the Northern Quark, idealised simulations were performed with a sea ice mechanics model calibrated for relatively small-scale problems as here (Wang et al., 2003). This is a viscous-plastic three-level model, which predicts the evolution of sea ice velocity, compactness, thickness of undeformed ice and thickness of deformed ice as forced by the wind field. The initial situation was specified by ice compactness equal to 0.95 in the Northern Quark and bay of Bothnia, while the Sea of Bothnia was ice-free. The wind was 10 m/s from northeast, driving the ice field of the Bay of Bothnia down. The initial ice thickness was varied, as was the extent of the fast ice zone.

Fig. 6 shows the result when the initial ice thickness was 10 cm and the fast ice boundary was taken as the 5-m depth contour of the sea. In south the ice flows out into the Sea of Bothnia, and in the Northern Quark above the narrow throughflow a heave ridging takes place with ice thicknesses almost 50 cm from this mechanical accumulation. On the northern fast ice boundary the lead opens up. Increasing the initial thickness to 80 cm, there was still throughflow but the less ridging took place. Extending the fast ice zone to the 10-m depth contour resulted in a large change, with almost no throughflow left in both initially thin ice (10 cm) and thick ice (cases). As thin ice is heavily ridging, it gains strength and becomes stuck. The critical point is therefore the geometry of the strait.

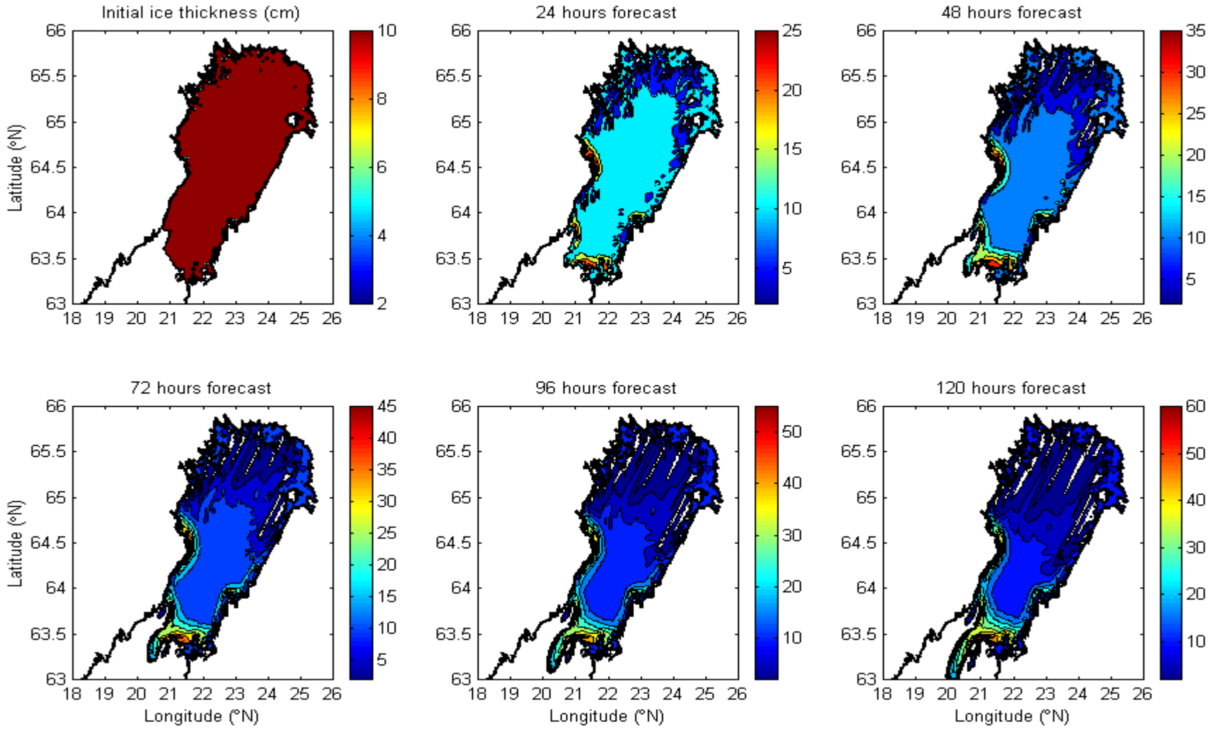

Fig. 6. Model simulation of the throughflow of the ice in the Northern Quark. The initial ice thickness and compactness are 10 cm and 0.95, and the wind blows from 20^{o} right from north. The initial situation and predictions at one-day time step are shown.

Conclusions

Sea ice investigations were initiated in 2004 off Umeå in the Northern Quark, Baltic Sea, as a part of our costal zone winter programme. In 18 November 2004 a float was deployed at the

Umeå Marine Sciences Centre for atmospheric surface layer, ice, and oceanographic measurements, but unfortunately this float then was destroyed in heavy storm in January 2005 with much of the atmospheric data lost. In 31 March – 1 April a short field trip was made with manual measurements of ice sampling and the light transfer. The throughflow of ice in the Northern Quark was examined by mathematical modelling.

The automatic station data showed that the water body cooled in the first two weeks. Ice formed at December 10th, and still after that there was a warm water inflow from the Sea of Bothnia. The salinity of the water was 4.0–4.6‰. At the time of the fast ice break-up the ice thickness was 10 cm, too small to be able to resist strong wind forcing. As a whole the winter was mild, and at the time of the field trip the ice thickness was only 25 cm, almost all congelation ice but most of it already porous. The albedo of the bare ice was 0.3, and the light penetration depth was 35 cm for clear ice and 10 cm for porous ice. In optics of natural water bodies the euphotic zone is taken as the level where the irradiance has dropped to 1% of the surface value. In practice this means 4–5 penetration depths, i.e. in the present case the ice takes just half of that amount. The model simulations for the ice dynamics showed that the geometry of the Northern Quark, in particular the fast ice boundary, is critical for the dynamics of the ice there. If the fast ice boundary is taken as the 10-m depth contour, almost no ice floes through the strait if the ice cover is initially compact.

The experience with the fast ice breakage was another good lesson, and also future studies need to be performed with low risk levels to obtain a good basic data set of the ice season in the Northern Quark. Anyway, winter 2004/2005 data as well as the model outcome are now being analysed for the final results.

Acknowledgement. This work has been supported by a grant from the Umeå Marine Sciences Centre of the Umeå University (project Seasonal evolution of sea ice, wintertime hydrography, and light conditions). Dr. Amund E. B. Lindberg from the Centre is thanked for his help in the recovery of the automatic station.

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Analysis of the Ice Model Simulation for the Gulf of Finland in 2002/2003

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Abstract

In this study we have analysed the multi-category sea-ice model (HELMI) results in order to examine characteristics of deformation in Gulf of Finland. We investigated how the increase of deformed ice is related to wind speed and direction and how the ice conditions varies in space and time.

Background

The seasonal ice cover is of great importance to the countries surrounding the Baltic Sea, as year-round navigation is essential for the national economies in these countries. The Gulf of Finland is an important corridor for Russian, Finland and Estonian shipping. In winter vessels must navigate through the ice, in normal winter at last 150 nautical miles and maximum sailing distance to the ice-edge was 400 nautical mile in 1961-1990 (Seinä 2003).

The first ice forms on the Gulf of Finland at the beginning of December and breaks up in the end of April. The thickness of undeformed ice in the Gulf of Finland may reach 0.8 m in the fast ice but in the pack ice region the thickness of level ice seldom exceeds 0.5 m, and ice ridges are typically 5-10 m thick.

During an average winter the whole northern Baltic Sea is ice covered. Even in a mild winter on the Gulf of Bothnia, Gulf of Finland and Gulf of Riga appears the ice. Sea ice is important because it regulates exchanges of heat and salinity in the sea. The sea ice affects both human activities and biological habitats.

Deformation of sea ice is a key process determing the evolution of the sea-ice thickness distribution. Apparent results of the deformation are leads and ridges. Recent observations of the thickness by Hans (2004) have reveled that the mean ice thickness over several km^2!! could be 2-3 meters in the Gulf of Finland. In this study we have analysed the multi-category sea-ice model (HELMI) results in order to examine characteristics of deformation in the Gulf of Finland, and have investigated how the increase of deformed ice is related to wind speed and direction and how the ice conditions varies in space and time.

Model Description

The HELMI model is a multicategory sea-ice model developed originally for the climate research (Haapala et al., 2005). The model physics and numerics are same both in operational and climate simulations. The only differences are in the horizontal resolution and atmospheric forcing used. The model resolves ice thickness distribution, i.e. ice concentrations of variable thickness categories, redistribution of ice categories due to deformations, thermodynamics of sea-ice, horizontal components of ice velocity and internal stress of the ice pack.

The redistribution function is dependent on ice thickness, concentration and the strain rates (Thorndike et al., 1975, Hibler, 1986). Continuum scale sea ice models resolve an average behavior of the pack ice and the subgrid processes are neglected or taken into account in a simplified manner. The following assumptions of the deformation processes in the present model have been made i) deformed ice is generated only from undeformed ice categories i.e. rafted ice is not deformed further in the model ii) cross-over thickness determines whether the undeformed ice is rafted or ridged. This assumption is based on the Parmeter (1975) law and field observations (c.f. Rothrock, 1979). It is also assumed that the thinnest 15 % of the ice categories experience deformations (Thorndike et at. 1975). Further assumptions are that the shear deformations are not taken into account and the shape and porosity of the ridges is constant. These assumptions are based on the field observations (Timco and Burden, 1997; Kankaanpää, 1997).

Ice motion is determined by the time dependent momentum balance equation, which takes into account a Coriolis force, wind and water stresses, sea surface tilt term and an internal stress. The internal stress of pack ice is calculated according to the viscous-plastic rheology (Hibler, 1979) but also relates consumption of the kinetic energy to the ice pack deformations (Rothrock, 1975).

The sea-ice model employs curvi-linear co-ordinates. Variables are spatially discretized in a c-crid. The advective part of the ice thickness and concentration evolution equation is solved by an upwind method. Momentum balance is solved by the line successive relaxation procedure proposed by Zhang and Hibler (1997).

Present set-up of the model predicts evolution of five undeformed and two deformed ice categories. Ice categories are "advected" in the thickness space without any limits, except that the thinnest category is not allowed to exceed 10 cm. Deformed ice is divided into separate categories of rafted and ridged ice types.

Horizontal resolution of the model is 1 nm. The model was forced by the daily NCEP/NCAR reanalysis. Initial SST is obtained from the ice charts.

Weather conditions

The model was forced by the daily NCEP/NCAR reanalysis. The NCEP/NCAR data is from the global atmospheric model of resolution 2.5°x2.5°. In order to study utility of the NCEP/NCAR data in regional studies, the data were compared to the Tallinn meteorological observations. The figure 1 shows a good correlation between the reanalysed and measured wind data. The correlation coefficient is 0.91 and 0.88 for meridional, zonal components respectively.

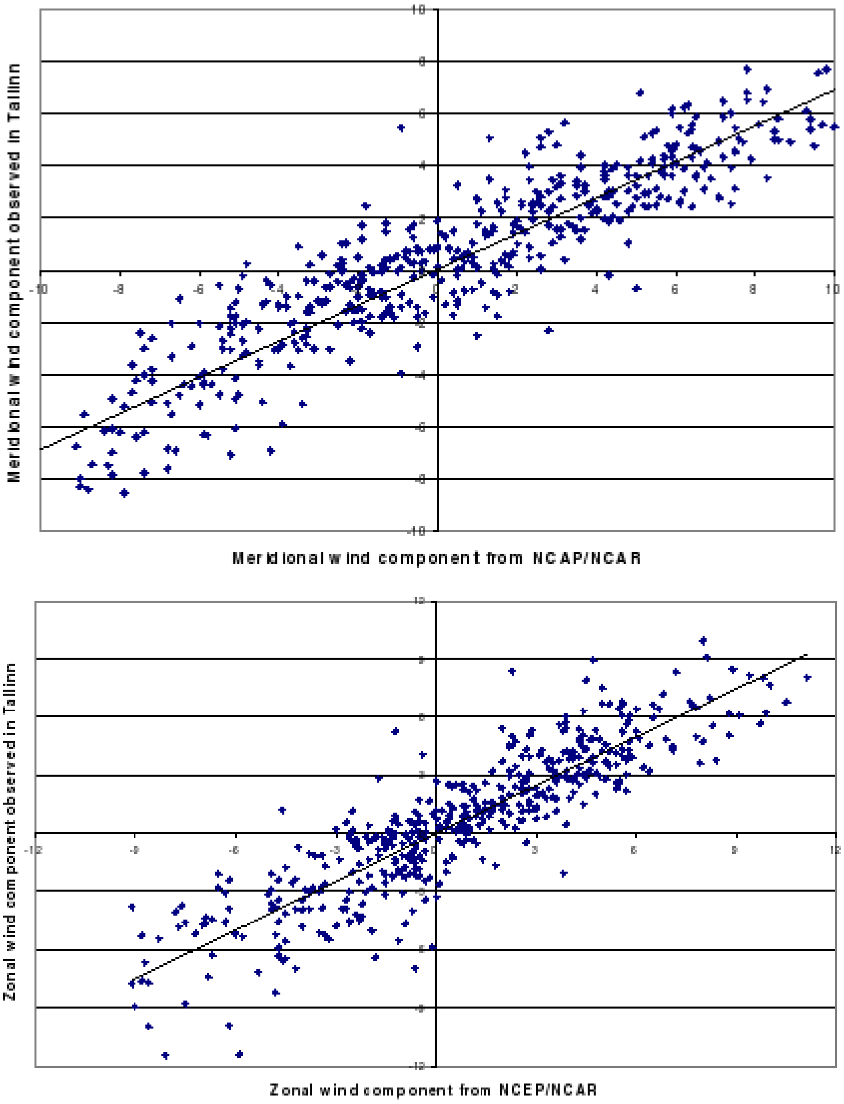

Fig.1. Wind data from these NCEP/NCAR reanalysis and observed data from Tallinn.

The weather conditions during the winter 2002/03 are shown in Figure 2-3. As the chart 2 shows us where come from the winds over 4 m/s in winter. Strongest winds in winter 2003 blew to direction between 10-70^o from SW and from NNE.

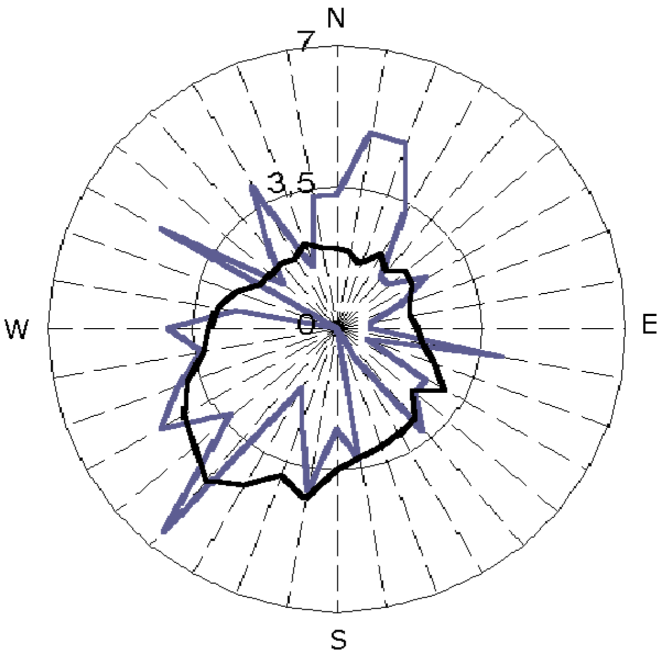

Fig. 2. Windroses for daily wind speed over 4 m/s in winter. Winds frequency in 2003 is light and in 1971-2004 is black line.

There are six different episodes when wind speed has been over 8 m/s. First of them are 16-19.01 (Fig 3) this time blew wind from SW direction, second was 26.01 wind from SW, 29-30.01 with NE winds, 2-4.02 first day blew wind from S in the course of next days dominated SW winds. Next was 10-13.03 dominated S and N winds, 20.03. was wind from the N.

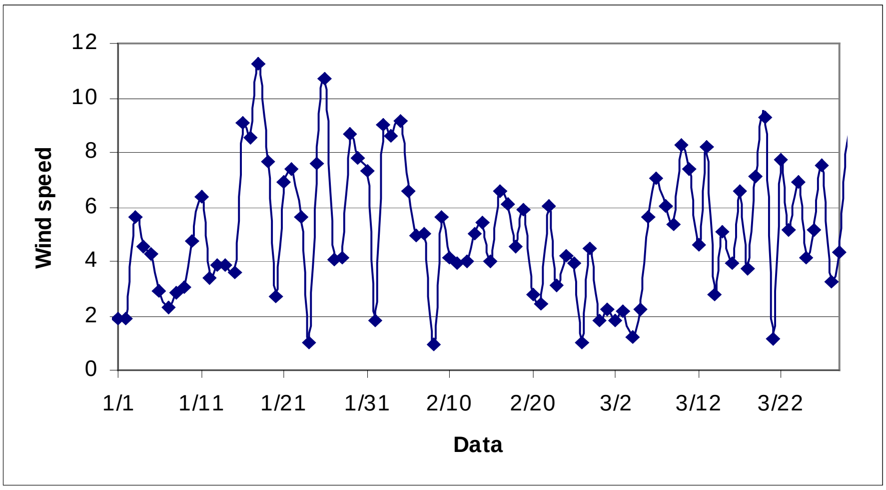

Fig. 3. Daily wind speed from NCEP/NCAR reanalysis.

Ice conditions

The ice season of 2002/03 started with rapid ice formation. In the early November 2002 ice cover begin to develop in the Bothnian Bay and in the Gulf of Finland. At the end of December the whole Gulf of Finland was covered by the ice, ice thickness was from 15 cm in west to 50 cm in east (Pastukhov 2003).

The maximum thickness of fast ice from 70 to 90 cm in the north of Bothnian Bay, 60 to 75 cm in the Sea of Bothnia, 50 to 65 cm in the western Gulf of Finland and 65 to 80 cm in the eastern Gulf of Finland. The maximum ice thickness in open sea was 40 to 60 cm in the Bay of Bothnia, 20 to 40 cm in the Sea of Bothnia, 5 to 20 cm in the northern Baltic Sea and 40 to 75 cm in the Gulf of Finland. The ice season lasted over one month longer than on the long-term average in the Gulf of Finland and about two weeks longer in the Bothnian Bay (FIMR, 2003).

In 2003 was ice very thick and deformated, navigation was difficult and restrictions valid 117-149 days (Seinä 2003) If the ice breaking was usually needed since January then 2003 year was different, icebreakers were needed already since December. And maximum extent of ice was achieved in Gulf of Finland on 5 of March with 232000 km^2.

Vessels needed already in January to navigate through the ice for the longest way in 40 years. Sailing distance reached up to 200 nautical miles, average distance is about 50 nautical miles.

The season 2002/03 was classificated as an average season in Baltic sea but severe ice thickness in Golf of Finland. (Seinä 2003).

Results

The total ice extent during the winter 2002/03 was already very large since at the beginning of January. On 16th of January total ice concentration decreases quickly from 100% to 70 % mains due to ice deformation (Fig 3). The ice deformed at sharply growing rate this time. Time series of simulated mean total ice concentration is in good agreement with observed data. We see the deformed ice concentration increasing at the fig. 4 between longitude 23.7-25E and 27.5-28E. We see in fig. 5, mean total ice thickness increase at the Estonian coast. Wind speed over 8 m/s blew to NE induce ice deformation at the south and east coast.

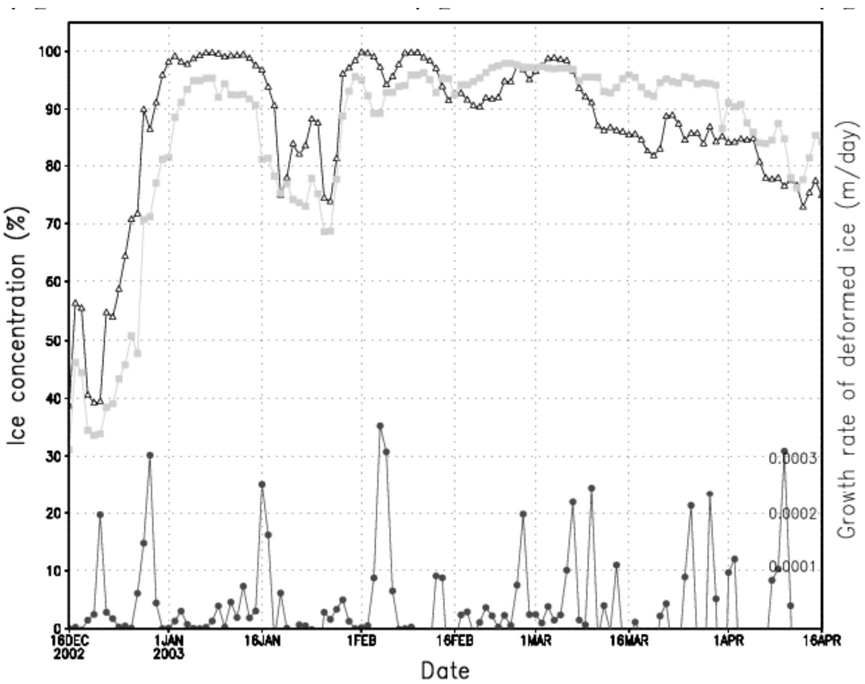

Fig. 3. Simulated and observed mean total ice concentration and deformed ice growth rate.

The deformed ice concentration illustrated a large variability in time and space. The mean total concentration of deformed ice was up to 12% from the area of Gulf of Finland. The maximum ice extent was middle of March.

The modelled largest fraction of deformed ice is located at 27.5-28.1E where the maximum concentration was up to 15 %. For this region the HELMI model produces constantally ice deformation for all the time considered an intense ice deformation. Comparatively less deformed ice was produced at 25.5-26.5 E. The deformation events are equally distributed over the ice season.

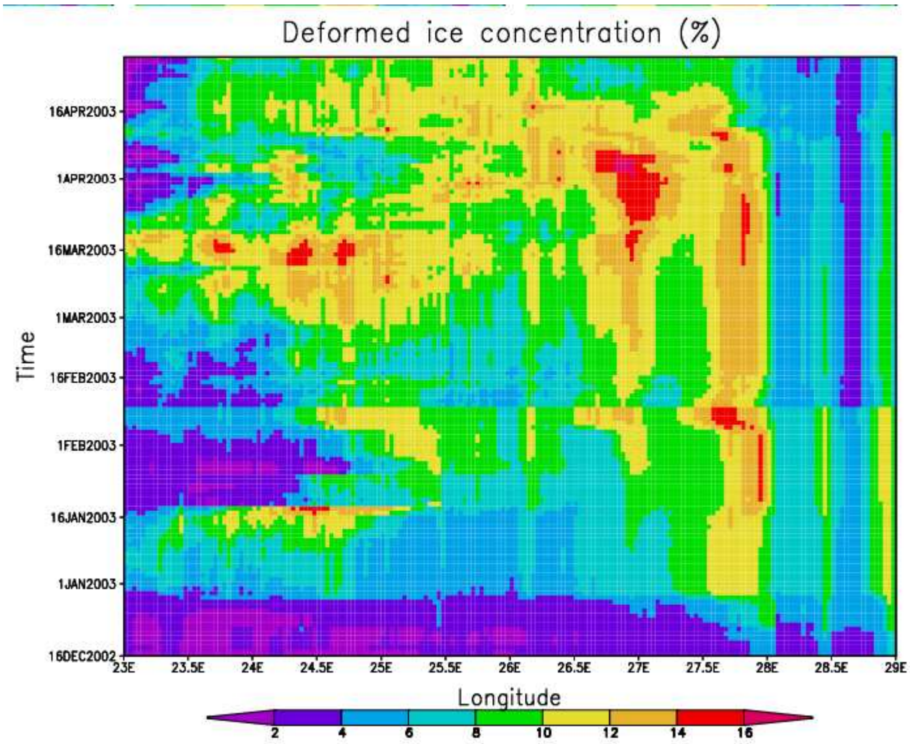

Fig. 4. Latitude integrated deformed ice concentration.

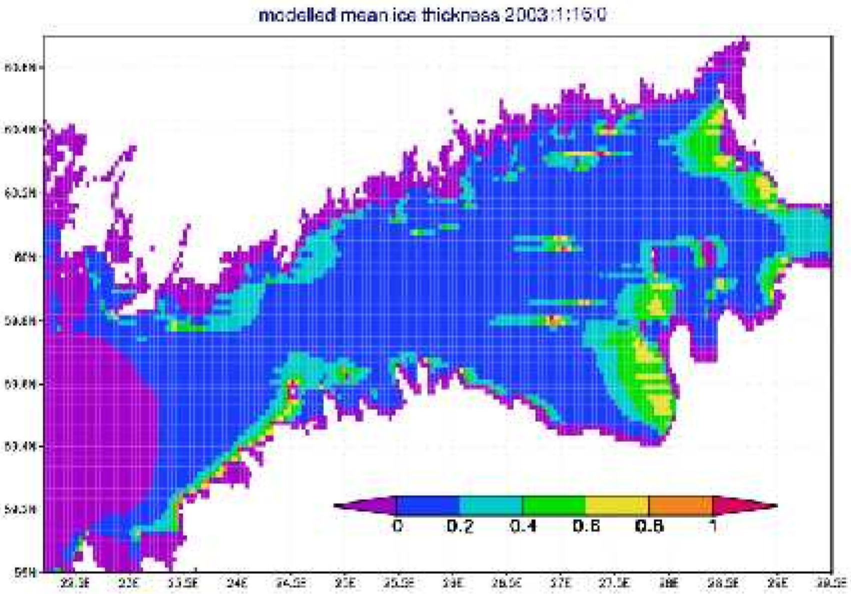

Fig. 5. Modelled total ice thickness on 16 January 2003.

In the framework of HELMI model we explore natural conditions for deforming. The wind speed and direction mainly determine the ice deformation rate.

A relationship between the wind direction and deformed ice growth rate were found. The most intensive ridging events occur during wind blowing from N, SE or NW (Fig. 6.). But is the modest correlation between the magnitude of wind speed and deformation. Then the deformed ice growth rate did not strongly depend on wind magnitude of speed. For example, wind speed over 4 m/s could cause large deformation events and sometimes deformation is very low during strong wind speed (7-9 m/s) and hence the wind direction is more important than the wind speed for the ice deformation during winter 2002/03.

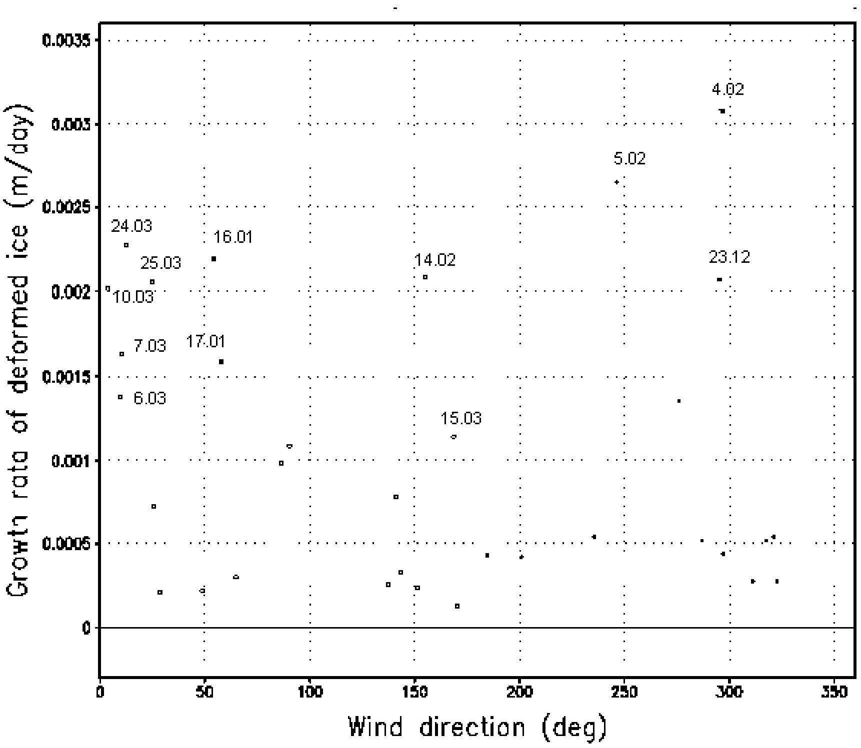

Fig. 6. Deformed ice growth rate and wind direction. The numbers on the plot are date.

Conclusions

The correlations were found between the wind direction, wind speed and deformed ice growth rate. The strongest wind blow from SW and NNE in winter 2003. The most intensive ridging events occurs during wind blowing from SW, SE and NW. The growth rate of deformed ice was not strongly dependent on wind speed. The mean total concentration of deformed ice was up to 12% from the area of Gulf of Finland. The modelled largest fraction of the deformed ice was located at 26.5-28 E. Comparatively less deformed ice was produced at 25.5-26.5E.

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Ice Winter Severity in the Western Baltic Sea in the Period 1301-1500

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Abstract

Variations in ice winter severity in the Western Baltic in the period 1301-1500 were analysed analogous to an investigation of data series covering the period 1501-1700. The poor reliability of reconstructed ice winter severity, especially in the period from 1301 to 1400, does not allow us a treatment of data in the usual way. A linear relationship between the number of anomalous ice winters per decade and the ice winter severity index, found by Koslowski, was used to calculate the value of the mean ice winter index for the above period.

Introduction

Variations in the ice winter severity in the Western Baltic (Figure 1) were analysed and described by Koslowski (1989) for the period 1897-1987, and by Koslowski and Glaser (1995, 1999) for the periods 1701-1896 and 1501-1700, supplemented by the years from 1988 to 1995.

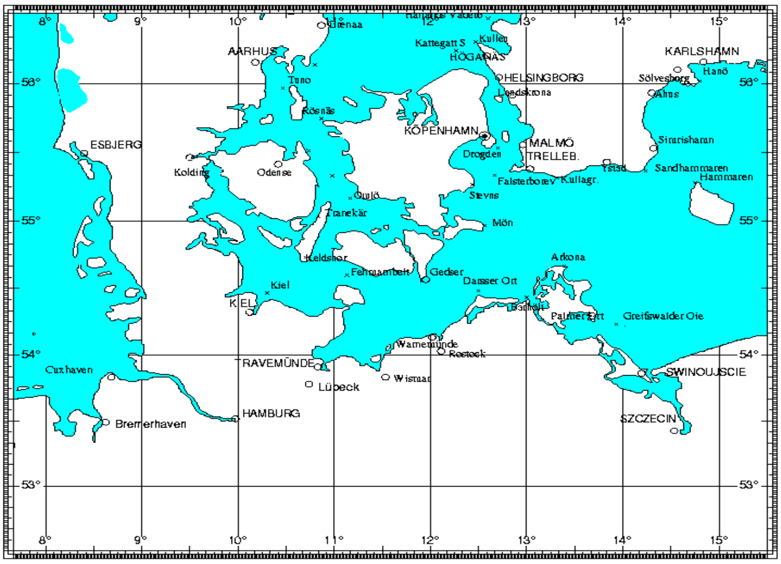

Fig. 1. Map of the Western Baltic showing area under discussion

Source material

1: The reconstruction of ice winter severity in the Western Baltic for the period 1879-2005 is based on the accumulated areal ice volume along the German Baltic coast (Koslowski, 1989; Schmelzer, 1994).

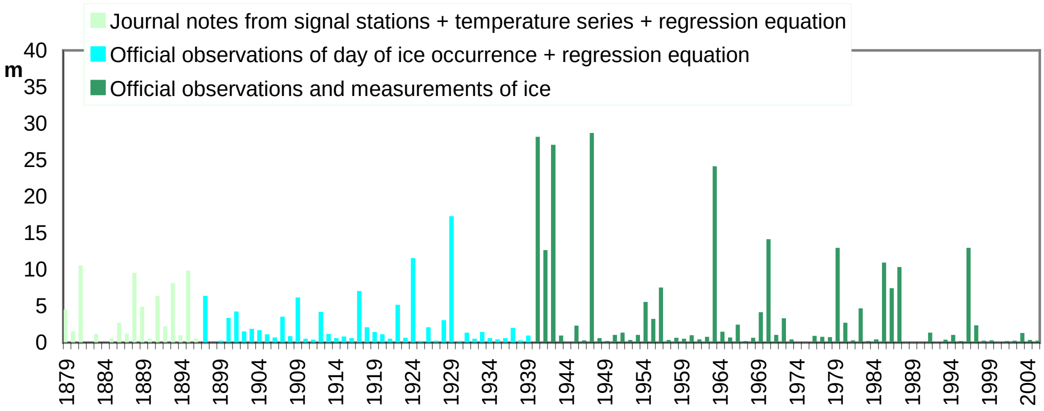

Fig. 2. Accumulated areal ice volume on the German Baltic coast in the period 1879-2005

2: The reconstruction of ice winter severity in the Western Baltic for the period 1701-1878 is based on the accumulated areal ice volume, subdivided into seven classes (ice winter severity types), (Koslowski and Glaser, 1995)

	V_{A} in m	Ice winter index numerals
Weak	< 0,50	0
Moderate$_-$	0,50-2,00	0.1
Moderate$_+$	2,01-4,00	0.3
Strong$_-$	4,01-6,00	0.5
Strong$_+$	6,01-9,00	1
Very strong	9,01-20,00	2
Extreme	> 20,00	3

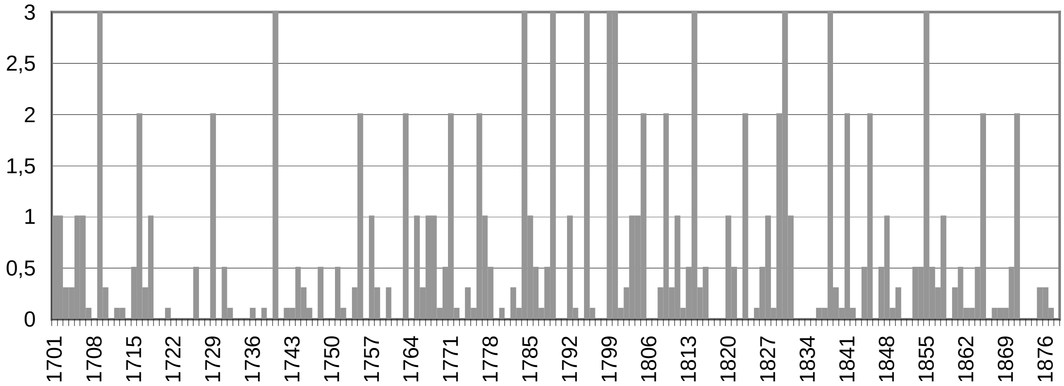

Fig. 3. Ice winter index numerals 1701 - 1878

3: The reconstruction of ice winter severity in the Western Baltic for the period 1501-1700 is based on seven ice winter severity types (Koslowski and Glaser, 1999)

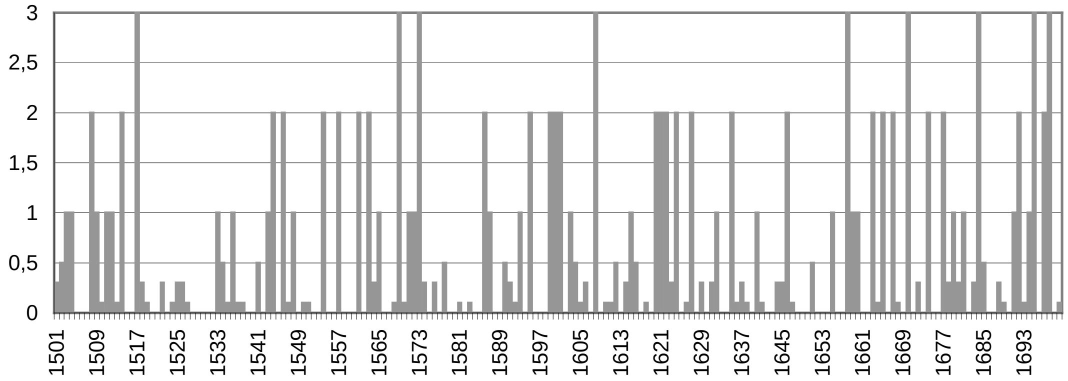

Fig. 4. Ice winter index numerals 1501 - 1700

In the meantime, ice winter severity in the Western Baltic has been reconstructed for the period 1301-1500 on the basis of seven ice winter severity types. The method used to reconstruct and analyse ice conditions during 1301-1500 is similar to that applied to the 1501-1700 period.

Reliability of reconstructed data

While the reconstruction of only a few winters is insecure in the 1501-1700 time series, the number of such winters in the period 1301-1500 is larger and, especially in the period 1301-1400, the number of winters with insufficient data availability is too large for an acceptable analysis by the usual method.

Table 1. Degrees of reliability of reconstructed ice winters

(*) Data from Koslowski and Glaser, 1999

Time	Reconstruction			
	Fully secured	Approximately secured	Weakly secured	Insecure
1501-1550 (*)	23	9	16	2
1551-1600 (*)	36	8	5	1
1601-1650 (*)	34	11	3	2
1651-1700 (*)	42	7	1	0
1301-1350	5	8		37
1351-1400	8	14		28
1401-1451	24	8		18
1451-1500	25	19		6

Nevertheless, most of the fully insecure cases in the period 1401-1500 are weak or moderate ice winters with an ice winter index of 0 or 0.1 and without any remarkable features, Figure 5. Therefore, the data series for the period 1401-1500 can be analysed by applying the Gaussian low-pass filter with a possible margin of error, Figure 6.

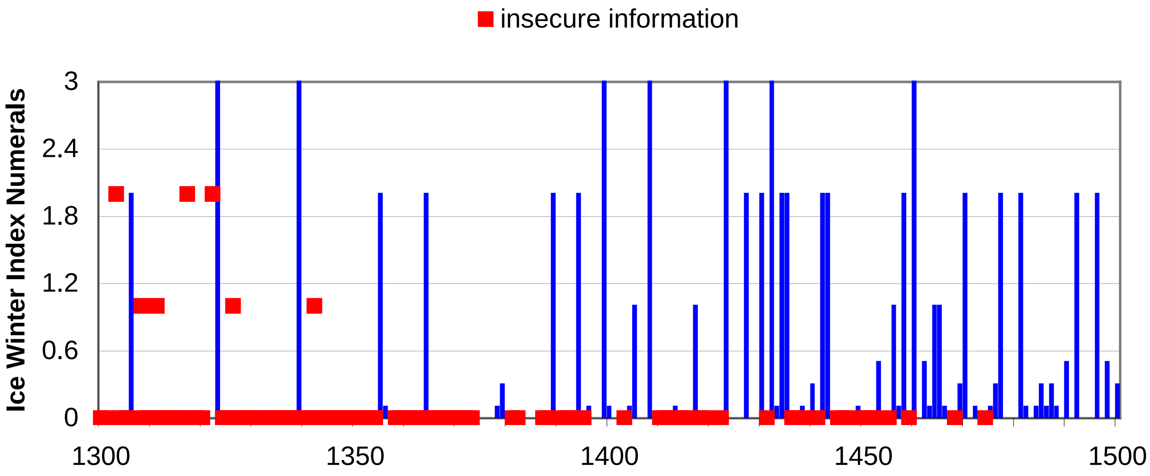

Fig. 5. Ice winter index numerals 1301-1500. Most uncertain cases in the period 1401 to 1500 are normal ice winters with an ice winter index of 0 and 0.1.

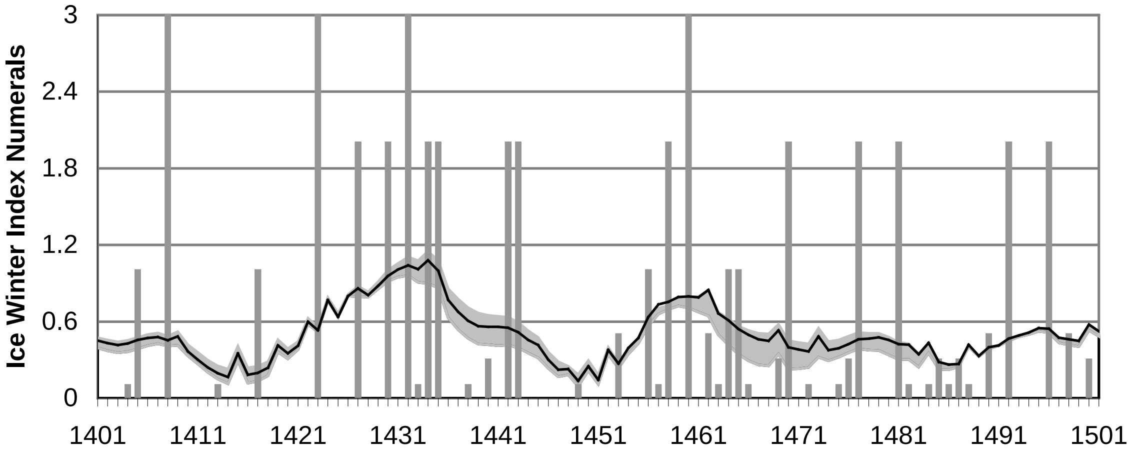

Fig. 6. Ice winter index numerals 1401-1500. The solid curves represent smoothed ice winter index numerals series obtained by applying a Gaussian low-pass filter with a 20- year cut-off period. The shaded areas denote the possible margin of error.

The ice winter index data series from 1401

Figure 7 demonstrates the long-term variations in the ice winter index numerals in the period 1401-1700. The thin and heavy solid curves represent smoothed ice winter index numerals series obtained by applying a Gaussian low-pass filter with a 20- and 40-year cut-off period, respectively. The horizontal solid line denotes the arithmetic mean of 0.529 for the period 1401-2005.

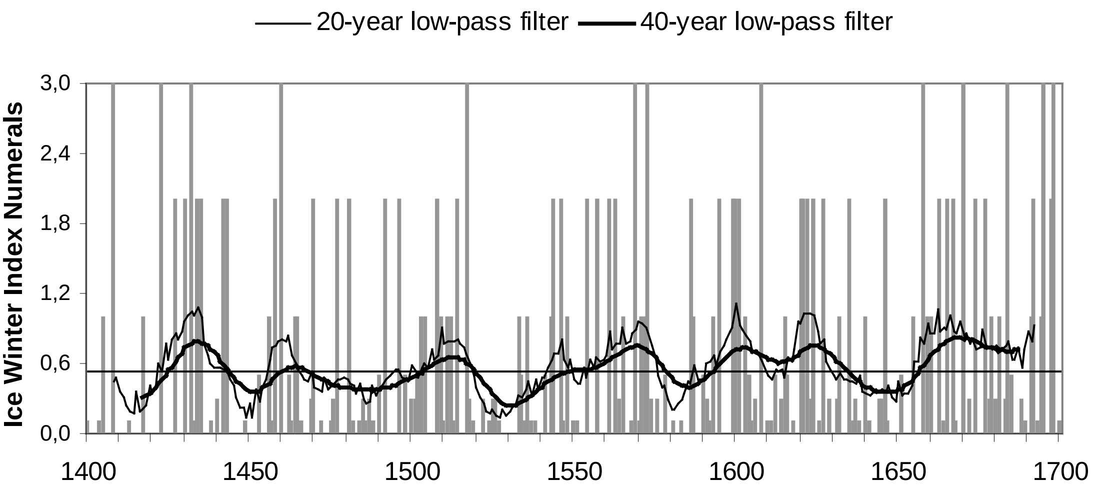

Fig. 7. Long-term variations in the ice winter index numerals in the period 1401-1700.

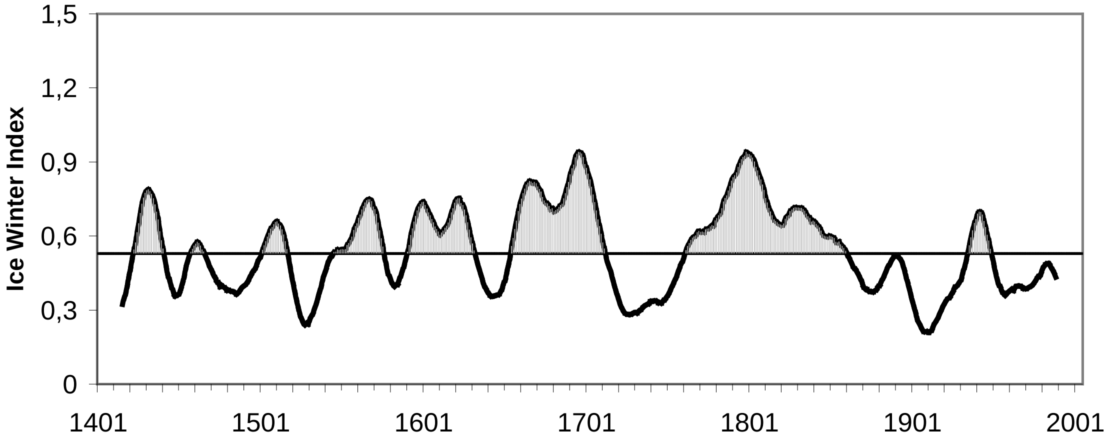

Fig. 8. Variations of the ice winter index since 1401.

The variations of the ice winter index for the total period 1401-2005 are shown in Figure 8. The solid curve represents the smoothed ice winter numerals obtained by applying a Gaussian low-pass filter with a 40-year cut-off period. The dark areas denote the period of increased ice winter severity with regard to the arithmetic mean of 0.529 for the period 1401-2005 (horizontal solid line). The standard deviation $\sigma = \pm 0.826$. This diagram can be compared with that for 1501-1995 period in Figure 3, by Koslowski and Glaser, 1999.

The periods with increased or reduced ice winter severity related to the arithmetic mean of 0.529 in the time from 1401-2005 have been compiled in Table 2. The results can be partly compared to the data in Table II shown by Koslowski and Glaser, 1999. The differences between the time periods in the two tables are attributable to the changed mean value for the total time period and to the inclusion of additional data for the period prior to 1520.

Table 2. Means and variances of the ice winter index numerals, ice winter severity related to the arithmetic mean of 0.529 for the time from 1401-2005, and number of normal and anomalous ice winters per decade in specific time intervals.

Period	Number of years	Ice winter index numerals		Ice winter severity related to mean ice winter index 1401-2005	Number of ice winters per decade	
		Means	Variances		Normal	Anomalous
1401-1424	24	0.342	0.749	Reduced	8.33	1.67
1425-1443	19	0.816	1.137	Increased	5.79	3.68
1444-1459	16	0.231	0.294	Reduced	8.12	1.25
1460-1468	9	0.633	0.958	Increased	5.56	3.33
1469-1503	35	0.426	0.471	Reduced	5.71	1.71
1504-1519	16	0.725	0.847	Increased	5.00	4.37
1520-1547	28	0.339	0.319	Reduced	6.43	1.79
1548-1578	31	0.639	0.864	Increased	5.48	3.23
1579-1592	14	0.293	0.321	Reduced	7.14	1.43
1593-1634	42	0.679	0.754	Increased	4.76	3.33
1635-1656	22	0.355	0.371	Reduced	6.36	1.82
Total period						
1401-2005	605	0.529	0.683		5.80	2.45

The severity of ice winters in the period 1301-1400. Anomalous ice winters.

Because of the large number of insecure reconstructed cases in the period 1301-1400, the severity of ice winters has been derived from the number of anomalous winters. Koslowski and Glaser (1999) defined anomalous ice winters as follows:

"The severity types weak and moderate$_-$ (index 0 and 0.1) with a frequency of 70% in the period 1501-1995, which lead only to ice formation in the inner coastal waters, are the norm. Strong$_+$, very strong and extreme severity types (index ≥1 with a frequency of 25.2 %), causing total ice cover in the Western Baltic with an ice thickness greater than 20 cm, can be regarded as anomalous".

In Figure 9, the occurrence of anomalous ice winters (anomalous ice winter = 1, normal ice winter = 0) is shown for the period 1301-2005. The thin and heavy solid curves are smoothed frequency curves obtained by applying a Gaussian low-pass filter with 20- and 40-year cut-off periods, respectively. The horizontal solid line denotes the arithmetic mean of 0.228 for the period 1301-2005. The areas above the mean line indicate phases with an increased number of anomalous ice winters (increased ice winter severity) and are comparable to those obtained for the period 1401-2005 as shown in Figure 8.

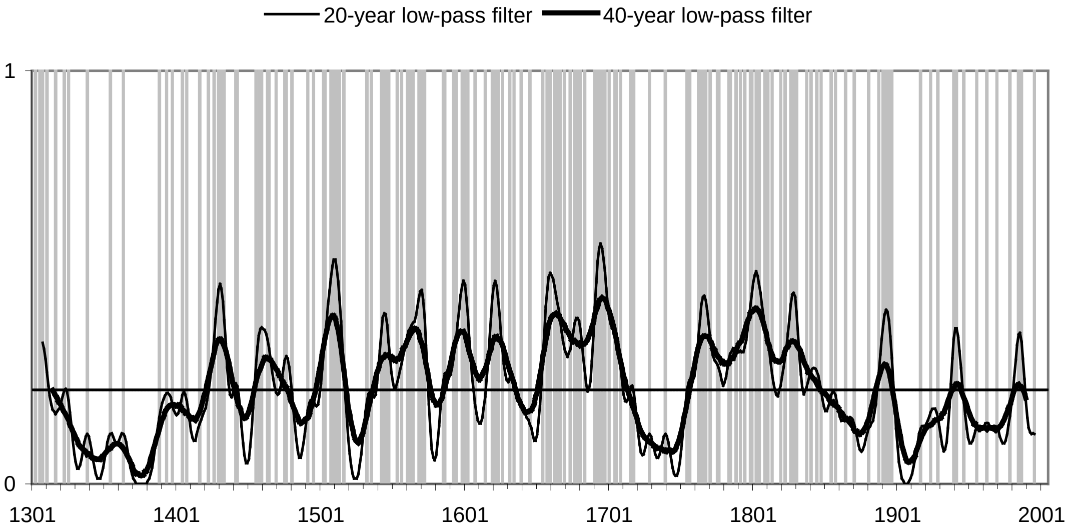

Fig. 9. Frequency of occurrence of normal (0) and anomalous (1) ice winters in the period 1301-2005

In the publication of Koslowski and Glaser (1999), the best relationship between the number of anomalous ice winters and the ice winter severity index was found for 19-year periods in the time from 1501-1994 and is linear, see Figure 10.

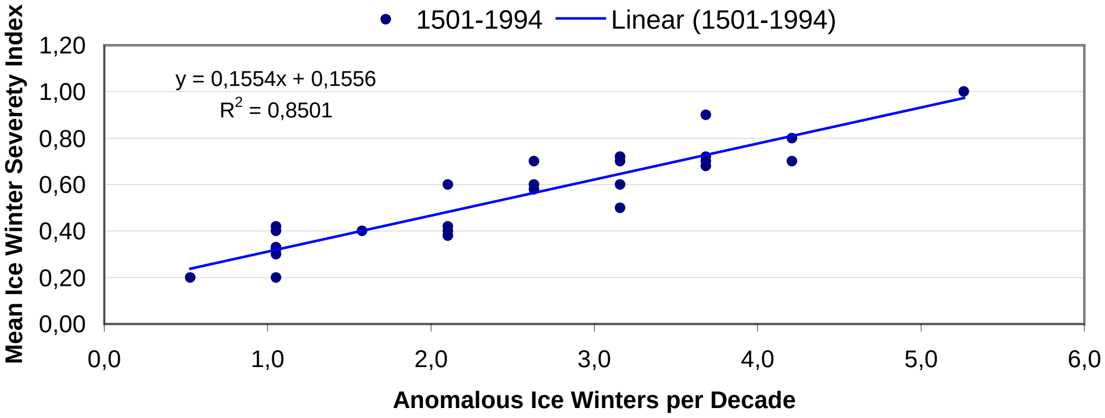

Fig. 10. Regression line for the mean ice winter severity index and number of anomalous ice winters per decade calculated for time intervals of 19 years for the period 1501-1994 (26 cases) Five cases in the period 1401-1500 are in very good agreement with the linear dependence in the period 1501-1994, Figure 11.

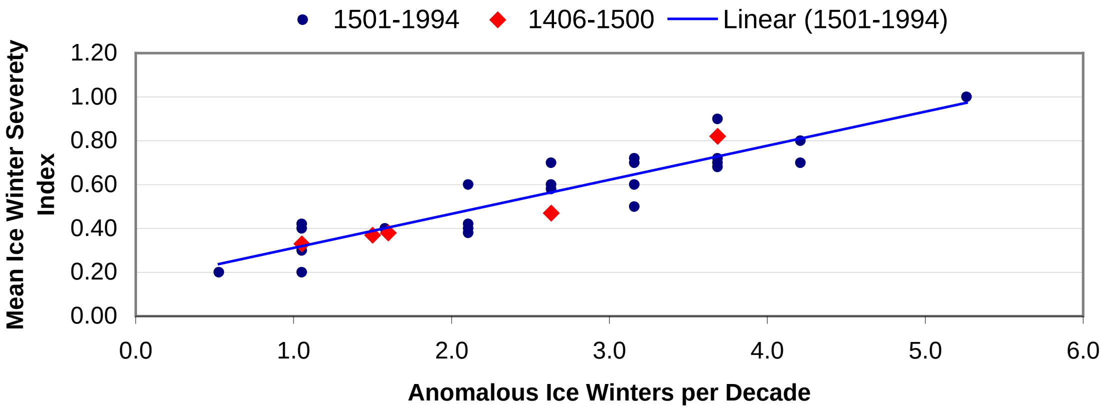

Fig. 11. Regression line for the mean ice winter severity index and number of anomalous ice winters per decade calculated for time intervals of 19 years for the period 1501-1994 (26 cases) and 5 other cases from the period 1406-1500.

The mean ice winter severity index for the 19-year time interval in the period 1301-1400 can be derived from the linear relationship found above. The results are shown in Table 3.

Table 3. Number of anomalous ice winters and calculated mean ice winter severity index for 19-year time intervals in the period 1301-1400.

Time interval of 19 years	Number of anomalous ice winters	Number of anomalous ice winters pro decade (x)	Mean ice winter severity index (y) : $y = 0.1554x + 0.1556$
1311-1329	4	2.11	0.48
1330-1348	1	0.53	0.24
1349-1367	2	1.05	0.32
1368-1386	0	0.00	0.15
1387-1405	4	2.11	0.48

Finally, in Figure 12, the variation of the mean ice winter severity index is shown during the period 1311-1994. The horizontal solid line represents the arithmetic mean of 0.529 for the period 1401-2005. The areas above this line denote phases with an increased ice winter severity and are comparable to those obtained for the period 1401-2005 as shown in Figure 8.

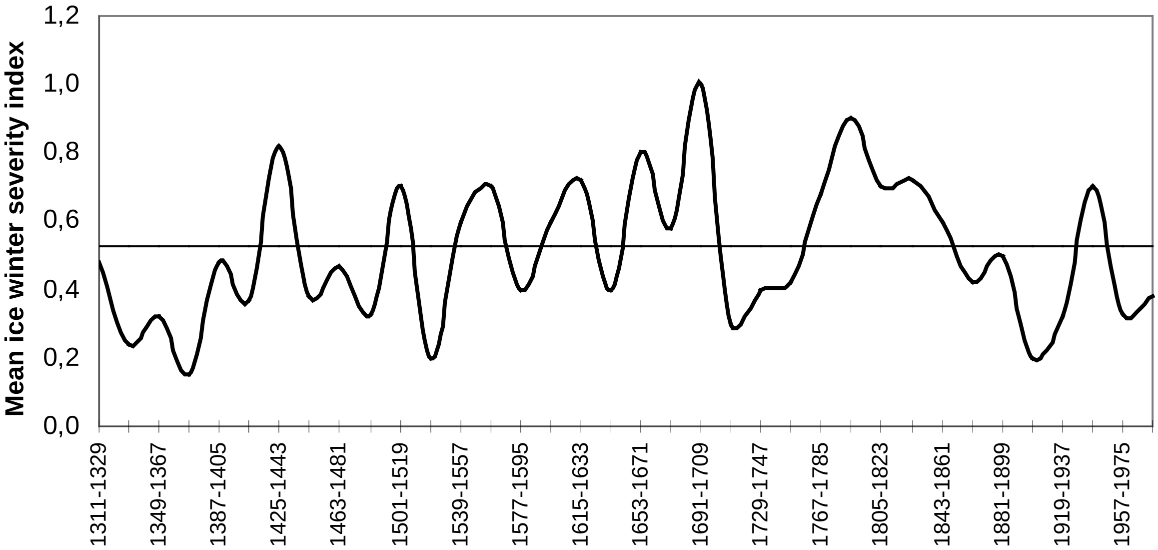

Fig. 12. Variations of mean ice winter severity index during the period 1311-1994 calculated from the number of anomalous ice winters per decade for time intervals of 19 years.

Conclusions

Ice winter severity in the Western Baltic has been reconstructed for the period 1301-1500 using the ice winter index numerals

The quality of reconstructed data for the period 1301-1500 is rather poor, especially in the first half of this period. However, the data series from 1401 to 1500 can be analysed with an acceptable error similar to the 1501-2005 time series

Compared to the 1401-2005 mean, the Gaussian low-pass filtered time series of the ice winter index numerals with a 40-year cut-off period shows a higher severity in 1423-1442, 1457-1468, and 1499-1517, while periods of lower severity occurred in 1401-1422, 1443-1456, and 1469-1498

The probability of occurrence of anomalous ice winters was investigated for the time period 1301-1400. A linear relationship between the number of anomalous ice winters per decade and the ice winter severity index, found by Koslowski (1999), was used to calculate the value of the mean ice winter index for this time period.

The level of ice winter severity between 1301 and 1400 is continuously below that of the reference period 1401-2005 and even slightly lower than that of the 20th century.

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Acknowledgement

Herewith we would like to express our sincere thanks to Mrs. Lange for the translation into English.

Notice

After publication of this article, the time series of the ice winter index in the period 1301-1500 will be available on the BSH’s website at
http://www.bsh.de/de/Meeresdaten/Beobachtungen/Eis/index.jsp

Sea Ice Conditions in Gulf of Gdansk in 15 century

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Abstract

The aim of the work was the reconstruction of the sea ice conditions in the Gulf of Gdańsk in 15 century. Regular observations of sea-ice in this region reach as far back as the beginnings of 20 century. For the time previous to 20 century reliable information can be also derived from written sources and by the comparison with information of sea-ice conditions in the Danish Straits.

Introduction

The sea ice conditions of the Baltic Sea are extremely sensitive to changes of climate (Sztobryn et al. 1997, Sztobryn, Krzymiński 1999). Knowledge of sea ice conditions' variations in the scale longer than 100 years would enable to find out what changes of climate occurred in the past, in what manner they affected the coast infrastructure and also what we may expect in the future. The knowledge can be applied for calibration/verification of global and regional climate models. The Gulf of Gdańsk, especially the Port of Gdańsk (so-called Aurea Porta of the Both Nations' Republic), has always been and still remains one of the most important water areas of Poland. The eventful history of this water area resulted in relatively great number of annals, in which one may find as well some notices on ice conditions, which can contribute to presentation of the changes' analysis, worked out basing on the chronicler's materials referring to Baltic freezing situations as well as to political changes, which took place therein.

Thus, the basis for the study was materials and extracts made of various Polish, Ukrainian, Russian and Lithuanian chronicles. Through the extracts made by different authors, also the Danish and Swedish chronicles' information became available. Owing to the above mentioned reporting, through comparison of ice conditions in 20 century (availability of daily observations), verification of a part of the notices became possible.

Source materials

To analyse the ice conditions in 20 century there have been used the observational data, from national services, mainly from the Danish, Polish and German. For evaluation of sea ice conditions which occurred in 15 century, the extracts of chronicles were applied. In general, the following works were examined: Walawender *in Polish, Latin and former Ukrainian;* Betin *in Russian;* Girguś *in Polish and in Latin.* Descriptions of winters and sea ice conditions included in these works are full of literary beauty, however to enable determination of winter severity in a numerical form (1- mild/extremely mild winter, 2 - moderate winter, 3- severe/extremely severe winter) it is necessary to take into account, among the others, the author's nationality (i.e. for example such a winter which in Lithuania seems to be normal for any Lithuanian, according to anybody from South of Europe, who is visiting this country for the first time, may appear extremely sever winter.)

Apart from the above, the contemporary works concerning maritime law and history of Gdansk have been employed. The mentioned publications include, among the others, information on legal regulations of Hanza Union forbidding (according to Lübeck regulations) sea navigation in winter season from 11 of November till 2/22 of February. However, this limitation was threatening for interests of Baltic's members of Hanza, which at least 3 times in 16 century tried to change the regulation. Finally, neither entry confirming nor annulling the above Lübeck regulation was found in Gdansk journals of law. But it means that for example the information about entering the port by the first ship in February is not synonymous with a date of last ice melting, whereas entering the port in May can be identified with such a date. Another factor, which should be taken into consideration in analyzing dates of the first and the last ice occurrence, is converting from Julian to Gregorian calendar by some countries.

Sea ice conditions on the Gulf of Gdańsk in 20 Century

Sea ice conditions on the Gulf of Gdańsk were analysed (Stanisławczyk, Sztobryn 2004) on the basis of observations carried out in Gdańsk area. Observations period started in winter 1922/1923 and the records contain complete material, including data up to 2000 and further, except winter 1945/46. Probability of ice formation on this water area is 48%. In 1922-2000 time there occurred 39 winters with no ice (lacking of data of winter 1945/46).

At the Gulf of Gdańsk ice formation at the earliest occurs in the north –west part of the Puck Bay and above the coastal shoals nearby Jastarnia, then in the coastal zone near Gdynia and Gdańsk, at the latest the first ice shows up close to the Town of Hel. The most often there appear new ice or floe.

In Table 1 there are presented parameters of ice formation for the analysed (for winters with ice) on the Gdańsk fairway. The first ice in this water area appears on 26 January on the average, and melts on 28 of February. On the average there occurs about 10 days with ice within one ice season, whereas duration of ice season is 16 days.

Table 1. The mean and extreme data referring to freezing (for winters with ice) at the Gulf of Gdańsk (Gdańsk water area) within a period 1922-2000

First sea ice			Last sea ice		
the earliest	on the average	the latest	the earliest	on the average	the latest
28.12	**26.01**	8.03	31.12	**28.02**	10.04
Number of days with ice			Duration of ice season (days)		
min	on the average	max	min	on the average	max
1	**10**	76	1	**16**	86

At the Gdańsk fairway, ice appeared on 28 December 1961 at the earliest, whereas at the latest the first ice was observed on 8 of March in winter 1970/71. Ice melting at the earliest occurred on 31 December in winter 1923/24, also in 1966/67 and 1996/97 seasons. In this water area, at the latest ice was melted on 10 April in winter 1955/56.

The maximal number of days with ice was 76 and occurred in very severe winter 1962/63. Also a high number of days with ice was observed in winter 1941/42 (73 days), it means of the same severity. On the contrary, the longest lasting ice season was reported in winter 1961/62, when ice appeared already 28 December and melted 23 of March. In connection with a possibility of multiple sea ice forming and melting in one winter season, for a majority of ice seasons a number of days with ice is lower or equal to the duration of ice season.

Comparison of Sea Ice Conditions on the Gulf of Gdańsk with Danish Straits

Regular daily observations of sea ice conditions (according to the codes jk, ijk, astk) of the Baltic Sea were begun either in 19 century or in the early part of 20 century, therefore the available comparative material is very broad. There has been carried out a comparison of numbers of days with ice for 3 main fairways of the Gulf of Gdańsk (Gdańsk, Hel and Gdynia) and a cold sum for all Danish water areas and the days with sea ice on open water as well as in the ports located in open water areas (Fig.1).

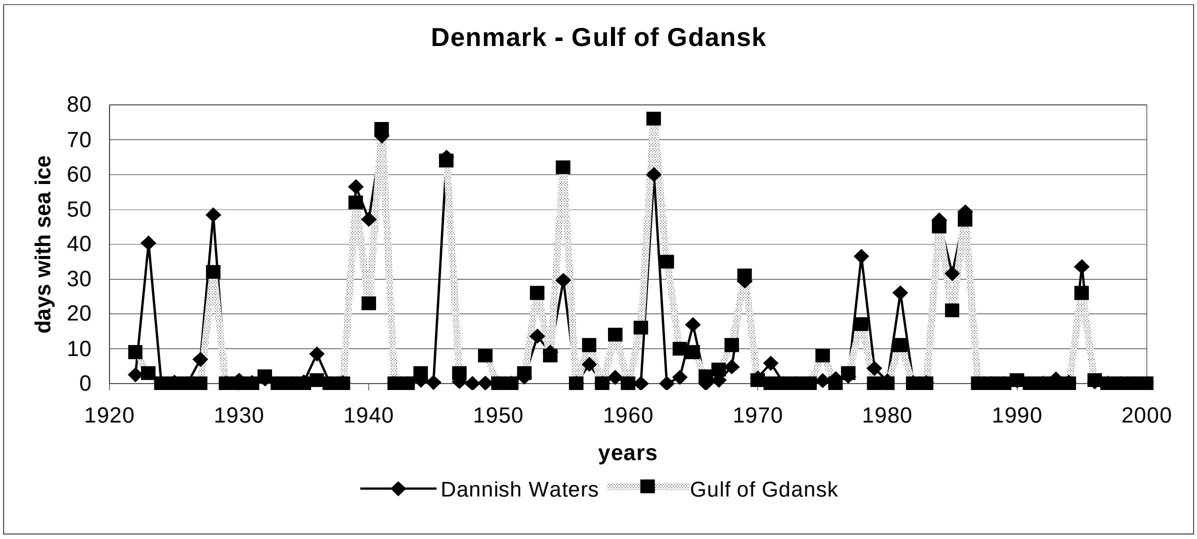

Fig.1. Comparison of days with sea-ice on the Gulf of Gdansk and on the open waters of Danish Straits in 20 century.

The high correlation coefficient (0.87-0.88) was calculated for the days with sea ice on fairways on Gulf of Gdańsk and open waters in Danish Straits. It shows that in the majority of winters a method of correlation could be applied for reconstruction of sea ice conditions in Gulf of Gdansk.

Sea ice conditions in Gulf of Gdańsk in 15 century

In 15 century the Baltic Sea was a very important trade route, dominated mainly by Hanza owing to assuring itself and the Union towns a favourable position. In Fig. 2 there are presented the main trade routes on the Baltic on the end of 15 and in 16 century. One of the longest one is Lübeck - Novgorod (till it was conquered by Russia), moreover the routes: southern – leading to The Polish – Lithuanian Federation (so-called Republic of the Both Nations) and the northern, leading to Sweden and Finnish towns. One may expect that a majority of accessible information concerning obstructions to navigation shall be referred to the above mentioned navigation routes.

Majority of the cities in Poland, including Krakow, belonged to Hanza. For this reason, Gulf of Gdansk with estuary of biggest Polish river: Wisla - was important navigation area in the Baltic Sea.

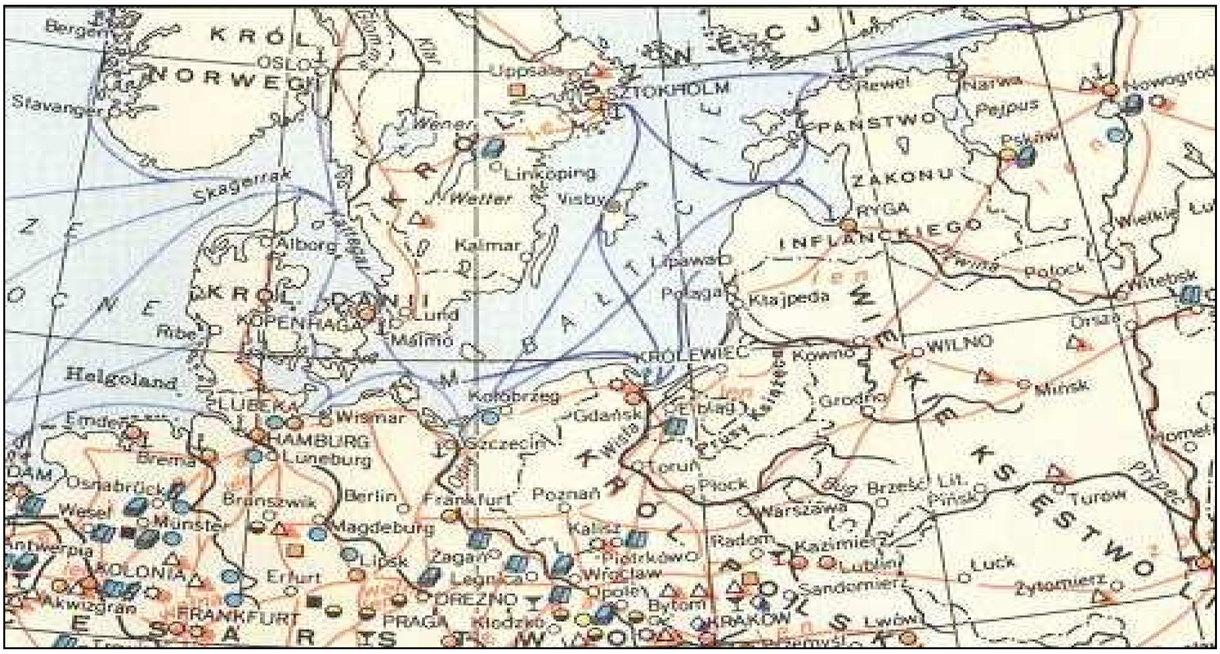

Fig. 2. Navigation on the Baltic Sea in 15 and 16 centuries (Atlas Historyczny)

Sea ice conditions in Gulf of Gdańsk and severity of winters is presented in a form of table extracts from historical sources (for example Table 2). The following division into 3 parts has been performed: the first contains information concerning freezing the Gulf of Gdańsk and additionally on severity of winters in Poland; in the second one there are presented extracts from sources referring to freezing the Danish Straits, the Baltic Sea and the European countries and in the third one there is included the calendar of history of Hanza. It was a meaning source of knowledge as well nevertheless of indirect character.

Sea ice conditions reconstruction was to present them in numerical form, applying 3 degree scale (1 - very mild; 3 - severe and very severe; 2 - others). In case of sea ice conditions in the Gulf, the determination of very mild and very severe winter could be done with very high probability. It was very difficult to separate mild winters (lacking of 1-3 days with sea ice on the main fairways) or normal (ice cover in shallow bays and lagoons). The results of studies are presented in Fig.3.

Table 2. Some extracts from historical sources

Winter	Gulf of Gdańsk, Southern Baltic, Poland	Baltic Sea and Europe	Hanza
1407		Denmark : severe winter (11.11-27.01 and from Mid. Of Feb. to first week of Apr) Passage on ice cover : 1.Gothland-Oland 2.Norway-Jutland-Denmark 3.Rostock-Gedser 4.Skagerrak - frozen + wolfs European rivers : Danube River ice bound along its whole Saara and Maas rivers entirely frozen	
1422	Wisla ice covered (4.12-12.03) Passage on ice cover : Gdańsk - Lübeck Gdańsk-Denmark	Baltic Sea : severe winter from 19.Nov.- till March Ice cover on the Baltic Sea after 12 Jan. Passage on ice cover : .Meklemburgy-Denmark .Pomerania-Denmark North Sea : Ice covered on large areas Twer, Sofia, Russia : 3 months of severe winter	
1431	25.11-23.04 Lower Wisla ice covered	Passage on ice cover : Sweden -Zeeland Germany : severe winter	War between Hanze and Denmark
1434		Belgium -2 feet thick ice cover on the rivers; Rhine ice bound	• War between Hanze and Denmark • Resolution of the rule, that only the townspeople born in any League member -town may enjoy the Hanseatic merchants' privileges passed
1454	Severe winter, army dismissal after 14.01 Gulf of Gdańsk – ice cover (2.02-21.03); Passage on ice cover : Gdańsk-Hel from 2.02 till 21.03		• Economic blockade of Flanders by Hanze was on • War between Poland (supported by Hanzeatic towns) and the Teutonic Knights occurred.
1459	Silesia – frost and ice till 21.03 Passage on ice cover : Gdańsk-Hel; ice extent – more than 80 km from Hel	Passage on ice cover : (some places from the end of Dec 6.02-17.03, whole Baltic from 14 Feb till 7 Mar.) Lubela,Wismar,Rostock, Stralsund - Denmark till 17 March Livonia- Revel, Denmark, Inflants - Sweden Denmark - Sweden Lubeck – Norway public road and military track on sea, military and goods carriages travelled on ice cover , 12- 16.03. Danube River was frozen for 2 months	War between Poland and the Teutonic Knights

1466	very warm winter, with no snow	Russia: 14.01 – hard frost, many people died 5.05 - snow,2.06 - frost	• War between Poland and the Teutonic Knights.The Peace Treaty was concluded in Torun • Gdańsk was reversed to the Kingdom of Poland • Conflict with France
1469	Silesia, Odra frozen down in full depth at many places from 30.11to 14.04	Germany : severe winter, Boden Zee got frozen (2.12-23.04)	Conflict with France
1470	Very severe (19.11-21.12) , Odra ice covered; 25-26.12: warming, all snow and ice melted	Russia: severe winter, the end of April and beginning of May – 9 days of frost (young oaks and ashes extinct)	• Conflict with France • War of Hanze against England
1471	Silesia: Easter – no winter; 12.02-28.03 – summer weather	Prussia: 24.02 - storms, 27.02 – return of storks and swallows	• War of Hanze against England • Cologne was excluded out of Hanze in a result of its trading with hostile England
1472	Silesia : 24.02 violets blooming, 14-21.03 – nearly all trees blooming	Germany : mild winter	War of Hanze against England
1488	Odra - Głogów, from 11.11to 7.12 ice cover; destroyed bridges; horses and carts travelled on ice cover	Baltic : 7 Dec – temperature changed, storm Ukraine : severe winter, heavy snow	
1492	Jan and Feb. : very warm winter; orchards'blooming, high grass, birds built nests March : frost killed everything; took 2 weeks;	Italy - Genoa; ice on sea 25-26 Dec	
1495	Passage on ice cover: Gdańsk – Hel after 2 Feb Hel - Wisla by 4 horses (6 March), sledge fully loaded with cod. 1of May: the first ships arrived to Gdańsk; float ice on open sea	Ice on the Baltic Sea till May Passage on ice cover: Pomerania–Denmark Pomerania– Gesso Pomerania pl - Mön	

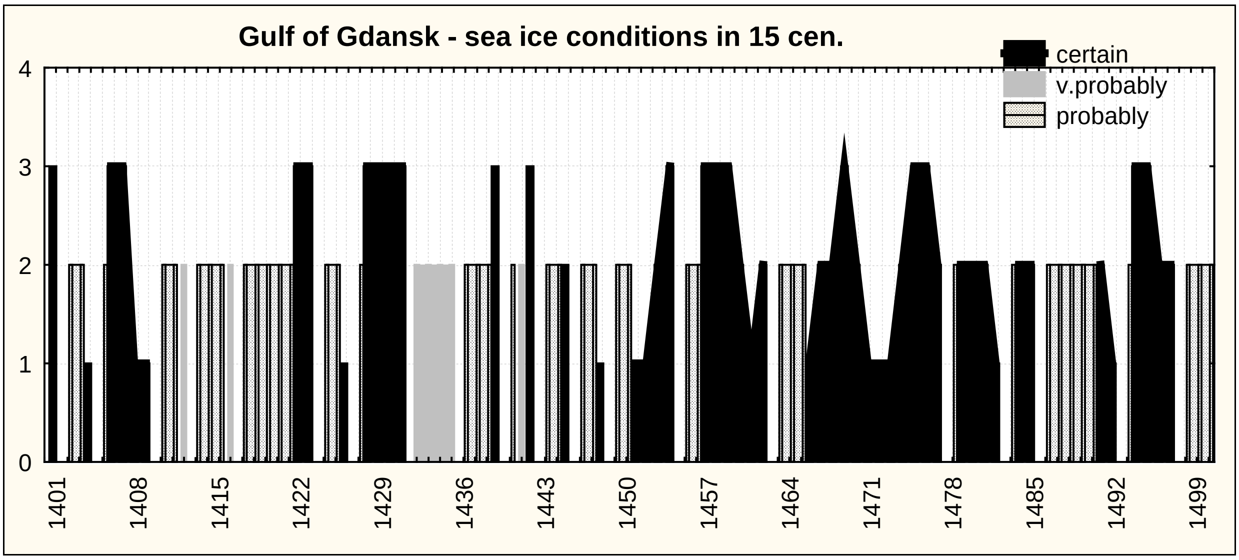

Fig. 3. Reconstruction of sea ice conditions in Gulf of Gdansk in 15 century

The dark bars indicate severe, very severe winters and also very mild, which could be determined as certain. The grey bars present the winters' severity classified as very probable. On contrary the winters, for which probability of determination of the severity rate was lower (however it oscillated between 1 and 2) are presented with dotted bars. 51 winters were classified as certain: 14 were the very mild, 20 severe and very severe and 17 as others (mild and moderate). Only 7 winters were classified with high probability as mild and moderate Sea-ice cover appeared on Gulf on Gdansk in first, and third decade. The highest number of severe and very severe winters occurred in fifties and from middle sixties till seventies of the 15 century. The second decade was without severe winters. The number of very mild winters were higher in the first half of investigated century.

Final comments

The study is a fragment of the publication just in the course of preparing, referring to sea ice conditions of the Gulf of Gdańsk and severity of winters within a period of 14 up to 18 century. The paper shall contain, among the others, extracts from historical sources and summary of their contents in a table form as well as the results concerning studies on severity of winters.

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Some Ideas on Sea Ice Climate and Navigation in the Baltic Sea

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Abstract

Sea ice has a great influence on navigation acting as an obstacle for the vessels in winter navigation or even preventing not suitable vessels from entering ice covered sea areas. Otherwise, mainly in the Baltic Sea with the over the last decades ever increasing sea traffic, there is also an essential influence of the icebreakers and assisted vessels on the character of the ice cover. Both aspects, the development of winter navigation in the Baltic Sea and the influence of navigation on the ice cover, are highlighted in this paper.

One of the major objectives of the Baltic Sea Ice Climate Workshops is the discussion of the different methods and parameters to be used for the classification of the ice winters in the Baltic Sea - either for the whole region, for sub-regions or single coastal and sea areas. In this paper the idea is discussed, to blend the parameter **Maximum Ice Extent**, presented since many years by the Finnish colleagues, with the length and the ice extent of the **Ice Phases**, also originating from Finland. The ice phases, characterising special stages of ice development mainly in the northern region of the Baltic Sea, depend mostly on natural conditions of the coastal and sea areas, and may describe the character of an ice winter in a better way than just the sometimes rather short maximum phase of the ice extent. In addition, also the possibility of making use of the restrictions to navigation to classify the severity of an ice winter is discussed. As some of the data still are under negotiation, this paper has to be considered as a *working paper* , see note on page 73.

Introduction

Most typical for the seasonal sea ice conditions in the Baltic Sea is the great variability in ice extent, thickness and concentration. Each ice season is different from the other, which is stressed e. g. by the wide range of maximum ice extent, which varies between about 51,000 km² (=12 % of the total area) and a total ice cover of the whole area of 420,000 km². And also the length of the ice winter varies considerably. It can start in late October and end in early June, but can last only from mid-December to the first decade of May. This was found in former times as well as in recent days, and it is documented e. g. by the relevant time series provided by the Finnish Institute of Marine Research - FIMR (Seinä and Palosuo, 1993).

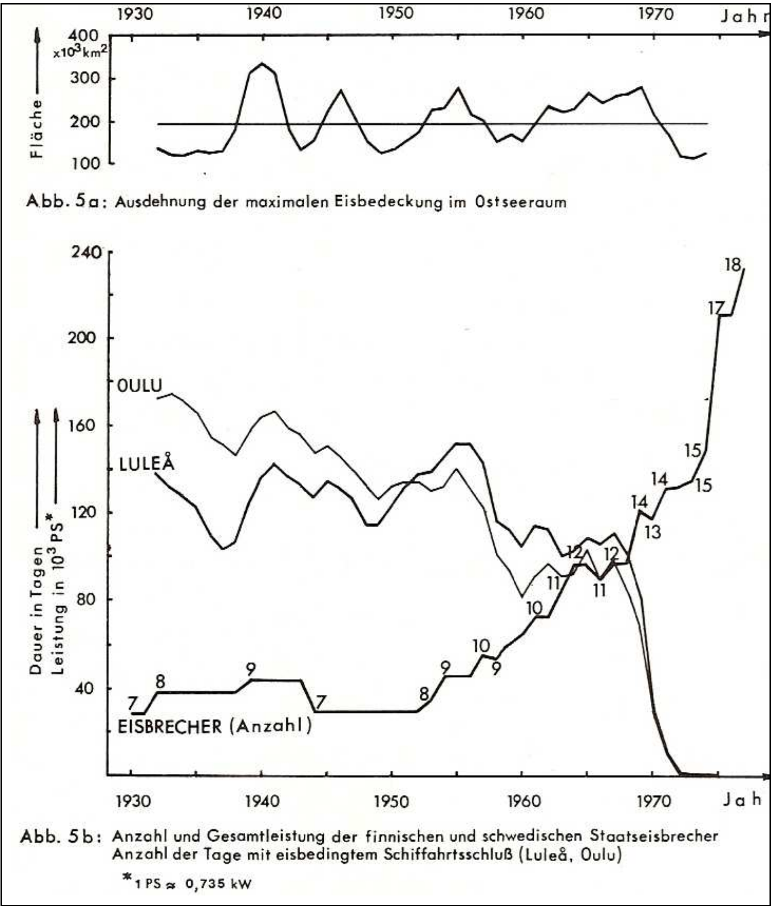
Winter Shipping

Sea ice in the Baltic Sea is not just a natural or climatologically phenomenon. However, in an intra-continental environment, which is since many centuries a focus of human development and cultural interconnections resulting in ever increasing trade and traffic, the sea ice cover of the Baltic Sea was always a very important and restrictive parameter for the navigation. The main facts are summarized in Table 1.

Table 1. Development of winter navigation in the Baltic Sea

- At times of sailing vessels no ice navigation: the length of ice season was nearly equal to the period of closed navigation.
- No essential changes in the early days of iron and steam vessels.
- At the end of the 19th century construction of first icebreakers.
- In the beginning of 20th century increasing navigation under light ice conditions, however, under more difficult conditions only ‘running fights’ to prevent ships to be beset and wintering in the ice area.
- Between the World Wars I and II extending navigation periods in the southern areas including the Gulf of Finland up to permanent winter navigation – beside in the more severe winters.
- Above was extended by increasing icebreaker fleets (due to economic pressure), improved vessels (ice strengthening), and adequate regulations for winter navigation
    - in the fifties and sixties to the Sea of Bothnia, and
    - in early the seventies to the northern Gulf of Bothnia.
- Since more than 30 years (restricted) navigation during the whole ice season.
- Today some ten thousand port calls per ice season.

These events are partly documented in Figure 1, which shows the strength of the joint Finnish and Swedish State icebreaker fleet (total number and horse powers) as well as the five years running means for the closing days of the harbours Luleå and Oulu in the northern Bay of Bothnia and the maximum ice extent of the Baltic Sea for the period 1930 to 1977. From the beginning of the thirties to the beginning of the fifties the joint icebreaker fleet consists of 7 to 9 icebreakers with up to 45,000 HP in total. The harbours Luleå and Oulu were closed between about 100 to 175 days depending on the severity of the ice winter with a slightly decreasing tendency. From the beginning of the fifties to the mid sixties the total number of the icebreakers were only increased by three up to 12, however, by replacing the older units by more powerful ones the total capacity was more than doubled to nearly 100,000 HP. By that the number of closing days for the mentioned harbours could be reduced to 80 to 110.



Source: Strübing, K., 1978, p. 13

Fig. 1. Maximum Ice Extent, days with ice-induced ceased navigation and number and power of the Finnish-Swedish State icebreaker fleet

The political decision – based on strong socio-economic requirements – to further increase and modernize the state icebreaker fleets in order to guarantee an unbroken navigation season for the whole ice winter, was performed from the late sixties to the season 1976/77, when new powerful icebreaker classes were introduced. The number of icebreakers was raised by 6 to 18, the total capacity was more than doubled to 231,000 HP (169,000 kW). The last winter with an interrupted navigation season for the main harbours in the northern Gulf of Bothnia was mostly 1969/70. This development was somewhat favoured by milder winters in the first half of the seventies.

The requirements for improving the icebreakers with respect to the modern development of the sea traffic (much more and bigger vessels) continued, and today the ‘old-fashioned’ ice-breakers are partly replaced by very powerful multi-purpose vessels (see Figure 2). In 2005 the icebreaking fleet available in Finland and Sweden consists of 19 units with in total about 325,000 HP (240,000 kW).

Ice Navigation

Navigation in ice covered areas does influence the character and behaviour of the ice cover itself. The intensity is of course depending on the number of the vessels and the frequency of passages. In polar regions with vast ice covered areas and only single ship movements the affect is negligible – as in former days in the Baltic Sea, too. However, today smaller sea areas as the Gulf of St. Lawrence and mainly the Baltic Sea with many thousand of port calls during each season, the navigation is affecting the ice cover considerably, even if the traffic is mostly restricted to special shipping lanes. However, these are fixed in position only in the coastal fast ice.

Photos 03/1999 by the author

Fig. 2. Swedish icebreaker YMER and Finnish multi-purpose vessel BOTNICA in ‘navigated ice’near lighthouse Norströmsgrund (Bay of Bothnia) and off Helsinki, respectively.

At sea due to often changing ice conditions and as ships come from different harbours and as the convoys are guided not always the shortest but if possible the easiest and perhaps faster way, after some time the ice cover is crossed (cut) in several directions as shown on the radar images in Figure 3. A variety of aspects of how navigation can work on the ice cover is listed in Table 2.

Courtesy: INTERA, Calgary
Aircraft SAR mosaic - Jan. 1985

Courtesy: FIMR, Helsinki
RadarSat-1 image of Jan 3, 2003

Fig. 3. ‚Navigated Ice’ in the northern Bay of Bothnia. The ship tracks are mainly documented by straight white lines.

Table 2. Results of ice navigation

- In former days the ice cover developed under natural conditions only. It staid 'virgin' and changed only due to the hydro-meteorological conditions or to stress factors like wind, current and waves.

- Nowadays powerful icebreakers and vessels navigate under nearly all ice conditions.

    - They cut navigation channels through the coastal fast ice up to the maximum possible thickness of about 120 cm.
    - Even heavy ridges are forced with the help of new propulsion systems like nozzles and azipodes.

- The ice is broken parallel and normal to the coast.

- The level ice cover is permanently broken, floes are transferred into ice cakes, ice cakes into brash ice.

- The ice at sea is crossed by a steadily increasing number of leads parallel to the main shipping lanes. Where today is a lead, there can be tomorrow an open fracture or a new ridge

- The approaches to the harbours or to the fast ice inlets (channels) develop to funnel-shaped brash ice fields with difficult navigation under converging (e. g. on-land wind) conditions.

- The traffic parallel to the coasts favours the development of open coastal leads or ridges, respectively, according to the prevailing wind conditions.

- Altogether winter navigation destroys the natural ice cover, decreases the floe size, favours the development of leads and ridges, and consequently makes the ice cover more dynamic – facts that have to be considered not only for the navigation conditions but for ice or climate models, too.

Ice Phases and other Natural Characteristics

Ice formation and development (increase and decay) of the ice cover in the different sea areas are mostly depending on the meteorological conditions (as temperature regime, prevailing wind directions and strength) during a given season. However, superimposed on this development are natural factors of the region as coastal morphology (type) and seabed configuration, water depth, heat content and salinity, currents and tides etc. For example, in German waters the ice winter type is defined by the length of the ice occurrence in the sections inner coastal water (a), outer coast (b) and open sea (c). These stages of ice development are normally correlated with special categories of ice thickness and ice concentration as shown in Table 3.

Table 3. Characteristical features of the Ice Winter Types in the German coastal and sea areas of the Baltic Sea (Number and percentage for the period 1961 to 2003)

Ice Winter Type number / %	**Area**	**Length of ice occurrence**	**Ice thickness** mostly	**Ice concentration** mostly
Very weak to weak 20 / 46 %	Inner coastal waters Outer coast	1 - 4 weeks up to 3 days	5 -10 cm up to 5 cm	6/10 - 8/10 1/10 - 3/10
Moderate 15 / 35 %	Inner coastal waters Outer coast	3 - 10 weeks up to 3 weeks	10 - 30 cm up to 10 cm	10/10 6/10 - 8/10
Strong 2 / 5 %	Inner coastal waters Outer coast, open sea	6 - 12 weeks 2 - 10 weeks	20 - 30 cm 15 - 25 cm	10/10 6/10 - 10/10
Very strong 5 / 12 %	Inner coastal waters Outer coast, open sea	2 - 3,5 months 1,5 - 3 months	30 - 50 cm 30 - 40 cm	10/10 9/10 - 10/10
Extreme strong 1 / 2 %	Inner coastal waters Outer coast, open sea	3 - 5 months 2 - 3,5 months	50-70 cm 50-70 cm	10/10 9/10 - 10/10

BSH, Ice Service - 09/2003

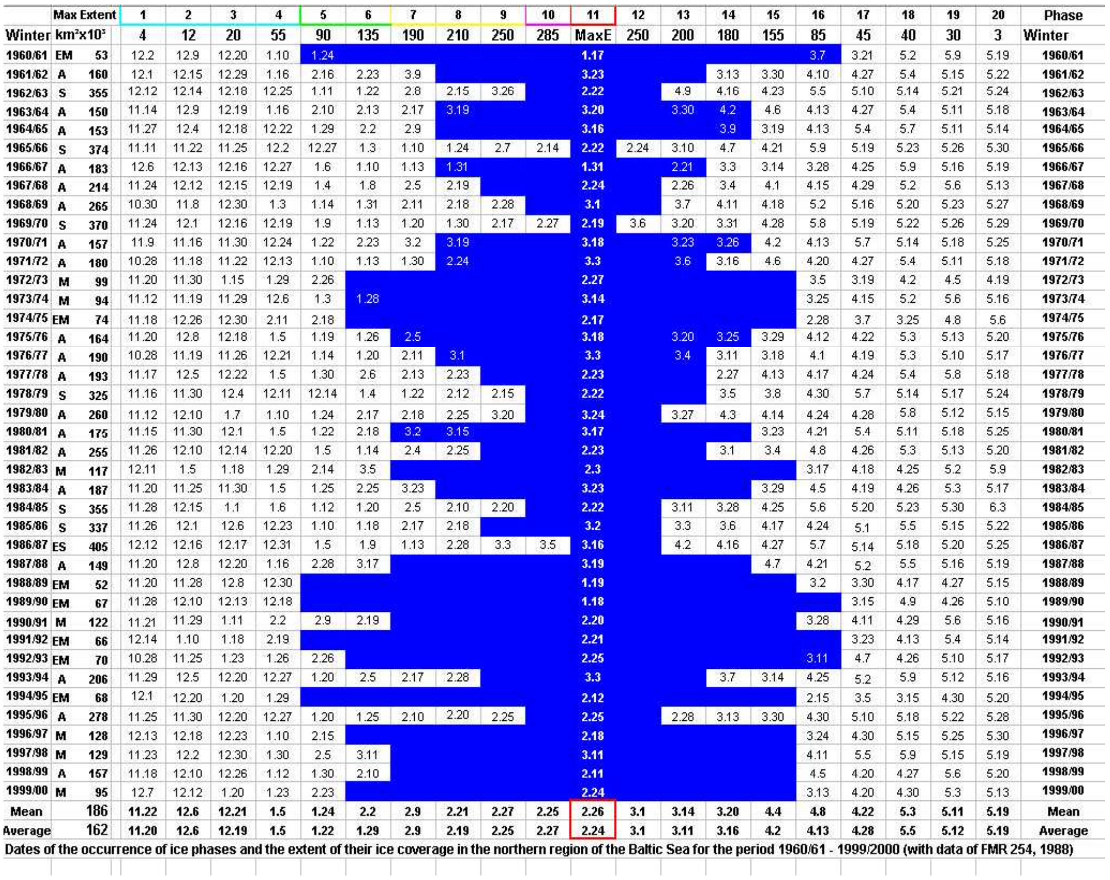
The **Ice Phases** defined by Finnish scientists mainly for the northern region of the Baltic Sea consider “the fact that the Baltic ice winter does not develop in accordance with average conditions, but instead according to certain phases that recur year after year” (Leppäranta, M. et al. 1988, p. 19). The defined 20 phases – *phases 1 to 10 for the ice formation period, phases 12 to 20 for the period of ice decay; phase 11, which should represent a complete ice cover of the Baltic Sea, did not occur in the period of investigation* – describe special stages of the ice development during the winter reflecting distinct geographical features of the ice distribution and extension as e.g. boundaries of the coastal fast ice and the seaward extension of the ice cover related to oceanographic boundaries and natural characteristics of the different sea areas.

In the above cited ‘Phase Atlas’ the ice phases and relevant statistical data were calculated for the 17 years period 1963/64 to 1979/80. This period was extended with respect to the dates of the occurrence of the different phases to the 40 years period 1960/61 to 1999/2000 (**Table 4**). Furthermore the ice extent (km²) was calculated for the single phases with the ICEMAP software (Berglund, R., 2003). As it has already been mentioned in the Atlas (p. 20), to fix the date of the beginning/ending of a special phase is a somewhat subjective decision, as there can be delays between the different sea areas (e. g. Gulf of Bothnia and Gulf of Finland) due to regional differences in the frost and wind regime. Nevertheless, the ice phases offer a good ‘natural synthetic’ approach to calculate the severity/character of an ice season.

This is done by using not just the ice extent of the single ice phases in a single winter, but consider their duration, too, in order to receive a ‘weighted’ measure for the season. The result is a *mean ice extent* – for each phase its duration (number of days) is multiplied with the ice extent (km²); the sum is divided by the total duration of the ice season.

The comparison of the *mean ice extent* and the maximum ice extent results in a sometimes quite different ranking of the single ice winters (**Table 5**).

Table 4. The extent and the first, mean and average dates of ice phases and the area and date of the maximum ice extent (1960/61 – 1999/2000)



	Max Extent		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Phase
Winter	km²x10³		4	12	20	55	90	135	190	210	250	285	MaxE	250	200	180	155	85	45	40	30	3	Winter
1960/61	EM	53	12.2	12.9	12.20	1.10	1.24						1.17					3.7	3.21	5.2	5.9	5.19	1960/61
1961/62	A	160	12.1	12.15	12.29	1.16	2.16	2.23	3.9				3.23			3.13	3.30	4.10	4.27	5.4	5.15	5.22	1961/62
1962/63	S	355	12.12	12.14	12.18	12.25	1.11	1.22	2.8	2.15	3.26		2.22		4.9	4.16	4.23	5.5	5.10	5.14	5.21	5.24	1962/63
1963/64	A	150	11.14	12.9	12.19	1.16	2.10	2.13	2.17	3.19			3.20		3.30	4.2	4.6	4.13	4.27	5.4	5.11	5.18	1963/64
1964/65	A	153	11.27	12.4	12.18	12.22	1.29	2.2	2.9				3.16			3.9	3.19	4.13	5.4	5.7	5.11	5.14	1964/65
1965/66	S	374	11.11	11.22	11.25	12.2	12.27	1.3	1.10	1.24	2.7	2.14	2.22	2.24	3.10	4.7	4.21	5.9	5.19	5.23	5.26	5.30	1965/66
1966/67	A	183	12.6	12.13	12.16	12.27	1.6	1.10	1.13	1.31			1.31		2.21	3.3	3.14	3.28	4.25	5.9	5.16	5.19	1966/67
1967/68	A	214	11.24	12.12	12.15	12.19	1.4	1.8	2.5	2.19			2.24		2.26	3.4	4.1	4.15	4.29	5.2	5.6	5.13	1967/68
1968/69	A	265	10.30	11.8	12.30	1.3	1.14	1.31	2.11	2.18	2.28		3.1		3.7	4.11	4.18	5.2	5.16	5.20	5.23	5.27	1968/69
1969/70	S	370	11.24	12.1	12.16	12.19	1.9	1.13	1.20	1.30	2.17	2.27	2.19	3.6	3.20	3.31	4.28	5.8	5.19	5.22	5.26	5.29	1969/70
1970/71	A	157	11.9	11.16	11.30	12.24	1.22	2.23	3.2	3.19			3.18		3.23	3.26	4.2	4.13	5.7	5.14	5.18	5.25	1970/71
1971/72	A	180	10.28	11.18	11.22	12.13	1.10	1.13	1.30	2.24			3.3		3.6	3.16	4.6	4.20	4.27	5.4	5.11	5.18	1971/72
1972/73	M	99	11.20	11.30	1.15	1.29	2.26						2.27					3.5	3.19	4.2	4.5	4.19	1972/73
1973/74	M	94	11.12	11.19	11.29	12.6	1.3	1.28					3.14					3.25	4.15	5.2	5.6	5.16	1973/74
1974/75	EM	74	11.18	12.26	12.30	2.11	2.18						2.17					2.28	3.7	3.25	4.8	5.6	1974/75
1975/76	A	164	11.20	12.8	12.18	1.5	1.19	1.26	2.5				3.18		3.20	3.25	3.29	4.12	4.22	5.3	5.13	5.20	1975/76
1976/77	A	190	10.28	11.19	11.26	12.21	1.14	1.20	2.11	3.1			3.3		3.4	3.11	3.18	4.1	4.19	5.3	5.10	5.17	1976/77
1977/78	A	193	11.17	12.5	12.22	1.5	1.30	2.6	2.13	2.23			2.23			2.27	4.13	4.17	4.24	5.4	5.8	5.18	1977/78
1978/79	S	325	11.16	11.30	12.4	12.11	12.14	1.4	1.22	2.12	2.15		2.22			3.5	3.8	4.30	5.7	5.14	5.17	5.24	1978/79
1979/80	A	260	11.12	12.10	1.7	1.10	1.24	2.17	2.18	2.25	3.20		3.24		3.27	4.3	4.14	4.24	4.28	5.8	5.12	5.15	1979/80
1980/81	A	175	11.15	11.30	12.1	1.5	1.22	2.18	3.2	3.15			3.17				3.23	4.21	5.4	5.11	5.18	5.25	1980/81
1981/82	A	255	11.26	12.10	12.14	12.20	1.5	1.14	2.4	2.25			2.23			3.1	3.4	4.8	4.26	5.3	5.13	5.20	1981/82
1982/83	M	117	12.11	1.5	1.18	1.29	2.14	3.5					2.3					3.17	4.18	4.25	5.2	5.9	1982/83
1983/84	A	187	11.20	11.25	11.30	1.5	1.25	2.25	3.23				3.23				3.29	4.5	4.19	4.26	5.3	5.17	1983/84
1984/85	S	355	11.28	12.15	1.1	1.6	1.12	1.20	2.5	2.10	2.20		2.22		3.11	3.28	4.25	5.6	5.20	5.23	5.30	6.3	1984/85
1985/86	S	337	11.26	12.1	12.6	12.23	1.10	1.18	2.17	2.18			3.2		3.3	3.6	4.17	4.24	5.1	5.5	5.15	5.22	1985/86
1986/87	ES	405	12.12	12.16	12.17	12.31	1.5	1.9	1.13	2.28	3.3	3.5	3.16		4.2	4.16	4.27	5.7	5.14	5.18	5.20	5.25	1986/87
1987/88	A	149	11.20	12.8	12.20	1.16	2.28	3.17					3.19				4.7	4.21	5.2	5.5	5.16	5.19	1987/88
1988/89	EM	52	11.20	11.28	12.8	12.30							1.19					3.2	3.30	4.17	4.27	5.15	1988/89
1989/90	EM	67	11.28	12.10	12.13	12.18							1.18						3.15	4.9	4.26	5.10	1989/90
1990/91	M	122	11.21	11.29	1.11	2.2	2.9	2.19					2.20					3.28	4.11	4.29	5.6	5.16	1990/91
1991/92	EM	66	12.14	1.10	1.18	2.19							2.21						3.23	4.13	5.4	5.14	1991/92
1992/93	EM	70	10.28	11.25	1.23	1.26	2.26						2.25					3.11	4.7	4.26	5.10	5.17	1992/93
1993/94	A	206	11.29	12.5	12.20	12.27	1.20	2.5	2.17	2.28			3.3			3.7	3.14	4.25	5.2	5.9	5.12	5.16	1993/94
1994/95	EM	68	12.1	12.20	1.20	1.29							2.12					2.15	3.5	3.15	4.30	5.20	1994/95
1995/96	A	278	11.25	11.30	12.20	12.27	1.20	1.25	2.10	2.20	2.25		2.25		2.28	3.13	3.30	4.30	5.10	5.18	5.22	5.28	1995/96
1996/97	M	128	12.13	12.18	12.23	1.10	2.15						2.18					3.24	4.30	5.15	5.25	5.30	1996/97
1997/98	M	129	11.23	12.2	12.30	1.30	2.5	3.11					3.11					4.11	5.5	5.9	5.15	5.19	1997/98
1998/99	A	157	11.18	12.10	12.26	1.12	1.30	2.10					2.11					4.5	4.20	4.27	5.6	5.20	1998/99
1999/00	M	95	12.7	12.12	1.20	1.23	2.23						2.24					3.13	4.20	4.30	5.3	5.13	1999/00
Mean		186	11.22	12.6	12.21	1.5	1.24	2.2	2.9	2.21	2.27	2.25	2.26	3.1	3.14	3.20	4.4	4.8	4.22	5.3	5.11	5.19	Mean
Average		162	11.20	12.6	12.19	1.5	1.22	1.29	2.9	2.19	2.25	2.27	2.24	3.1	3.11	3.16	4.2	4.13	4.28	5.5	5.12	5.19	Average

Dates of the occurrence of ice phases and the extent of their ice coverage in the northern region of the Baltic Sea for the period 1960/61 - 1999/2000 (with data of FMR 254, 1988)

For technical reasons the dates in the columns 1-20 are given in the form mm.dd. (month.day.)

In the column for the maximum ice extent the numbers for the whole Baltic Sea are listed (Seinä, A., Palosuo, E., 1993), while the ice extent for the phases is calculated for the northern region only.

A – average, EM – extreme mild, ES – extreme strong, M – mild, S – strong ice winter

Numbers 1-10 and 12-20: phase no.

Column 11: date of the maximum ice extent

Blue sector: The maximum ice extent was less than the extent of the phases related to this sector. If dates are given in this sector, see note below.

The basic reason is that e. g. a winter with a rather great maximum ice extent can have only short periods with the greater extent and vice versa. However, beside that - as result of the calculation with the ice extent for the single phases, some discrepancies with the official values for the maximum ice extent have been found as well as with some data given in Table 1 of the ‘Phase Atlas’ (note: *these discrepancies are presently under negotiation. Therefore, so far the given values in this paper have to be considered as preliminarily*). For example, in the ice winter 1973/74 the maximum ice extent is given as 94,000 km². This value does not fit with the data from the ‘Phase Atlas’ that on January 20 phase 6 was reached, the extent of which is calculated to be about 135,000 km². As the retreat of the ice is given to start with phase 16 (about 85,000 km²), which is within the range of the given maximum ice extent, the ice charts for that ice season have been checked, and as a result it is suggested to delete phase 6. On the other hand, for the winter 1970/71 the phases 8 and 13-14, respectively, could be confirmed. This does not fit with the maximum ice extent of 157,000 km^2, it must be at least in the range of 190,000 to 200,000 km^2.

Table 5. Comparison of the ranking of the ice winters related to the maximum ice extent and to the phase related mean ice extent

a) Chronological order b) Order by maximum ice extent

	Max. Extent		Mean Extent			Max. Extent		Mean Extent	
Winter	km^2x10^3	Rank	Rank	km^2x10^3	Winter	km^2x10^3	Rank	Rank	km^2x10^3
1960/61	53	39	34	40	1986/87	405	1	1	162
1961/62	160	21	27	66	1965/66	374	2	6	120
1962/63	355	4	2	141	1969/70	370	3	3	129
1963/64	150	25	23	72	1962/63	355	4	2	141
1964/65	153	24	16	92	1984/85	355	5	5	125
1965/66	374	2	6	120	1985/86	337	6	8	111
1966/67	183	17	9	110	1978/79	325	7	4	126
1967/68	214	12	7	115	1995/96	278	8	10	109
1968/69	265	9	11	103	1968/69	265	9	11	103
1969/70	370	3	3	129	1979/80	260	10	15	95
1970/71	157	22	22	78	1981/82	255	11	12	103
1971/72	180	18	14	100	1967/68	214	12	7	115
1972/73	99	31	36	36	1993/94	206	13	13	102
1973/74	94	33	21	79	1977/78	193	14	17	90
1974/75	74	34	40	29	1976/77	190	15	19	84
1975/76	164	20	18	85	1983/84	187	16	25	71
1976/77	190	15	19	84	1966/67	183	17	9	110
1977/78	193	14	17	90	1971/72	180	18	14	100
1978/79	325	7	4	126	1980/81	175	19	20	83
1979/80	260	10	15	95	1975/76	164	20	18	85
1980/81	175	19	20	83	1961/62	160	21	27	66
1981/82	255	11	12	103	1970/71	157	22	22	78
1982/83	117	30	30	54	1998/99	157	23	24	72
1983/84	187	16	25	71	1964/65	153	24	16	92
1984/85	355	5	5	125	1963/64	150	25	23	72
1985/86	337	6	8	111	1987/88	149	26	27	62
1986/87	405	1	1	162	1996/97	128	27	26	69
1987/88	149	26	27	62	1997/98	129	28	29	62
1988/89	52	40	35	40	1990/91	122	29	31	53
1989/90	67	37	33	44	1982/83	117	30	30	54
1990/91	122	29	31	53	1972/73	99	31	36	36
1991/92	66	38	39	34	1999/00	95	32	32	52
1992/93	70	35	37	35	1973/74	94	33	21	79
1993/94	206	13	13	102	1974/75	74	34	40	29
1994/95	68	36	38	35	1992/93	70	35	37	35
1995/96	278	8	10	109	1994/95	68	36	38	35
1996/97	128	27	26	69	1989/90	67	37	33	44
1997/98	129	27	29	62	1991/92	66	38	39	34
1998/99	157	23	24	72	1960/61	53	39	34	40
1999/00	95	32	32	52	1988/99	52	40	35	40

In addition to the comments above, from Table 5b, in which the maximum ice extent (which includes also the ice cover from the southern Baltic Sea) is used for the ranking, it becomes obvious by comparing the ranks of the maximum ice extent with those of the mean ice extent that only few ice winters (6) show the same order number, however, already 16 ice winters differ only by two ranks. The overall range is plus 12 ranks in 1973/74 (which may result from ‘overestimation’ of phase 6 – see above) and minus 9 ranks in 1983/84. The mean absolute difference is 3 ranks. Some possible reasons have already been mentioned, but more detailed checks are necessary to ‘judge’ on the value of the one or other method. The diagram in Figure 4 shows at least for both time series the characteristic year to year variations, but of course for the mean ice extent in a smoothed version.

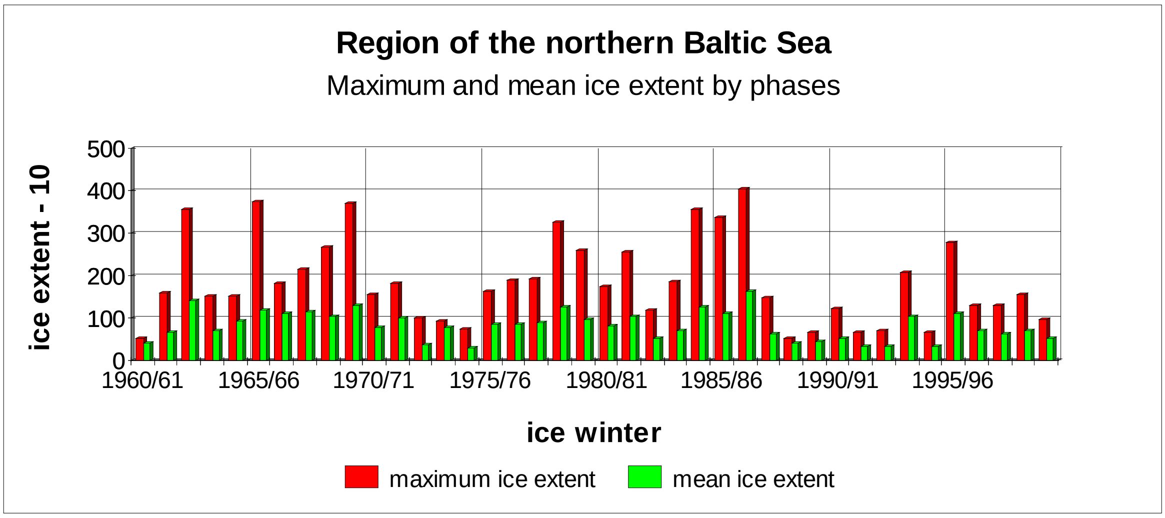


Fig. 4. Comparison of the mean ice extent by phases for the northern Baltic Sea and the maximum ice extent for the period 1960/61 to 1999/2000

Concerning the above diagram as well as table 5 it has again to be considered that the values for the maximum ice extent are calculated for the Baltic Sea in total, i.e. with contributions from the southern regions. The comparison can be improved for the more severe winters, if only the ice cover for the northern region is calculated.

Nevertheless, the use of the ice phases is a good help for the characterization of an ice winter. In Figurte 5 the columns show the ice extent for the phases 1–9 and 12-20 in comparison to the development of the ice extent in the winter 2002/03 calculated from the twice weekly ice charts (Mondays and Thursdays). The graph shows clearly the very rapid ice formation at the beginning of the winter - related mostly to the Gulf of Finland, which results already in early January in an ice extent of a nearly average winter. The considerably ice decay later on in January produces then an about normal ice extent in mid-winter, however, the ice thickness in the Gulf of Finland staid well above the mean values.

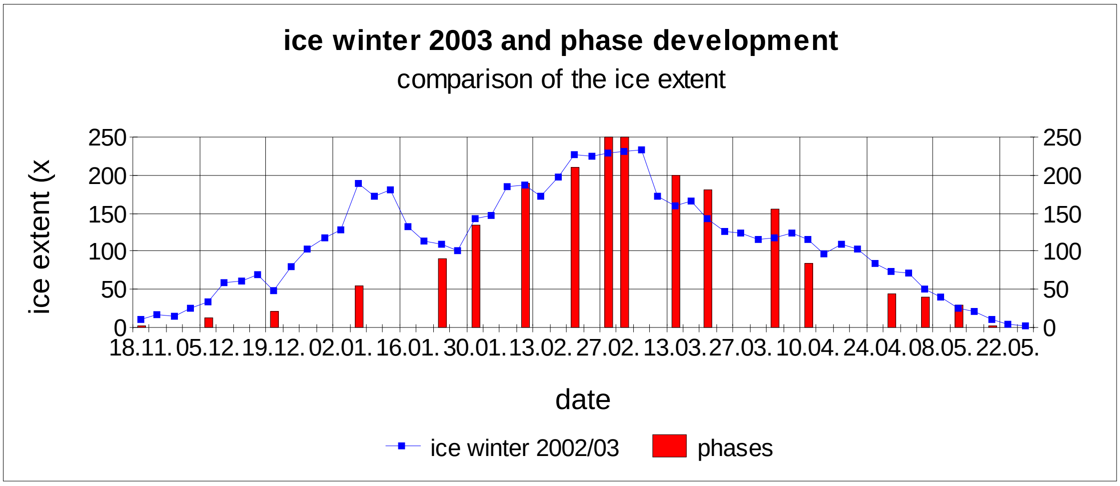


Fig. 5. The development of the ice extent in the winter 2002/03 compared with the average of the ice phases for the period 1961 - 2000

Restrictions to Navigation

In order to keep the traffic running and to avoid delays by vessels not suited for winter navigation, *restrictions to navigation* have been introduced some decades ago by the Finnish and Swedish Maritime Administrations. This has been recently pushed again by the HELCOM Recommendation 25/7 (adopted 2 March 2004) as result of the severe ice conditions experienced in the Gulf of Finland in 2003 (Mylly, M. 2004). The restrictions, i.e. special requirements with respect to the ice classification and size/power of the vessels, which allow them to receive Governmental icebreaker assistance, are set with respect to the severity of the ice conditions in the different sea areas. So, they may be used as a classification parameter/method for the character of an ice winter, too. An example is given in Figure 6.

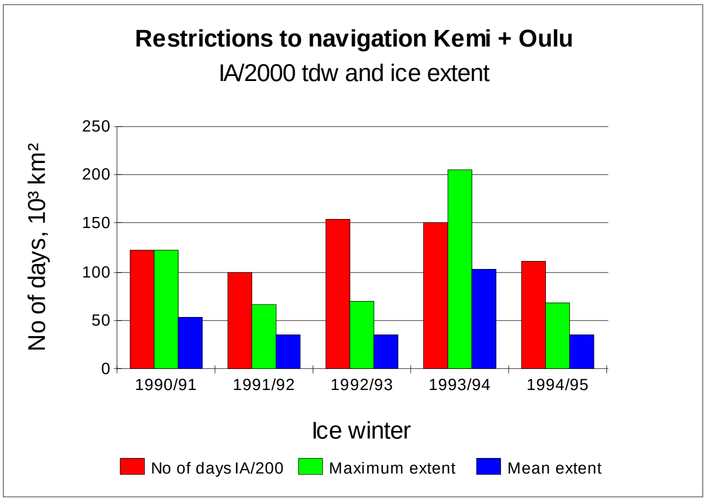


Fig. 6. Comparison of the duration of the restriction to navigation for the harbours Kemi and Oulu with the maximum and mean ice extents.

The columns show that the number of days, when ice class IA and at least 2000 tdw where requested, relate somewhat to both ice extents. However, by comparing the seasons 1992/93 and 1993/94 it has to be recognized that in the first season with much less than 50 % of the ice extents, the mentioned restrict-ions were valid even some days longer (154:150 days). This may indicate that e. g. the severity of the ice cover in a given region is not that much related to the ice extent but more to the local ice conditions – perhaps as result of the influence of navigation on the ice cover (see Table 2).

Results and Conclusions

After a sketch of the development of the winter navigation in the (northern) Baltic Sea, the possible influence of the ship traffic on the character and dynamics of the ice cover in highly cruised sea areas has been discussed. It is not only the opinion of the author that there is an essential influence, which should be somehow considered in models and in the evaluation of long-term time series on the different aspects of the ice climate of the Baltic Sea.

The so far published period for Ice Phase data (1963/64 to 1979/80) has been extended backwards to the ice winter 1960/61 and forwards to 1999/2000 from 17 to 40 years. The data have been used to characterize the ice winters in a more integrated manner by defining a *mean ice extent*, which takes into account both, the length and the ice covered area of the different ice phases reached in an ice season, compared to the single value of its *maximum ice extent*. The respective ranking of the ice winters shows differences that must be discussed considering the different ‘weight’ of the used parameters. In addition, some discrepancies e.g. in comparing the published data for the maximum ice extent and the occurrence of ice phases became obvious. Therefore, the presented data have to be considered to be provisionally, and they must be subject to further negotiations and joint ‘tuning’.

As ‘final idea’ the use of the *restrictions to navigation* is discussed as possible additional parameter to characterize the severity of an ice season, as they integrate aspects of the given ice conditions and the ice navigation. An example was calculated for the five seasons 1991 to 1995. The preliminary result shows that there can be distinct differences between the duration of special restrictions and the maximum and mean ice extent, which require further detailed cause study and basic discussion.

Acknowledgement

The author is particularly grateful Dr. N. Schmelzer, German Ice Service, for computing of some of the new ice phase data.

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Reconstruction of Annual Maximum Ice Extent in the Baltic Sea 1660–2005

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Abstract

The annual maximum ice extent A_{max} in the Baltic Sea is an important indicator of regional winter climate in northern Europe. Apart from modern-day operational ice charts, proxy data such as coastal observations, mean winter air temperature, and ice break-up dates have been used to reconstruct A_{max} back to 1660.

A consolidated time series was constructed by giving the proxy time series different weights. These weights were calculated as inversely proportional to the mean square errors of the time series during the calibration period 1961–1990.

The consolidated time series indicates a large interannual as well as interdecadal variability. In spite of the recent mild winters in the Baltic Sea region, the large interannual variabilitiy of A_{max} makes the calculated trend over moving 30-year windows mostly insignificant in a statistical sense.

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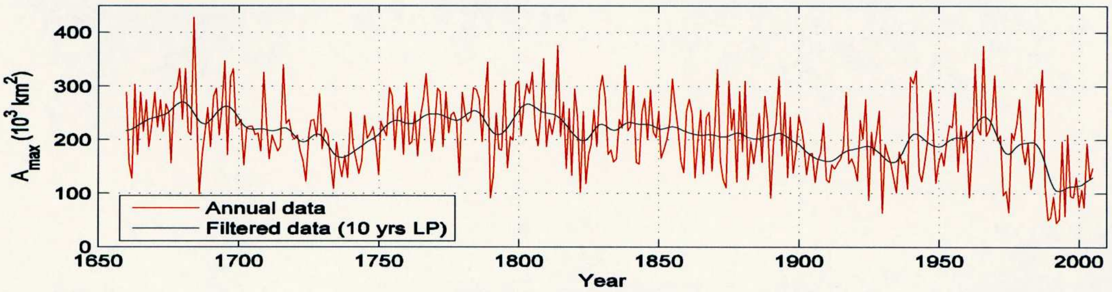

Figure 1. Annual maximum ice extent based on proxy data and ice charts.

Data used in the reconstruction:

- Swedish and Finnish ice charts: 1961—2005
- coastal observations: 1871—1990
- Stockholm winter (DJF) air temperature: 1756—1990
- Uppsala winter (DJF) air temperature: 1722—1990
- Central England winter (DJF) air temperature: 1660—1990

Consolidation method:

- all proxy-based ice extents weighted as

$$A_j = W_1 A_{j1} + W_2 A_{j2} + \ldots$$

where W_i is the weight corresponding to the i:th reconstruction

- weights calculated according to

$$W_i^{-1} = \sum_j E_i^2 / E_j^2$$

where E_i^2 are the mean-square errors

Regression methods:

- calibration period: 1961—1990
- ice charts used as reference
- regression of winter air temperature T_w against ice charts: $A_j = c_0 + c_1 T_w$
- c_0 and c_1 calculated for calibration period for each temperature data set
- A_j calculated for period 1660—1960
- regression of coastal observations δ_{ji} against ice charts: $A_j = \delta_{ji} a_i$ where j denotes year, i denotes the number of the coastal station, and a_i is the ice area associated with coastal station i
- a_i is calculated with a least-squares technique for the calibration period
- A_j calculated for period 1871—1960

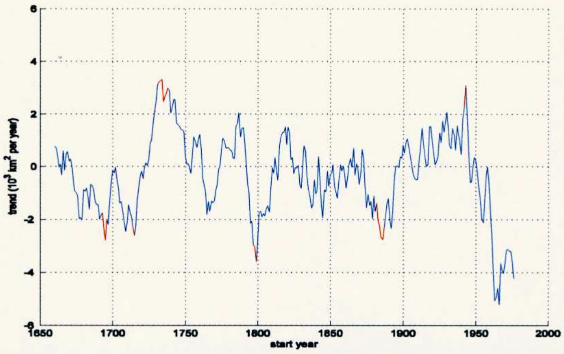

Figure 2. Calculated trends over moving 30-year windows. Mann-Kendal's test was applied on test time series $B_j = A_j - \alpha A_{j-1}$, where α is the autocorrelation for time lag 1 year [i.e. corr(A_j, A_{j-1})]. Significant trends (95% C.I.) coloured red.

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Numerical Sea Ice Forecast Experiment of PIC Model for the Bohai Sea

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Abstract Based on dynamic and thermodynamic research of sea ice and the ice conditions in the Bohai Sea, a Particle-In-Cell (PIC) sea ice model has been applied to sea ice forecasting in the Bohai Sea. The PIC method is introduced into the sea ice model to efficiently reduce the numeric diffusion inherent in the Bohai Sea operational ice model. The multi-category ice thickness distribution is used to replace the three-level ice thickness distribution as well. Numerical sea ice experimental forecasts for the Bohai Sea were made by using the PIC model for 3 winter seasons, and the statistical analysis and comparison of sea ice forecast results were made.

Key words Sea ice; Numerical sea ice forecast; Particle-In-Cell method; Statistical verification

Sensitivity of Arctic Sea ice in Rossby Centre numerical models

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Abstract

The Rossby Centre modelling system (RCO for the ocean, RCA for the atmosphere and RCAO for the coupled setup) is applied in a wider arctic domain. Validation and sensitivity runs are carried out based on ERA-40 forcing.

RCAO and its component models have earlier been successfully applied in a Baltic Sea domain. Application of the very same model in the Arctic reveals a tendency towards too much sea ice.

Sea ice extent and concentration serves as a sensitive integral measure of

(1) the models capability to respresent relevant processes and
(2) the influence of initial conditions.

Process formulations such as atmospheric radiation, reflection at the ice surface (albedo), sea ice parametersand, the sea ice-atmosphere coupling algorithm and the atlantic oceanic boundary condition are tested for their influences.

A long-term goal for the model development are more robust, physically based and thus more universal model formulations which hold for many application domains.

Berichte des Bundesamtes für Seeschiffahrt und Hydrographie

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