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On the Relation Between Annual Maximum Extent of Ice Cover in the Baltic Sea and Sea Level Pressure as Well as Air Temperature Field

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Abstract

The annual sea ice cover in the Baltic Sea is a component of the cryosphere which is sensitive to climatic changes.

The annual maximum extent of ice cover in the Baltic Sea 1720-1996 (Seinä and Palosuo, 1993) is a suitable time series to estimate the intensity of the ice winter in this sea. The time series shows a significant negative trend.

By calculating the correlation coefficient fields between ice time series and air temperature field as well as sea level pressure field, the areas and the periods of maximum correlation could be found. As far as the temperature field is concerned there are significant correlation coefficients in the area around the Baltic Sea from November to April, while the sea level pressure field in the Northern Norwegian Sea and the Western Mediterranean Sea shows significant coefficients from December to March.

An exponential regression model containing the mean temperature from November to March of the 10° gridpoint area (55-65° N, 20-30° E) as predictor explains 86 % of the variance.

An estimate of the future development of the annual maximum extent of ice cover in the Baltic Sea can be obtained with the help of temperature time series of same area and period computed by the coupled General Circulation Model ECHAM4/T42_OPYC3 (Max-Planck-Institute for Meteorology, Hamburg). As to IS92a scenario (IPCC[1]) a drastic decrease in the mean extent of ice cover would follow in the next 100 years.

Key words: ice in the Baltic, climatic change, downscaling method

[1] Intergovernmental Panel on Climate Change

1. Introduction

Especially in former times, severe ice winters in the Baltic Sea area had a great influence on the economic activities of the population at the coast, all maritime activities being either disturbed or interrupted. That is why reports about severe winters are widely discussed in old chronicles and historical documents. For instance in *Hennig* (1904) and *Weikinn* (1958) there are reports on the Baltic Sea in the Middle Ages which had been completely ice covered over several winters, making passenger travel and transport of goods from coast to coast possible.

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Speerschneider (1915) collected information about the ice in Danish waters. He found reports in old chronicles on ice winters as early as 690 and noted that there has been no significant change in the character of ice winters over the last centuries.

First irregular observations of the break up of ice in the port of Riga started in 1530 (*Betin* and *Preobrazenskij*, 1959).

Tarand (1992) reconstructed a complete and homogenized time series of the break up of ice in Palmse (a manor 70 km east of Tallinn) over the winters between 1709 and 1980. He discovered that there had been no significant changes until 1900, from when the break up of ice would begin 8-10 days earlier.

Koslowski and *Glaser* (1995) presented an ice index which characterizes the ice winter severity in the Western Baltic since 1701. The ice index has a maximum around 1800.

A good measure for the ice conditions of the whole Baltic Sea is the time series of the annual maximum extent of ice cover published by *Jurva* (1944). Original data were destroyed in Word War II. The time series was reconstructed and presented by *Palosuo* (1953). The values of the ice time series include the area of the Baltic Sea (420 000 km^2), which is covered by fast and drift ice during maximum extent of ice cover.

The ice conditions of the Baltic Sea are a good indicator for climatic change because the ice cover is very sensitive to alterations in the air temperature in North and Central Europe in winter. The temperature distribution in Europe corresponds to the sea level pressure field over the North Atlantic Ocean and Europe. All the other meteorological factors which are important for ice growth, for instance snow fall, atmospheric moisture, wind direction and wind velocity depend on large scale circulation. The oceanographical and morphological factors which have an impact on ice development like salinity, water temperature, water depth, depth of the layer of discontinuity and configuration of coast, are relatively stable or depend on meteorological elements, too.

Several authors have investigated the connection between ice conditions in the Baltic Sea and, for example winter temperature (*Palosuo,* 1965; *Alenius and Makkonen,* 1981; *Leppäranta* and *Seinä,* 1985; *Alenius,* 1989, *Koslowski,* 1989; *Leppäranta,* 1989; *Tinz* 1995), sum of negative daily mean temperatures from November to March (*Hupfer* 1967), several parameters of circulation (*Koslowski,* 1964; *Hupfer,* 1967; *Malicki* and *Wielbinska,* 1992; *Koslowski* and *Loewe,* 1994; *Tinz,* 1995), water temperature (*Hupfer,* 1967; *Tarand,* 1992) and the sea level of the Baltic Sea (*Lisitzin,* 1958; *Omstedt* and *Nyberg,* 1991).

In conclusion it can be stated that it is sufficient for statistical investigations to discover the relation between the ice conditions of the Baltic Sea and sea level pressure as well as the near surface temperature field.

2. *Statistical parameters of annual maximum extent of ice cover in the Baltic Sea*

The time series of annual maximum extent of ice cover in the Baltic Sea includes the winters between 1719/20 and 1995/96; a period which is longer than most of the meteorological time series. Several authors, such as *Palosuo* (1953), *Betin* and *Preobrazenskij* (1959), *Alenius* and *Makkonen* (1981) and *Seinä* (1993) give detailed information on quality and homogeneity of ice time series. Consequently, values of the annual maximum extent of ice cover in the Baltic Sea since the year 1890 are reliable and older data are a good estimate for the ice conditions. The stable correlation coefficient with the mean temperature of Stockholm from November to March since 1756 on a high level (*Seinä*, 1993, see also Fig. 8b) is a favourable argument for the quality of the ice time series.

Some of the statistical parameters are printed in the cited publications; the following statements can be regarded as a summary and an update (Table 1).

Table 1. Statistical parameters of the annual maximum extent of ice cover in the Baltic Sea (1720-1996).

statistical parameter	annual maximum extent of ice cover in the Baltic Sea
number	277 years
mean	(217 000±13 000) km²
median	182 000 km²
minimum	52 000 km²
maximum	420 000 km²
standard deviation	114 000 km²
trend	-19 000 km²/100 years (error probability=1 %)

All of the following statistical conclusions, if not specified, are on the significance level of 95 % as well as with 5 % error probability. The significance level of the correlation coefficient was tested with the t-test, the linear trend with the trend test after Cox and Stuart, the frequency distribution with the chi-square test of goodness of fit and confidence intervals for mean and correlation coefficient are also given (see *Sachs*, 1992).

The annual maximum extent of ice cover in the Baltic Sea varies between 52 000 km² (winter 1988/89) and 420 000 km² (in 15 winters). This "total freezing" - when the Baltic Sea is completely covered by fast and drift ice - is rare. In this century, it has only occured in the winters of 1939/40, 1941/42 and 1946/47.

The ice time series shows a significant negative trend of -19 000 km²/100 years (Fig. 1). This trend is overlapped by a long oscillation, with a maximum in 1810, a climax of the "Little Ice Age". The maximum was also found by *Koslowski* and *Glaser* (1995) analysing the severity of ice winters in the Western Baltic. The minimum in 1940 is characterized by a period of dominating mild, but also some extremely severe ice winters.

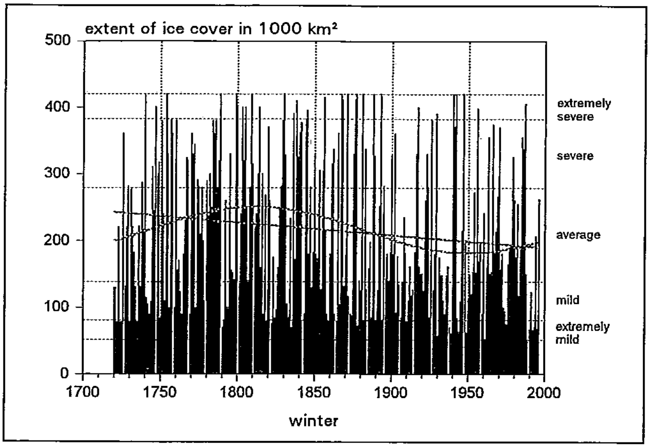

Fig. 1. Annual maximum extent of ice cover in the Baltic Sea (1720-1996), linear trend, long oscillation and classification of ice winters after *Seinä* and *Palosuo* (1993).

The difference between arithmetic mean at 217 000 km² and median at 182 000 km² is significant. Consequently the bimodal frequency distribution (no Gaussian distribution) shows two maximum values at 90 000 km² and at 400 000 km² (Fig. 2). The first maximum reflects the fact that the majority of winters in Baltic area is milder than the average and the minority of winters is far colder, as the distribution of the winter temperatures with negative skewness shows (*Warmbt*, 1941). The second maximum is limited by the size of the Baltic Sea (420 000 km²) and the nonlinear process of ice growth. An ice-covered area of 180 000 km² is a critical value (*Seinä*, 1993). After reaching this mark the ice grows rapidly and covers large areas of the Baltic Sea over a short period.

The ice time series has been classified by *Seinä* and *Palosuo* (1993) in extremely mild (52 000 - 81 000 km²), mild (81 001 - 139 000 km²), average (139 001-279 000 km²), severe (279 001 - 383 000 km²) and extremely severe (383 001 - 420 000 km²) ice winters.

As a consequence of recent climatic changes the relative frequency of ice winter types is variable (Fig. 3). While mild and extremely mild ice winters remain relatively constant at 30 % of all winters, severe ice winters reduced their percentage distribution from 40 % to 10 %. Average ice winters have increased from 20 % to 50 %, especially in this century. The percentage distribution of extremely severe ice winters is relatively constant at 10 % over the whole period.

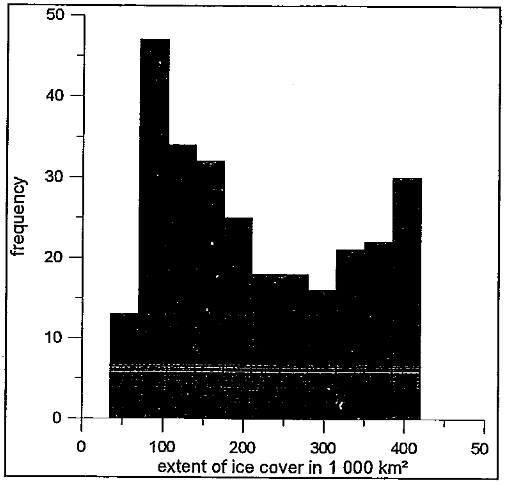

Fig. 2. Frequency distribution of annual maximum extent of ice cover in the Baltic Sea (1720-1996).

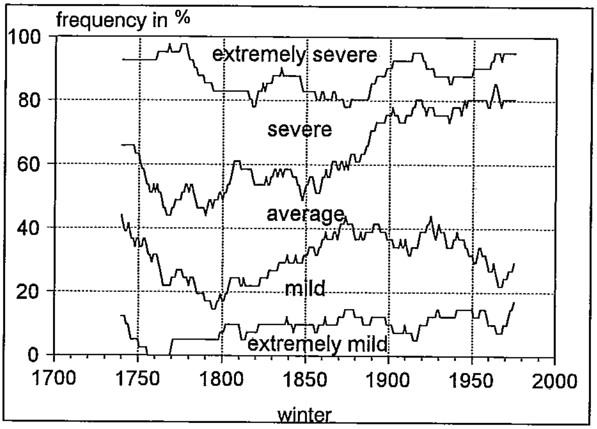

Fig. 3. Moving frequencies of classified ice in % by using 41 year overlapping intervals (1740-1976).

The long-term behaviour of the annual maximum extent of ice cover in the Baltic Sea corresponds to the climatic changes in North and Central Europe, as the long temperature time series of Berlin (from 1728) and Stockholm (from 1756) indicate (*Jones* and *Bradley*, 1992).

3. *Correlation between annual maximum extent of ice cover in the Baltic Sea and sea level pressure as well as air temperature field*

Gridpoint data were used to discover the area and the period of maximum correlation between annual maximum extent of ice cover of the Baltic Sea and sea level pressure as well as temperature field. Further information on the gridpoint data sets are given in Table 2.

Table 2. Details of the used gridpoint data sets of sea level pressure in hPa and near surface (2 m) air temperature in °C.

parameter	sea level pressure in hPa	near surface temperature in °C
resolution	5° x 5°	5° x 5°
area	30-85° N; 60° W-60° E	45-70° N; 5° W-40° E
time	1899-1993 (95 years)	1854-1990 (137 years)
data source	*NCAR*[1] (1994)	*Chadwyck-Haely Ltd.* (1992)

The annual maximum extent of ice cover does not follow the Gaussian distribution (chapter 2). That is why the nonparametric Spearman rank correlation coefficient r_S was used. However, differences to the Pearsons correlation coefficient r_P are very small.

3.1 *Correlation with sea level pressure field*

Spearman rank correlation coefficients between the annual maximum extent of ice cover in the Baltic Sea and the gridpoint data of sea level pressure were calculated over 24 months, that is from January before to December after the ice winter. Significant correlation coefficients ($|r_s|>0.20$) were found only over four months, from December to March.

There are two areas with significant correlation, the first one with positive coefficients in the Northern Norwegian Sea and the other one with negative coefficients in the Western Mediterranean Sea.

A higher correlation could be found by using the mean sea level pressure of January and February (Fig. 4).

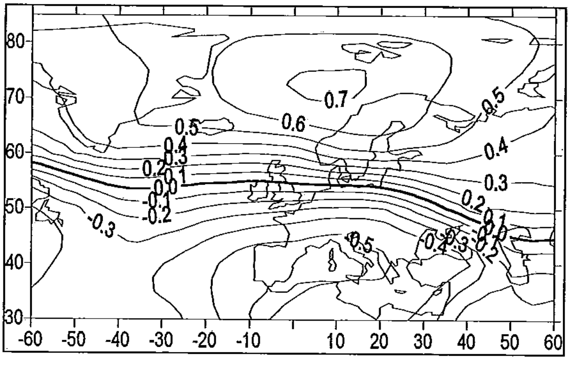

Fig. 4. Spearman rank correlation coefficients between the annual maximum extent of ice cover in the Baltic Sea and the mean sea level pressure of January/February (1899-1993).

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[1] National Center for Atmospheric Research, Boulder (Colorado)

The gridpoint with maximum positive correlation (r_s=0.71±0.10) is situated in the Northern Norwegian Sea at 70° N, 10° E. Positive sea level pressure anomalies in this area are connected with severe ice conditions in the Baltic Sea. The gridpoint with the maximum absolute value of negative correlation coefficient (r_s=-0.59±0.13) is situated near the Strait of Gibraltar at 35° N, 10° W. Both correlation coefficients are highly significant (significance level 99.9 %), but they can explain only up to 50 % of variance.

By using a zonal index, defined as the average sea level pressure difference January/February between the mentioned gridpoints with the highest absolute values of correlation coefficients, the correlation increased to r_s=0.72±0.10 (r_p=0.73±0.10). -

The high values of zonal index are connected with an enhanced circulation and a corresponding increased advection of mild air-masses from the North Atlantic Ocean and ice conditions below mean value in the Baltic Sea. The time series shows no significant trend, but a long oscillation (Fig. 5). The values of the zonal index are positive; only in the extremely severe ice winter of 1946/47 the pressure difference is negative.

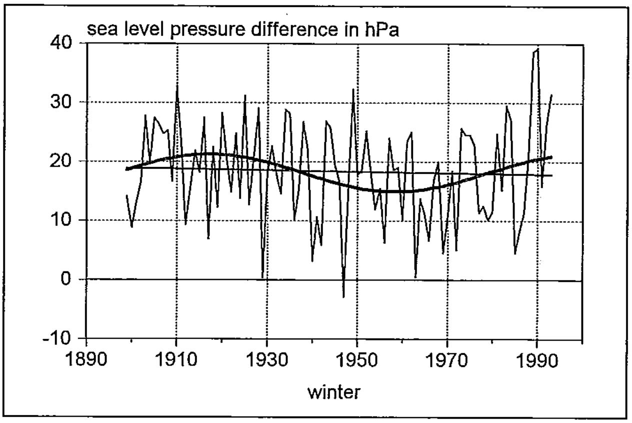

Fig. 5. Time series of the difference of the mean sea level pressure of January/February (1899-1993; zonal index) between the gridpoints (35° N, 10° W) and (70° N, 10° E) with linear trend and oscillation.

The predominant mild winters of the last years in the Baltic result from this increased circulation over the North Atlantic Ocean.

3.2 *Correlation with air temperature field*

Spearman rank correlation coefficients between the ice time series and monthly values of near surface air temperature were computed in the same way as with the sea level pressure field. Some missing values of the temperature data set were reduced by using linear regression equations and neighbouring grid boxes.

Significant correlation coefficients ($|r_s|>0.17$) were found over six months, from November to April.

The correlation coefficients are negative; which means positive temperature anomalies in the Baltic Sea area are related to conditions below normal value. The first significant correlation coefficients over Northern North Europe were in November. Until February the coefficients increased and reached $r_s=-0.75$. In spring, the coefficients decreased first slowly, then faster.

The area with maximum correlation moves, during the course of winter, from Northern North Europe to the Central Baltic.

The best correlation could be found by using the mean temperature from November to March of the four grid boxes 55-65° N, 20-30° E (Fig. 6). Spearman rank correlation coefficient reaches with the temperature series of the 10° gridpoint area to $r_s=-0.92\pm0.03$ ($r_p=-0.93\pm0.03$). The temperature time series shows a significant positive trend of 0.9 K/100 years (Fig. 7). It is similar to the global temperature course (*Houghton et al.*, 1996).

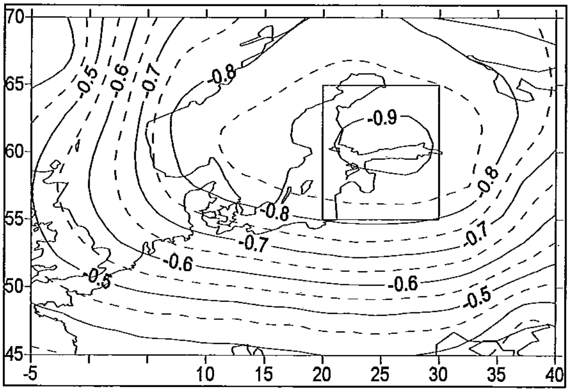

Fig. 6. Spearman rank correlation coefficients between the annual maximum extent of ice cover in the Baltic Sea and the mean temperatures from November to March (1854-1990). The 10° gridpoint area (55-65° N, 20-30° E) is marked.

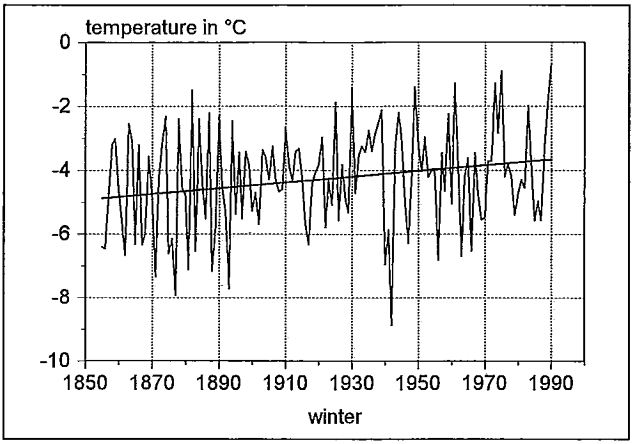

Fig. 7. Mean temperature in °C from November to March of the 10° gridpoint area (55-65° N, 20-30° E; 1855-1990) and linear trend.

The investigation shows that there is no opportunity forecasting the annual maximum extent of ice cover in the Baltic Sea with the sea level pressure field as well as the near surface temperature field before the ice winter.

3.3 Regression equations

A necessary condition for putting up a regression equation is a stable correlation coefficient over the whole time. Fig. 8 shows the Spearman rank correlation coefficient between annual maximum extent of ice cover in the Baltic Sea and zonal index as well as air temperature time series as a function of period.

The correlation coefficients are always highly significant (99 % significance level), but the correlation coefficient with the zonal index is unstable, whereas the correlation coefficient with the temperature is stable.

Fig. 9 shows the close relationship between the zonal index respectively the mean temperature from November to March of the 10° grid box 55-65° N, 20-30° E and the annual maximum extent of ice cover in the Baltic Sea.

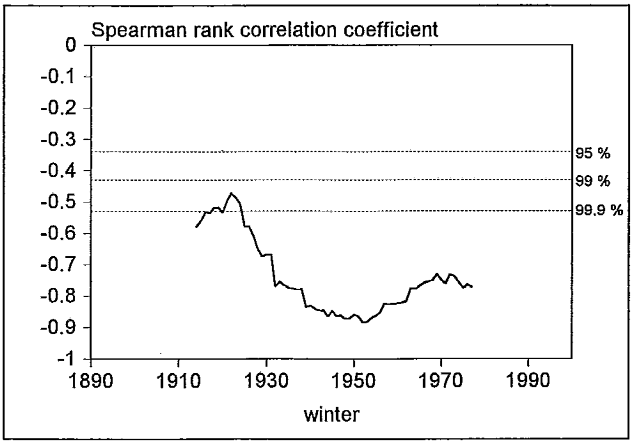

Fig. 8a. Zonal index (1914-1978).

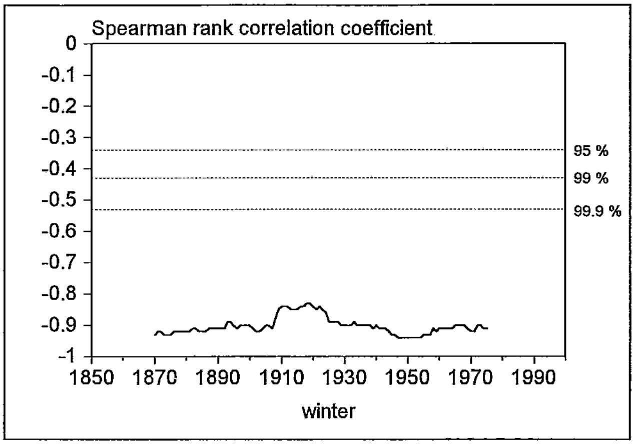

Fig. 8b. Temperature (1870-1975).

Fig. 8. Spearman rank correlation coefficients between the annual maximum extent of ice cover in the Baltic Sea and the difference of mean sea level pressure of January/February between the gridpoints (35° N, 10° W) and (70° N, 10° E) in hPa as well as the mean temperature from November to March of the 10° gridpoint area (55-65° N, 20-30° E) in °C calculated by the gradual shifting of a 31-year-old interval (1914-1978). Several significance levels are drawn up on the right axis of ordinates.

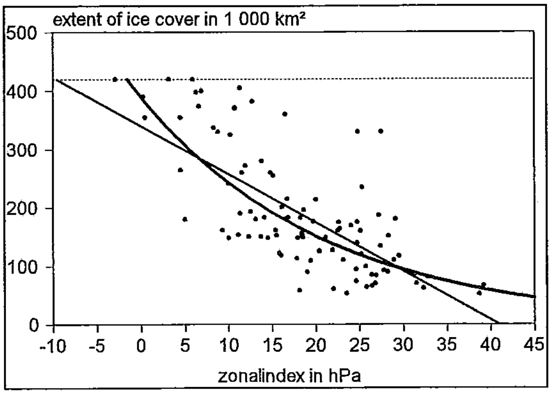

Fig. 9a. Zonal index (1899-1993).

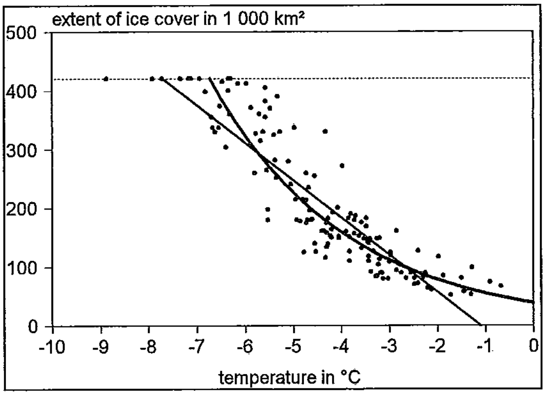

Fig 9b. Temperature (1855-1990).

Fig. 9. Annual maximum extent of ice cover in the Baltic Sea in km² as a function of the difference of the mean sea level pressure difference of January/February between the gridpoints (35° N, 10° W) and (70° N, 10° E) as well as the mean temperature from November to March of the 10° gridpoint area (55-65° N, 20-30° E) and linear and exponential regression model.

Different linear and curvilinear regression models were tested. For extents of ice cover between 100 000 and 300 000 km² the linear regression model shows a good fit. But an exponential model with the temperature as predictor (Eq. (1)) led to the best results (Table 3):

$$A_{Ice} = e^{(10{,}57 - 0{,}354 * T_{Nov\text{-}Mar})}, \quad (1)$$

with the side condition:

$A_{Ice} = 420\ 000\ \text{km}^2 \Leftrightarrow T_{Nov\text{-}Mar} < -6.71\ °C$, with:

- A_{Ice} - annual maximum extent of ice cover in the Baltic Sea in km²,
- $T_{Nov\text{-}Mar}$ - mean temperature from November to March of the 10° grid area (55-65° N, 20-30° E) in °C.

The side condition is valid because of the limited area of the Baltic Sea of 420 000 km². Smaller extent of ice covers especially, at temperatures above -2 °C can be better estimated in the exponential model because there is no unrealistic zero at -1.1 °C as in the linear model. The exponential regression model can describe the curvilinear process of ice growth and the bimodal distribution of the ice time series. Consequently, it explains 86 % of the variance, whereas the linear model can only explain 70 % of the variance.

Table 3. Root mean square error and variance explained by the tested statistical models.

statistical parameter	zonal index		temperature	
	linear model	exponential model	linear model	exponential model
root mean square error	81 000 km²	85 000 km²	46 000 km²	45 000 km²
variance	52 %	54 %	70 %	86 %

The data set has been split up to test the exponential model with the mean temperature from November to March of the 10° gridpoint area (55-65° N, 20-30° E). Then the extent of ice cover of the even years (1856, 1858, ..., 1990) has been computed with the help of the regression equation of the uneven years (1855, 1857, ..., 1989) and the temperature of the even years (Fig. 10).

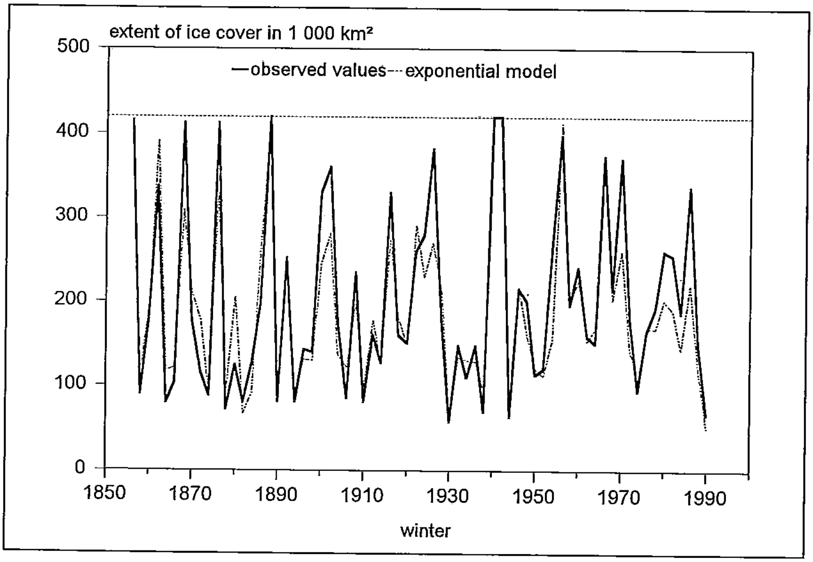

Fig. 10. Annual maximum extent of ice cover in the Baltic Sea: values observed and estimated by the exponential regression model, drawn up with the mean temperature from November to March of the 10° gridpoint area (winter 1856, 1858, ..., 1990).

The values of the extent of ice cover, computed by the exponential regression model, are a good estimate for the observed values.

4. *Typical sea level pressure and air temperature field in extremely mild and extremely severe ice winters*

The mean sea level pressure field in January/February is dominated by the Icelandic depression and the high pressure area over the Azores (Fig. 11). The Baltic Sea is situated between these pressure areas resulting in a WSW air current. A high pressure area over East Europe and Asia has no direct impact on the Baltic Sea area.

The temperature field is closely linked with the sea level pressure field. That is why a temperature gradient from northeast to southwest over Europe can be found in winter (Fig. 12). The mean temperature from November to March over the Baltic Sea is between 2 °C at the German and Danish coast and -6 °C at the Northern Gulf of Bothnia. Temperature anomalies over the Baltic water body in summer and winter, which are shown in observations (*DHI*[2], 1978), cannot be reproduced by the gridpoint data set.

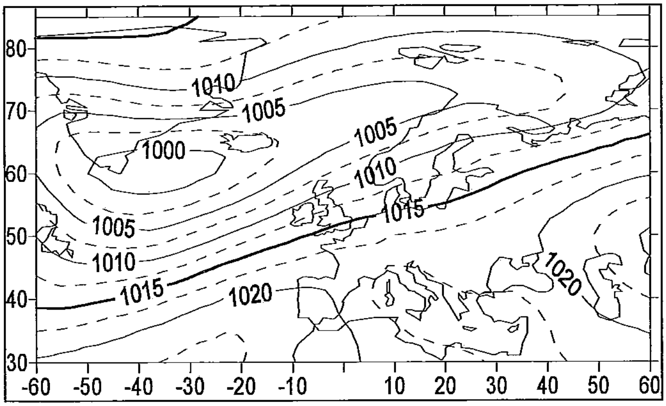

Fig. 11. Mean sea level pressure in hPa of January/February (1899-1993).

Ice winter types are related to typical sea level pressure and air temperature fields. The mean sea level pressure field in the extremely severe ice winters is dominated by the shift to the southwest of the Icelandic depression and its weakening as well as the increase in high pressure over East Europe (Fig. 13). The Baltic Sea area is below a weak atmospheric pressure gradient. The pressure anomalies vary between -4 hPa from the Western Mediterranean Sea to Labrador and 10 hPa over the Norwegian Sea (Fig. 15).

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[2] Deutsches Hydrographisches Institut, Hamburg

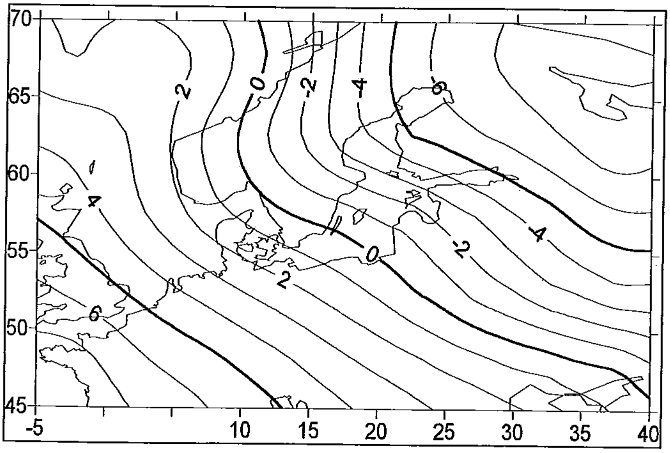

Fig. 12. Mean temperature from November to March in °C (1961-1990).

The sea level pressure distribution in extremely mild ice winters is similar to the mean field, but with a stronger gradient and an increased zonal circulation (Fig. 14). The Baltic Sea is situated on the warm side of the frontal zone. This pressure distribution shows anomalies to the mean field between -8 hPa at the Greenland Sea and 4 hPa at the Ligurian Sea (Fig. 16).

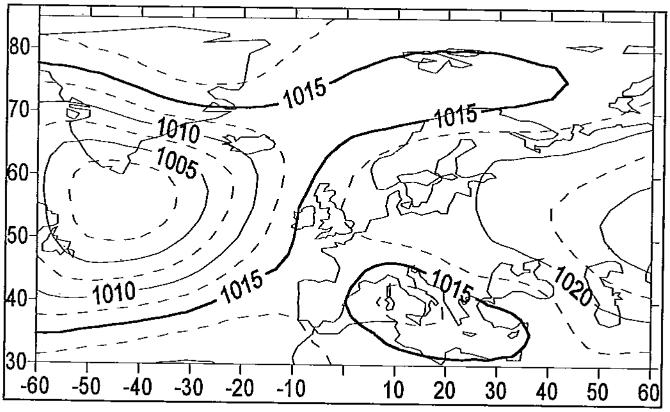

Fig. 13. Mean sea level pressure in hPa of January/February of the 7 extremely severe ice winters (1899-1993).

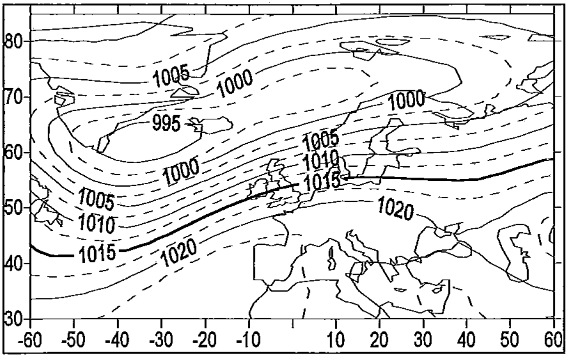

Fig. 14. Mean sea level pressure in hPa of January/February of the 12 extremely mild ice winters (1899-1993).

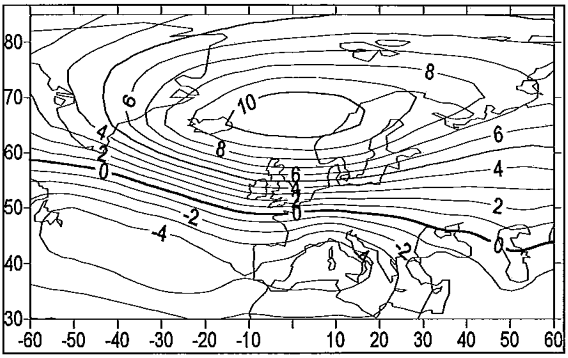

Fig. 15. Anomalies of mean sea level pressure in hPa of January/February in the 7 extremely severe ice winters (1899-1993) in comparison to the mean sea level pressure (1899-1993).

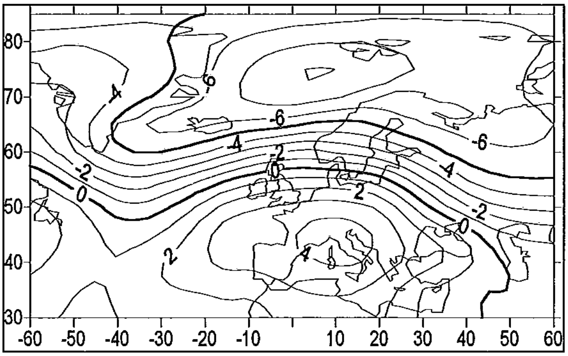

Fig. 16. Anomalies of mean sea level pressure in hPa of January/February in the 12 extremely mild ice winters (1899-1993) in comparison to the mean sea level pressure (1899-1993).

The sea level pressure conditions of the ice winter types have consequences to the temperature field. In extremely severe ice winters the temperature over the Baltic Sea is between -9 °C at the Northern Gulf of Bothnia and 0 °C at the German coast (Fig. 17). The temperature anomalies amount to -3 K and -2 K over the Baltic Sea (Fig. 19). In extremely mild ice winters the temperatures are between -4 °C at Northern Gulf of Bothnia and 3 °C at the German coast (Fig. 18). The temperature anomalies over the Baltic Sea are between 1 K and 2 K (Fig. 20).

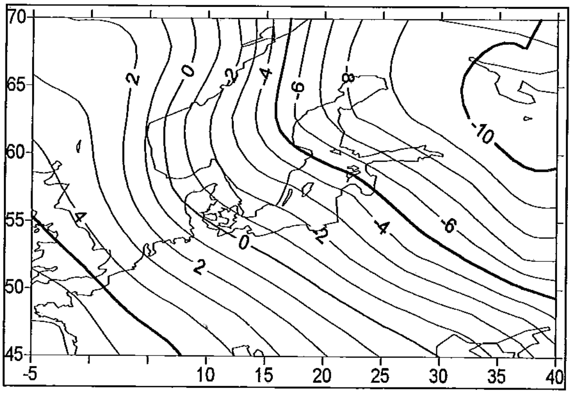

Fig. 17. Mean temperature from November to March in °C of the 16 extremely severe ice winters (1855-1990).

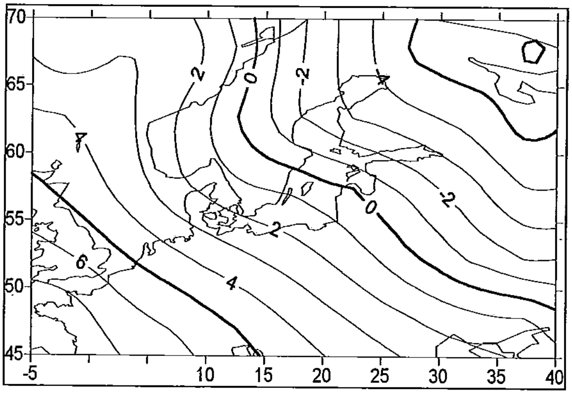

Fig 18. Mean temperature from November to March in °C of the 16 extremely mild ice winters (1855-1990).

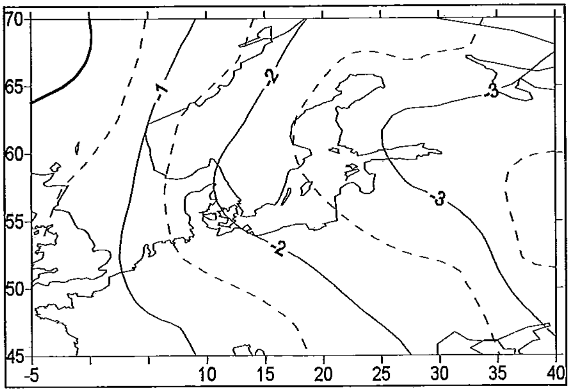

Fig 19. Temperature anomalies from November to March in K of the 16 extremely severe ice winters (1855-1990) in comparison to the mean temperatures (1961-1990).

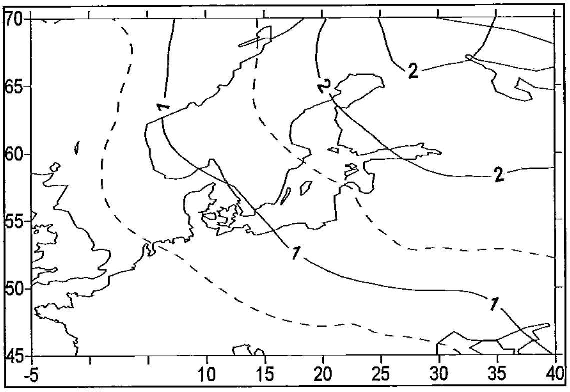

Fig. 20. Temperature anomalies from November to March in K of the 16 extremely mild ice winters (1855-1990) in comparison to the mean temperatures (1961-1990).

In average ice winters there are no significant anomalies of sea level pressure and temperature in the Baltic Sea area with regard to the mean conditions.

5. A possible future development of the annual maximum extent of ice cover in the Baltic Sea

Seinä (1993) gives an estimate of the future development of the annual maximum extent of ice cover in the Baltic Sea. According to his information the number of mild ice winters will increase and, as a consequence, the one of severe ice winters will decrease.

In this investigation a simple downscaling method was used in order to estimate the development of the annual maximum extent of ice cover in the Baltic Sea in the next 100 years. The basic idea of downscaling methods is to deduct regional-scale features or parameters which are either inaccurately or not at all simulated by large scale quantities, calculated by a GCM (*Jacob*, 1993; *Storch et al.*, 1993; *Frey-Buness et al.*, 1995; *Cubasch et al.*, 1996).

The results presented in this investigation have been obtained from the new Max-Planck-Institute for Meteorology, Hamburg (MPI) coupled model ECHAM4_OPYC3 (*Roeckner et al.*, 1996a). The atmospheric part of this model, *ECHAM4 (Roeckner et al.*, 1996b), is the most recent in a series evolving originally from the numerical weather prediction model of the European Centre for Medium Range Weather Forecasts (ECMWF). The oceanic part, OPYC3, is an updated version of the isopycnal general circulation model developed by *Oberhuber* (1993). The coupled model has a relatively high horizontal resolution of T42, corresponding to a Gaussian grid of about 2.8 degree in longitude and latitude. An annual mean flux correction of heat and freshwater is employed (*Bacher et al.* 1996) which proved sufficiently to prevent the model from drifting to an unrealistic state.

Two long term simulations have been performed with this model (*E. Roeckner*, pers. comm.). In an unforced control experiment the model is run for about 250 years under present-day conditions, i.e., the concentrations of all greenhouse gases (GHGs) are specified according to their 1990 values (*Houghton et al.*, 1990). Moreover, observed sea surface temperatures and atmospheric fluxes for the decade 1980 to 1990 have been used to spin up the ocean model prior to coupling. Hence, the climate simulated in this control experiment should be comparable to modern observations; say, for the decade 1980 to 1990.

In a second experiment, the GHG concentrations (carbon dioxide, methane, nitrous oxide and several CFCs) are allowed to change from 1860 to 1990 as observed and from 1990 to 2100 according to IPCC scenario IS92a (*Houghton et al.*, 1996). The IS92a forcing corresponds to that resulting from an increase in carbon dioxide concentrations of nearly 1 % per year (compounded). This experiment will be referred to as 'GHG scenario' hereinafter. It is important to note that the model is initialized (nominally in the year 1860) with the same oceanic state and atmospheric GHG concentrations as in the control run which actually corresponds to ~1990 conditions. This initial offset is crucial for interpreting the results of the GHG scenario: While climatic trends should be similar to the observed because the GHG forcing is prescribed as observed, the absolute values are expected to differ. For example, the temperatures simulated in the GHG scenario should be systematically higher than observed.

These caveats apply to Fig. 21 which shows a comparison between observed and simulated time series of surface air temperature in the 10° gridpoint area (see caption) for the winter period November to March. The control run shows hardly any drift but indicates a cold model bias of nearly 1 K (compared to the observational record during the last decades). In the GHG scenario, the warming trend during the first part of the simulation (1860 - 1990) is similar to the observed trend. The rapid warming after about 1980 is consistent with the prescribed GHG forcing which increases almost linearly between 1980 and 2100 (not shown).

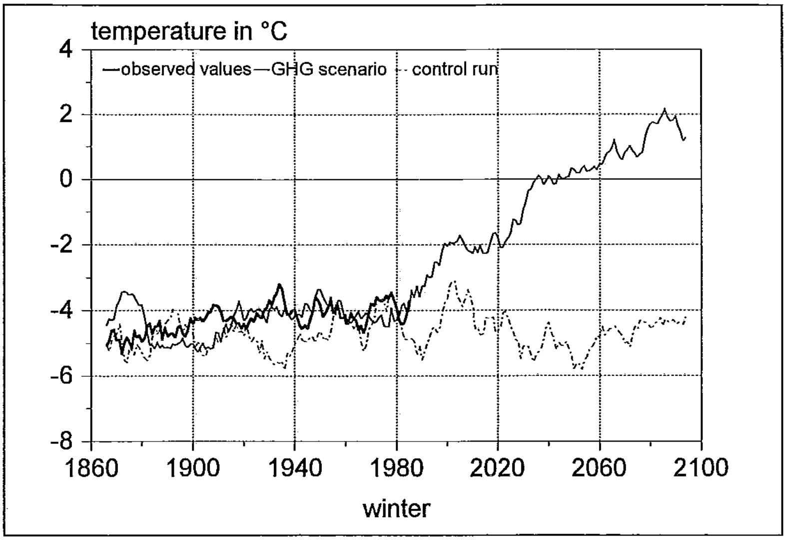

Fig. 21. 11 year moving average temperatures in °C from November to March of the 10° gridpoint area (55-65° N, 20-30° E): observed values (1861-1990), values of the GHG scenario (1861-2099) and values of the control run (first 239 years of simulation).

According to Table 4, the parameters of the distribution such as the mean and the standard deviation are well simulated. However, as explained earlier, the good agreement between the observed means of temperature and sea ice and those simulated in the GHG scenario is partly fortuitous.

Table 4. Statistical parameters of mean temperatures in °C from November to March of the 10° gridpoint area (55-65° N, 20-30° E) and the annual maximum extent of ice cover in the Baltic Sea.

	temperature			ice time series	
statistical parameter	observed values (1861-1990)	GHG scenario (1861-1990)	control run (first 130 years)	observed values (1861-1990)	IS92a scenario (1861-1990)
number	130 years	130 years	130 years	130 years	130 years
mean	(-4.25±0.28) °C	(-4.27±0.28) °C	(-4.76±0.30) °C	(203 000±20 000) km^2	(200 000±17 000) km^2
minimum	-8.8 °C	-8.0 °C	-8.7 °C	52 000 km^2	34 000 km^2
maximum	-0.7 °C	0.4 °C	0.6 °C	420 000 km^2	420 000 km^2
standard deviation	1.6 °C	1.6 °C	1.8 °C	11 000 km^2	10 000 km^2

Then, the annual maximum extent of ice cover of the Baltic Sea of the GHG scenario from 1861 to 1990 was calculated by using the regression equation 1. The statistical distribution of the resulting ice time series is statistically similar to the observed values (Tab. 4). It can be said that the used downscaling method is able to simulate the observed ice conditions in the Baltic Sea.

The calculated future development of the annual maximum extent of ice cover of the Baltic Sea in comparison to observed values is shown in Fig. 22.

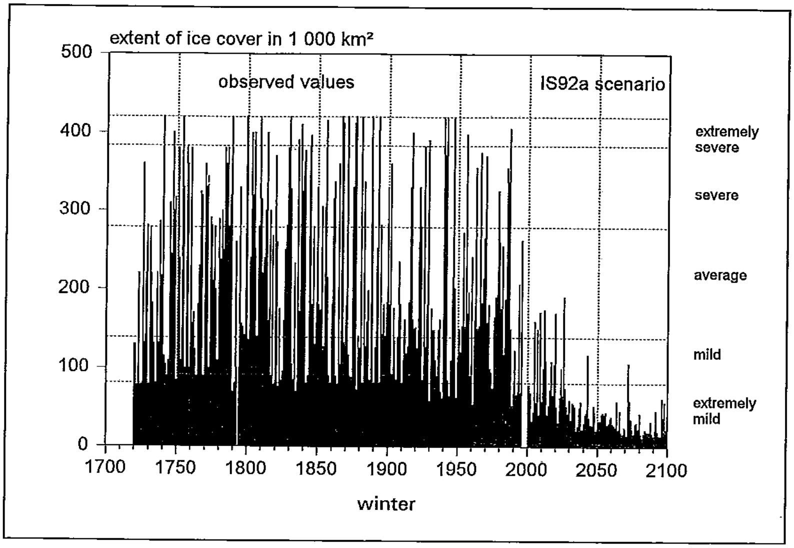

Fig. 22. Annual maximum extent of ice cover in the Baltic Sea: observed values (1720-1996) and values calculated corresponding to IS92a scenario (2001-2099).

According to the model projection, a drastic decrease in the mean extent of ice cover would follow in the next century. Mild and extremely mild ice winters would be dominant, severe and extremely severe ice winters would not occur. Beginning in the 2030's, the majority of ice winters would be milder than the mildest winter which has been observed until today (ice winter 1989).

The model projection according to IS92a should not be confused with a forecast. It is obtained under the very unlikely assumption that the GHG forcing continues to rise at about the current rate while all other external forcings remain unchanged throughout the simulation period.

6. Conclusions

The ice conditions of the Baltic Sea represented by the annual maximum extent of ice cover in the Baltic Sea are closely related to the large scale atmospheric circulation. The areas of maximum correlation between the ice time series and the sea level pressure field coincide with the areas of maximum sea level pressure anomalies in extremely severe as well as in extremely mild ice winters. Temperature anomalies in extremely ice winters concern large areas of Europe, while significant correlation coefficients between ice time series and air temperature field can be found around the Baltic.

A reliable forecast of the annual maximum extent of ice cover in the Baltic Sea using a GCM scenario and a downscaling technique is not possible at present. An estimate of the future trend of the ice conditions shows a drastic decrease in ice in the next 100 years under the assumption that the GHG forcing increases according to the

IPCC scenario IS92a while all the other constituents such as tropospheric and stratospheric aerosols remain unchanged.

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