RECONSTRUCTION OF THE ICE WINTER SEVERITY SINCE 1701 IN THE WESTERN BALTIC

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Abstract. This reconstruction of the ice winter severity in the Western Baltic is based for the period 1878–1993 on the accumulated areal ice volume along the German Baltic coast with observations from 13 coastal stations; for the period 1701-1877 it is based on the accumulated areal ice volume divided into 7 classes (ice winter severity types). The various types of data consulted in the latter case provided ice data of good spatial and temporal resolution.

Speerschneider's compilation of data relating to ice conditions in Danish Baltic waters was found to be a valuable source of information. Using a classification table for the periods 1907–1943 and 1947–1992, five of the seven ice winter types have been derived with certainty as they are characterized by typical stages of maximum ice cover throughout the Western Baltic.

The Gaussian lowpass-filtered time series of the ice winter index numerals with a 20 year cutoff period shows four periods of varying ice winter severity over a secular range:

1701–1720: slightly increased ice winter severity with regard to the mean of the 1701–1993 time series; this period can be assigned to the end of a cooling phase during 'Little Ice Age' which in central Europe peaked in the second half of the 17th c.
1721–1760: ice winter severity is clearly reduced in this period.
1761–1860: ice winter severity is clearly increased (maximum occurs around 1800) towards the end of the 'Little Ice Age', associated with increased variability of ice production.
1861–1993: the present-day ice winter regime when three short intervals with increased ice winter severity (the 1890s, 1940s and 1980s) and a period of greatly reduced ice winter severity (between 1900 and the mid-1920s) stand out.

1. Introduction

Historical climatology has increasingly become a focus of attention over recent years (cf. Wigley *et al.*, 1981; Glaser and Walsh, 1991). The aim of this discipline is to reconstruct the climate of the past. 'Historical' in this context refers to a time before which official and standardized weather observations were made and for which various types of record exist. Climatic processes have been neither constant nor linear; changes both in the short-term and long-term are observed. Historical climatology thus not only provides insights that are relevant to climatological questions but also gives important insights into the historical context itself (see Rotberg and Rabb, 1981). Information is forthcoming about human reactions to changing climate and strategies employed by the people confronted with changed climatic

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conditions. In many cases, historical situations cannot be fully understood without an awareness of the determining environmental factors. To make quantifiable statements, different types of data are used; among the most important are:

1. descriptive records of the weather and climate;
2. so-called proxy data;
3. historical, instrumentally-measured data;

Data sources must be examined critically to avoid error. Each must be identified and its authenticity and reliability checked together with its date and location (see Ingram *et al.* (1981) or Glaser (1991) for details).

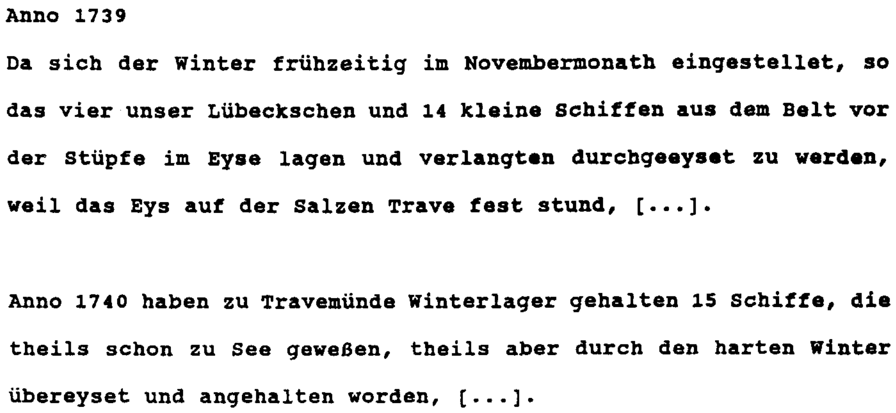
Historical climatologists have relatively seldom considered parameters such as the occurrence of duration of ice for reconstruction purposes – although ice is a meaningful indicator of climatic conditions (cf. Flohn, 1985). The sheer wealth of the historical record demands that greater account should be taken of ice data.

It was often the economic consequences of ice formation that prompted chroniclers to describe the phenomenon. When Dutch canals froze over in the 17th and 18th centuries, shipping was brought to a standstill and merchants were forced to make use of sledges for the onward transport of their goods. The records describing the freezing of Dutch canals are accurate and go far back in time. Van den Dool *et al.* (1978) has parameterized and related them to the long temperature series from De Bilt.

Religious and mystical traditions frequently caused records to be kept. In Japan cracks in frozen Lake Suwa, 'Omiwatari', were honoured as footpaths used by the gods and meticulously recorded in chronicles that today form the basis of long and meaningful historical climatic time series (Yazawa, 1976). In central Europe, too, the freezing of large lakes has always attracted attention (Maurer, 1929; Lemans, 1963; Schmidt, 1967).

Climate reconstructions based on ice parameters are used to determine winter severity; for example Camuffo's (1987) investigation of freezing of the Venetian lagoon, or with Catchpole and Hanuta's (1989) work on ice cover in Hudson Bay, or with Rannie (1983).

This contribution presents methods permitting the reconstruction of ice conditions in the Western Baltic using historical ice data. Ice conditions can be represented by a time series of ice winter severity from which reasonable assertions can be made about long-term variations in ice production since 1701. This paper forms part of a project by the German 'Regional Historical Climatology' working group to reconstruct a transect of climatic conditions from the foothills of the Alps to the North Sea and Baltic Sea coast.



Anno 1739

Da sich der Winter frühzeitig im Novembermonath eingestellet, so das vier unser Lübeckschen und 14 kleine Schiffen aus dem Belt vor der Stüpfe im Eyse lagen und verlangten durchgeeyset zu werden, weil das Eys auf der Salzen Trave fest stund, [...].

Anno 1740 haben zu Travemünde Winterlager gehalten 15 Schiffe, die theils schon zu See geweßen, theils aber durch den harten Winter übereyset und angehalten worden, [...].

Fig. 1. Extract from the 'Eysbuch' (courtesy of City of Lübeck Archives) giving details of part of the river Trave in the winter of 1739/40. The ships were ice-bound throughout the winter right into spring. Ice must have covered the Trave from the beginning of December far into March; an extreme ice winter can therefore be assumed to have occurred.

2. Source Material

This investigation is based on a series of data sources which have been critically examined and assessed. These are:

1. The accumulated areal ice volume data series from the German Baltic coast for the period 1897–1993 (for the coast of Schleswig-Holstein cf. Koslowski, 1989). This time series is based on official observations and measurements of ice;
2. Journal notes from signal stations on the occurrence of ice along the German Baltic coast from 1878–1896. These are the original records of daily observations by trained staff; their value as sources is thus high;
3. Data from 1851–1877 on the occurrence of ice in German Baltic coastal areas; taken from the 'Segel-Handbuch für die Ostsee' (Hydrographisches Amt der Kaiserlichen Marine, 1878);
4. The 'Eysbuch' held in the archives of the city of Lübeck. This contains descriptions of ice conditions on the river Trave between Lübeck and Travemünde for 35 ice winters during the period 1701–1848. The purpose of the entries in the ice book (see e.g. Figure 1) was to calculate the cost of ice-breaking and to act as a record of payment of ice-breaking in the shipping channel. Besides details of the duration of ice cover, some entries also contain observations on the thickness of ice;
5. Records from the minutes of sessions of the Hamburg Senate. The odd record exists from the period 1700–1740, but thereafter until 1824 a nearly complete record exists of the state of ice cover on the river Elbe and other water bodies near Hamburg. The consequences for the city were far-reaching when the

Alster, the port, canals and the river Elbe itself froze over. Besides economic losses, security aspects had to be considered when the city's moats or wells froze over. When this happened, administrative measures were taken such as ordering public employees to form ice-breaking squads, to maintain ice bridges, and to organise fire watches, while the city's brewers were required to maintain a ready supply of warm water for fire-fighting purposes. As all these measures were discussed before the Senate, and had important financial implications, it is assumed that the details are exact;

6. Records of ice cover along the North Sea and Baltic coast from newspaper reports, for instance the shipping news from the *Addreß- und Comtoirnachrichten der Hansestadt Hamburg* after 1774 or the *Wismarsche priviligierten wöchentlichen Anzeigen und Nachrichten.* Because such publications were also intended for use by shipping and the postal service, they may be assumed to contain authentic information;
7. Data from 1701–1860 on the duration of ice cover in Danish Baltic waters, with notes on the ice cover along the German coast in very severe winters (Speerschneider, 1915). This is a compilation by Speerschneider of various original sources. A high level of agreement was found between the original data and Speerschneider's data.
8. The *Spangenberg-Chronik* of the City of Hamburg. Because the original sources of this compilation could not be researched, it was consulted only when other sources were unavailable; the *Stralsunder Chronik,* although written later, contains original quotations.
9. Extracts from the *Historische Klimadatenbank Deutschland* (HISKLID, cf. Glaser and Militzer, 1993) and other material not directly related from various regional archives (Bremen, Hamburg, Lübeck, Wismar, Rostock, Stralsund, Greifswald).

Use was also made of air temperature observations at Schleswig since 1879, Kirchdorf on the island of Poel since 1853, Putbus on the island of Rügen since 1854 and the Berlin mean monthly temperature series since 1701 (with interruptions) (Schlaak, 1982). In addition, data on the annual maximum ice extent in the Baltic Sea from 1720–1951 (Palosuo, 1953) were also considered. The periods covered by the data sources are shown in Figure 2.

In summary, the sources can be said to be very good with respect to their temporal and spatial resolution while the complexity of the various types of data becomes apparent.

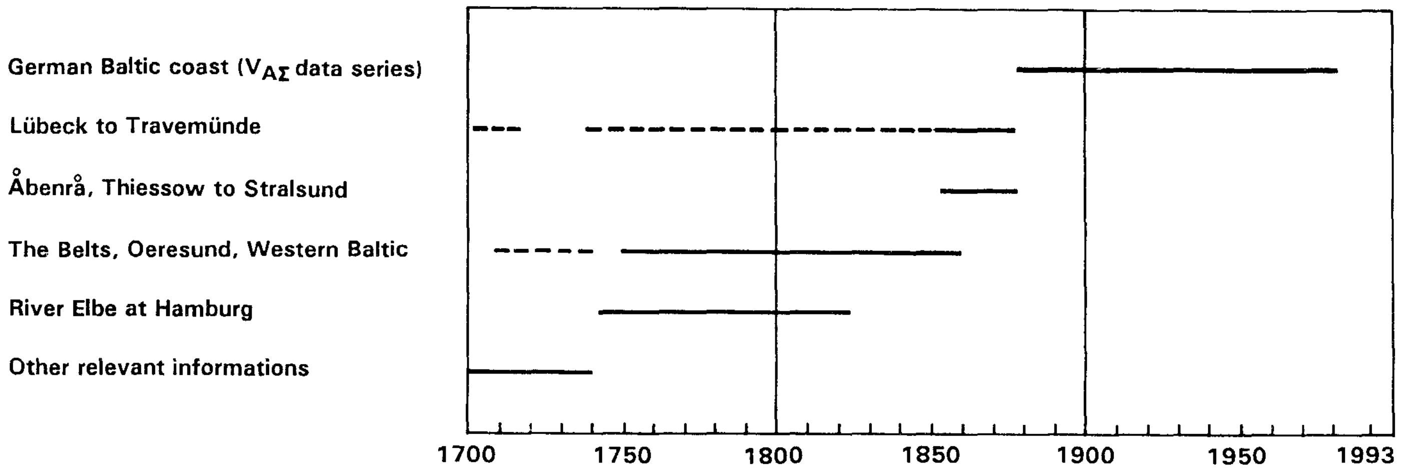


Fig. 2. Span of ice records from Danish and German Baltic coastal waters. The solid lines denote periods with complete data; the dashed lines denote periods with missing data.

3. Data Processing and Classification

3.1. EXTENSION OF THE ACCUMULATED AREAL ICE VOLUME DATA SERIES ($V_{A\Sigma}$) FROM 1878–1896

Data on the duration of ice at only ten of the thirteen stations on which the official 1897–1993 data series are based were gleaned from the diaries of the pilot stations. The gaps in the data from the three missing stations were filled using observations from other stations with similar ice development. It was necessary to use the daily air temperature values at Schleswig, Kirchdorf (island of Poel) and Putbus (island of Rügen) to do so. For the coastal sections of Schleswig-Holstein and Mecklenburg-Vorpommern the data were derived separately from the station average of the number of days of ice occurrence, using a regression formula relating this parameter to $V_{A\Sigma}$ during the period 1940–1987 (for Schleswig-Holstein cf. Koslowski and Loewe, 1994). The $V_{A\Sigma}$ data for the whole German coast from 1878–1896 are based on the average values of the two coastal sections.

3.2. RECONSTRUCTION OF CLASSIFIED $V_{A\Sigma}$ DATA (ICE WINTER SEVERITY TYPES)

For the period from 1851–1877, data on the duration of ice were available from only three stations (Figure 3): the port of Åbenrå, from the river Trave between Lübeck and Travemünde and from the Thiessow channel to Stralsund (Greifswalder Bodden). As three stations are insufficient to determine $V_{A\Sigma}$ values, ice duration data were assigned to classified $V_{A\Sigma}$ values (ice winter severity types) by means of classification tables for the period 1878–1993. These ice winter severity types were derived from the frequency distribution of $V_{A\Sigma}$ in the period 1878–1993 and are defined for the whole German Baltic coast as shown in the first column of Table I.

The reconstruction of the ice winter severity types in the Western Baltic for the period 1701–1850 is mainly based on Speerschneider's data (1915) on the duration of ice occurrence and ice cover in the Belts, the Öresund and the Baltic, in particular around Bornholm. The material includes indications of the ice occurrence for 29 winters beyond the German Baltic coast. Thus almost all very strong and extreme ice winters in that period were recorded. Table I was used to derive the ice winter severity types from Speerschneider's data. The Table contrasts ice winter severity types with the duration of ice occurrence (upper line) and ice cover (lower line) in the Danish sector of the Baltic in the periods 1907–1943 and 1947–1992. Danish ice data were taken from the following original sources: Danske Meteorologiske Institut, Nautisk-Meteorologisk Aarbog (1907–1932), Ministeriet for Søfart og Fiskeri (1934–1936, Statens Isbrydnings- og Ismeldings-tjeneste (1937–1943), Statens Istjeneste (1947–1987), Søfartsstyrelsen (1988–1992). The right-hand column shows the number of winters that corresponded with the ice winter severity types for the German Baltic coast as derived from the frequency

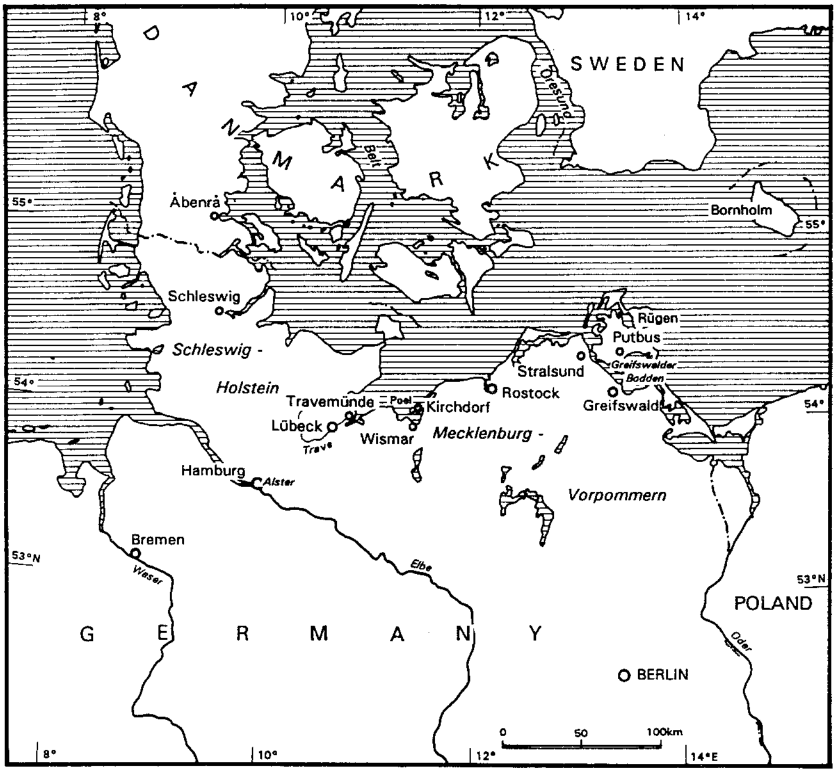


Fig. 3. Map of the Western Baltic showing the locations of the stations used in reconstructing the ice winter severity types for the period from 1701–1877.

distribution of $V_{A\Sigma}$, both as regards the duration of ice occurrence and the duration of ice cover in Danish waters. The figures show that the four strongest types (frequency of 22.9% in the periods 1907–1943 and 1947–1992) are well reflected by the ice data from Danish waters. The weak ice winters (frequency of 38.6%) are reproduced adequately. In the case of the two moderate types (frequency of 38.5%), however, there is no satisfactory agreement. For the period 1850–1701, Speerschneider's data can be expected to be suitable for a reconstruction of the four strongest severity types and the weak type, but less suitable for a reconstruction of both moderate types.

Extracts from the city of Lübeck's 'Eysbuch' are another important source of data. They contain information on the duration and thickness of the ice on the river Trave between Lübeck and Travemünde for 35 winters from 1701 to 1848. Thirty of these winters correspond to ice winter severity types as derived from Speerschneider's data; data from the remaining five winters, together with information from other sources, fill the gaps that exist in Danish material for the period 1701–1749 (Figure 2).

TABLE I

The ice winter severity types at the German Baltic coast compared with the duration of ice occurrence (first row) and ice cover (second row) in the Danish Baltic waters given in days (period 1907–1992, except from 1944 to 1946)

Ice winter severity $V_{A\Sigma}$ in m	Little belt	Great belt	Öresund	Baltic east of Bornholm	Number of winters with correspondence
Extreme > 20	> 70	> 70	> 80	> 20	4 of 4
	> 50	> 25	> 34	> 3	
Very strong	65–72	45–56	44–70	< 35	7 of 7
9.01–20.00	16–49	6–22	8–37	< 16	
Strong$_+$	30–42	38–40	36–44	13–22	3 of 3
6.01–9.00	15–19	13–14	18–20	< 5	
Strong$_-$	31–50	20–35	26–28	0	5 of 5
4.01–6.00	7–18	2–3	7–10		
Moderate$_+$	14–28	10–24	8–26	0	5 of 8
2.01–4.00	< 6	< 7	< 10		
Moderate$_-$	< 5	< 3	< 5	0	13 of 24
0.50–2.00	0	0	< 4		
Weak < 0.50	0	0	< 2	0	27 of 32
	0	0	0		

Other sources include in particular the annual maximum ice extent data series in the Baltic Sea (Palosuo, 1953). A comparison with the ice winter severity types in the period 1878–1992 revealed that the winters with a maximum ice extent $< 81 \cdot 10^3$ km^2 can be assigned to the weak type for the Western Baltic. For winters with larger maximum ice extent values, no clear attribution to ice winter severity types is possible. Six weak ice winters were thus reconstructed for the period 1720–1739; three other winters of this type agree with the results obtained from Speerschneider's data and the 'Eysbuch'. Further data were provided by the storm surges that occurred repeatedly along the German North Sea coast between mid-December and the end of February (HISKLID). They are related to increased zonal atmospheric circulation above the North Atlantic between December and February (strong westerlies); this circulation is responsible for weak ice production (weak ice winter severity type) in the Western Baltic (Koslowski and Loewe, 1994). The data on the occurrence in January of strong westerlies over the British Isles and central Europe is another source of information (Lamb, 1977). Although these data refer only to January, experience shows that only the weak or the moderate$_-$ type is possible.

Based on the available material and the other sources mentioned, it has been possible to reconstruct the ice winter severity types for the whole period from 1701–1993. It may be assumed that the four strongest types and the weak type have been estimated correctly. Because only Speerschneider's data could be used, uncertainty surrounds the determination of both moderate types. This is the case for the seven winters of moderate type between 1701 and 1850. As shown by a comparison with 1907–1943 and 1947–1992, these seven types may have been underestimated rather than overestimated. It cannot be ruled out that some of these winters should be assigned to the next highest type that is moderate$_+$.

3.3. ICE WINTER SEVERITY IN RELATION TO THE MAXIMUM ICE COVER IN THE WESTERN BALTIC

Koslowski (1989) stated that the ice winter severity types resulting from the classification of $V_{A\Sigma}$ (Table I) agree with those types which can be derived from the ice charts of the German Ice Service by considering typical states of maximum ice cover in the Western Baltic. This is demonstrated here using charts of the arithmetical mean ice concentration for the ice severity types moderate$_+$, strong$_-$, strong$_+$ and very strong for the period 1955–1993 (Figure 4). They were obtained by digitizing ice charts constructed for dealing with questions of ice climatology. The charts showing the distribution of the arithmetical mean of the ice thickness are not reproduced here. Figure 4, however, shows typical ice thickness. The extreme ice severity type, only represented by the winter of 1963 in the period 1955–1993, is not shown here as its ice concentration distribution is similar to that of the very strong type; its ice thickness, however, is 40–70 cm. In the case of the moderate$_-$ and weak severity types, sea areas are free of ice while inner coastal waters are covered with ice of varying thickness.

It is remarkable that the arithmetical mean of the ice concentration of the very strong and strong$_+$ ice severity types hardly differs (illustration (a) and (b) in Figure 4). Moreover, there is no great difference between typical ice thicknesses. Far greater differences in both parameters exist between the strong$_+$ and strong$_-$ types, however. A comparison of the individual charts on which these types are based confirms the similarity in the ice concentration distribution between the very strong and strong$_+$ ice winters. Greater differences, however, are to be expected in ice thickness than those shown in illustrations (a) and (b) in Figure 4. The reason for this is that in 1956 – i.e. one of the two strong$_+$ winters on which these calculations are based – ice thickness seems to have been overestimated because of the poor density of observations at sea in some areas.

While the distribution of the ice concentration and ice thickness at the state of maximum ice cover in individual stronger ice winters is typical, great differences exist between the ice winters of moderate$_+$ type. Of the five such winters

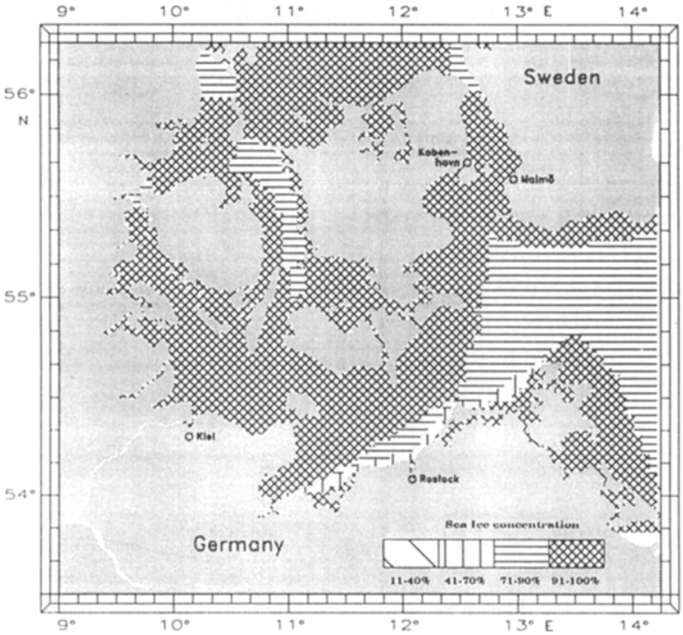
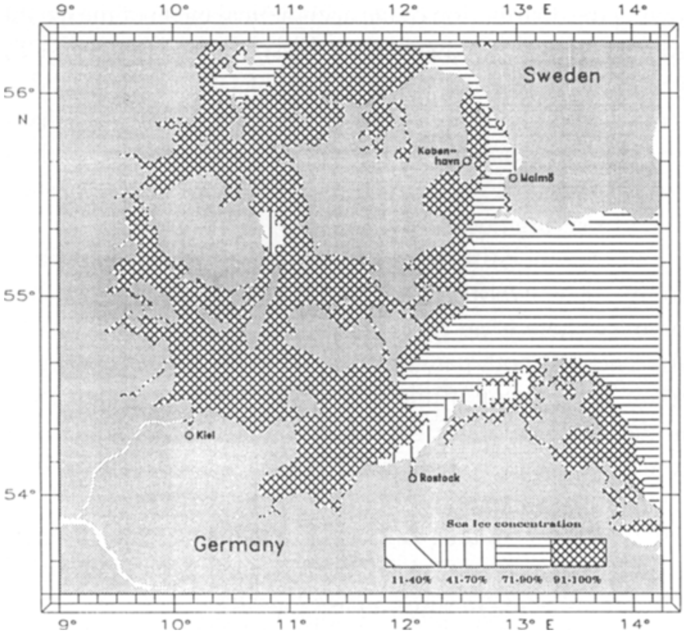

9°
10°
11°
12°
13° E
14°
56° N
55°
54°
Sweden
København
Malmö
Kiel
Rostock
Germany
Sea Ice concentration
11-40%
41-70%
71-90%
91-100%

Fig. 4a.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Sea Ice concentration
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Fig. 4b.

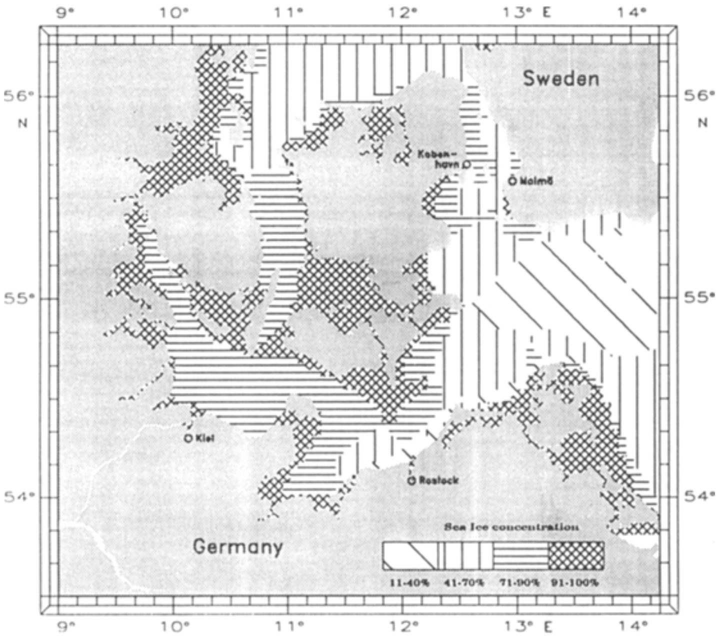

Fig. 4c.

under discussion here, one was almost ice-free at sea; it belongs to those in the periods 1907–1943 and 1947–1992 whose low ice occurrence in Danish waters did not correspond with the severity of ice production in German coastal waters (Table I).

3.4. SIGNIFICANCE OF THE ICE WINTER INDEX NUMERALS

In principle, the six weak to very strong ice winter severity types can be quantified by mid values of $V_{A\Sigma}$ classes in the 1878–1993 time series (the first column in Table I). It must be remembered, however, that individual $V_{A\Sigma}$ values within the classes are not evenly distributed. This is why both the median and the arithmetic mean in the classes is not identical with the mid value. The moderate$_+$, strong$_-$ and strong$_+$ ice winter severity types in the period 1878–1993 each occurred on only seven occasions; the very strong type occurred on ten occasions. It should be noted that the extreme type, which occurred only four times, does not have an upper class limit. For this a ‘guide value’ must suffice here. For a time series analysis, it seems appropriate to introduce ice winter index numerals which are smaller than the corresponding mid values of $V_{A\Sigma}$ classes and which at the same time are directly related to them (Table II). If the index numerals of two adjacent ice winter severity types as given in Table II are compared, their ratio corresponds roughly to that of the relevant mid values of $V_{A\Sigma}$ (e.g. for moderate$_+$/moderate$_-$ the ratio in the ice winter index = 3 and in the mid value of the $V_{A\Sigma}$ = 2.5).

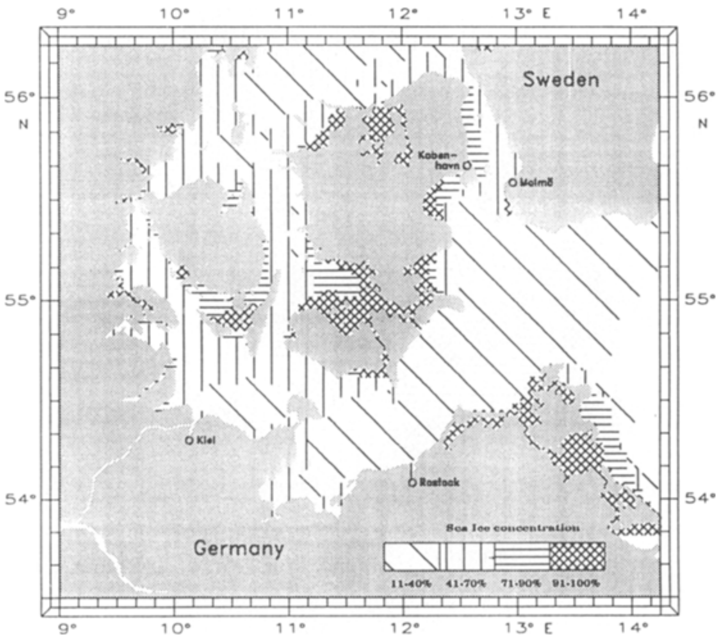

Fig. 4d.

Fig. 4. The sea ice concentration of maximum ice cover in the Western Baltic given in percent for four ice winter severity types (arithmetical mean of the period 1955–1993). (a) Very strong: ice thickness is 20–40 cm; (b) Strong$_+$: ice thickness is mainly 20–40 cm, otherwise 16–19 cm; (c) Strong$_-$: ice thickness is mainly 16–30 cm, otherwise 10–15 cm; (d) Moderate$_+$: ice thickness is mainly < 10 cm.

4. Temporal Variations in the Ice Winter Index Numerals

4.1. GENERAL CHARACTERISTICS

Figure 5 shows the ice winter index numerals of the winters in the period 1701–1993. Some important statistics are: median = 0.100; arithmetic mean = 0.510; standard deviation = ± 0.807; skewness = 1.923; kurtosis = 2.672; variation coefficient = 158.2%.

The arithmetic mean lies in the lower range of the strong ice winters. Its value is far higher than the climatological mean for the period 1901–1960 of 0.385 (the dotted line in Figure 5). The distribution is positively skew as weak and moderate ice winters predominate (frequency of 68.3%) and the strong to extreme ice winter types occur less frequently (31.7%). Both the mean and the variance of the ice winter index numerals are determined by the very strong and extreme ice winters (frequency of 13.3%) which exceed the mean by more than one standard deviation.

TABLE II

Ice winter severity types with their corresponding ice winter index numerals and frequencies

Ice winter severity $V_{A\Sigma}$ in m	Middle of $V_{A\Sigma}$ classes in m	Ice winter index numerals	% Freq. 1701–1993
Extreme > 20	27	3	5.1
Very strong 9.01–20.00	14.5	2	8.2
Strong$_{+}$ 6.01–9.00	7.5	1	8.2
Strong$_{-}$ 4.01–6.00	5.0	0.5	10.2
Moderate$_{+}$ 2.01–4.00	3.0	0.3	11.3
Moderate$_{-}$ 0.50–2.00	1.2	0.1	25.9
Weak < 0.50	0.2	0.0	31.1

It is remarkable that around 1800 two and in the 1940s three of the most severe ice winters on record occurred in succession (for the 1940s event cf. Koslowski and Loewe, 1994).

4.2. VARIATIONS ON THE SECULAR TIME SCALE

In Figure 5 the bold line represents the long-term variations in the ice winter index numerals. This curve was obtained by applying a Gaussian lowpass filter with a 20 year cutoff period to the original series. The course of the curve is determined by the frequency of the strong to extreme ice winter severity types. On the secular time scale, 4 time intervals of different ice winters severity can be identified:

1701–1720: the ice winter severity in the Western Baltic was relatively high in the first two decades of the 18th century which came at the end of a period of severe and very severe meteorological winters during the 17th century (cf. Lamb, 1977, pages 476, 564 and 569) when ice production was certainly greater.

1721–1760: between c. 1720 and c. 1760, there was a clear reduction in ice winter severity. This phase was dominated by weak and moderate ice winters and was similar to the period between 1900 and c. 1940.

1761–1860: around 1760 a long phase of increased ice winter severity began that peaked around 1800 and ended around 1860. If the long-term mean of 0.51 of the 1701–1993 time series is taken as the criterion for its length, the smoothed curve always exceeds this mean value. This long-term interval of increased ice winter

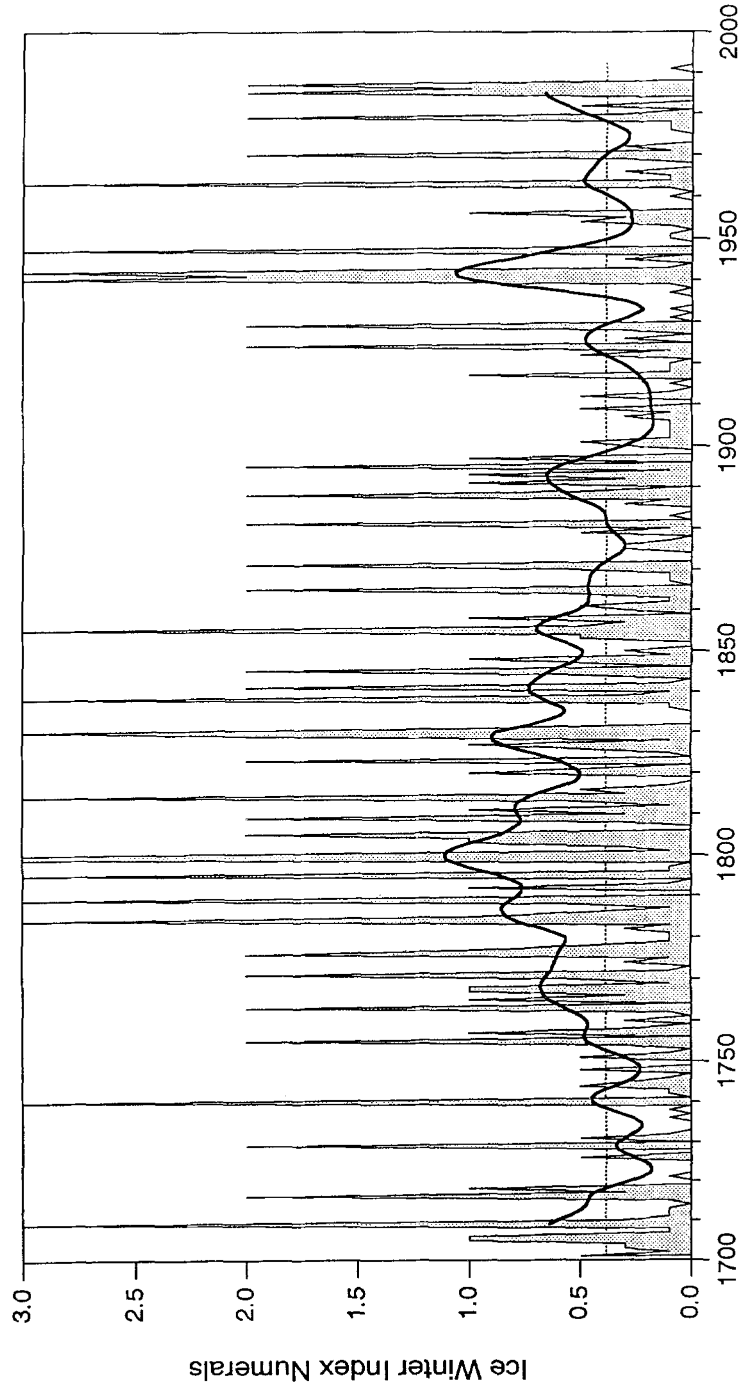

Fig. 5. The ice winter index numerals from 1701 to 1993. The horizontal dotted line denotes the climatological mean of 0.385 for the period 1901–1960. The heavy solid curve represents smothed ice winter index numerals obtained by applying a Gaussian lowpass filter with a 20 year cutoff period.

severity belongs to the last cool phase of the 'Little Ice Age' which is widely felt to have ended in western and central Europe around 1850 (cf. Lamb, 1977; Grove, 1988).

1861–1993: the present ice winter regime has prevailed since the 1860s; since then three short periods with noticeably increased ice winter severity have occurred – the 1890s, 1940s and 1980s, while a somewhat longer period of reduced ice winter severity is apparent between 1900 and the mid-1920s (cf. Koslowski and Loewe, 1994). The 1940s maximum almost reaches the peak value, lying around 1800, of the smoothed curve of the ice winter index numerals between 1701 and 1993.

The results obtained for the ice winter severity in the four periods using the smoothed time series agree with the behaviour of the winter air temperature data series (DJF) from central England (cf. Figure 13.1(a) in Jones and Bradley, 1992) and from Switzerland (cf. Figure 6.4 in Pfister, 1992). The Berlin winter air temperature data series from the period 1760–1780, on the other hand, indicates a higher temperature level (cf. Figure 13.1 (a) in Jones and Bradley, 1992). According to the Berlin series, the phase of increased ice winter severity (third period) would be expected to begin 20 years later than suggested by the smoothed ice data time series. This, however, conflicts with the confirmed phase between 1761 and the end of the 1850s of weakened zonal atmospheric circulation above the northeast North Atlantic that was particularly weak between 1780 and 1820 and which had its absolute minimum around 1800 (cf. Figure 3 in Kington, 1991). This zonal circulation weakness was compensated by a greater frequency of winter blocking patterns with stronger advection of cold air from the north or east depending on the location of the blocking high pressure area. It is known that only these advection patterns cause strong ice production in the Western Baltic (cf. Koslowski and Loewe, 1994). The time of the phase of weak westerlies and its minimum agree with the reconstructed increased ice winter severity as shown by this investigation.

4.3. VARIABILITY OF ICE PRODUCTION

With regard to the intensity of ice production in the Western Baltic, the ice winter severity types may be classed in three groups: the strong$_+$, very strong and extreme types cause strong ice production; the moderate$_+$ and strong$_-$ types cause moderate ice production; and the weak and moderate$_-$ types cause weak ice production. The ratio between the types producing a lot of ice and those that produce only a little ice – namely the strong$_+$ + very strong + extreme/weak + moderate$_-$ types – provides a simple measure of the intensity of ice production during the periods of different length being compared (section 4.2). When ice production is strong, the number of the ice winters of the strong$_+$ + very strong + extreme group increases at the expense of weak + moderate$_-$ types; when ice production is weak, the opposite is true – provided that the moderate$_+$ and strong $_-$ types occur equally frequently. This hypothesis is confirmed in Table III both by the frequencies of the ice winter severity types classed in three groups and the values of the ratio between the types

TABLE III

Ice winter type frequencies, the ratio between winters with strong ice production (column (3)) and those with weak ice production (column (1)) as well as the means and variances of the ice winter index numerals for specific time intervals and the period from 1701 to 1993

Time	Ice winter type frequencies (%)			Ratio col(3)/col(1)	Ice winter index numerals	
	Weak and moderate$_-$ (1)	Moderate$_+$ and strong$_-$ (2)	Strong$_+$ to extreme (3)		Means	Variances
1701–1720	50.0	25.0	25.0	0.50	0.52	0.593
1721–1760	67.5	22.5	10.0	0.15	0.31	0.405
1761–1860	44.0	24.0	32.0	0.73	0.71	0.859
1861–1993	64.6	18.8	16.5	0.26	0.42	0.539
1701–1993	57.0	21.5	21.5	0.38	0.51	0.651

producing a lot of ice and those producing only a little ice. The ratio in the period 1761–1860, characterized by strong ice production, is 0.73 – i.e. five times greater than the ratio of 0.15 for the period 1721–1760 that was characterized by weak ice production. As expected, the present-day ice winter regime from 1861–1993 with a ratio of 0.26 is far weaker than the ratio of the whole period from 1701–1993 (ratio of 0.38), but is much stronger than that for 1721–1760.

The varying intensity of ice production during the four periods is also reflected in the behaviour of the variance of the ice winter index numerals (last column in Table III). The variance from 1761–1860 is twice as great as that from 1721–1760. During the phase of increased ice winter severity, the variability of ice production was far greater than during the previous phase of weakened ice winter severity because the strong$_+$, very strong and extreme ice winter severity types increased greatly at the expense of weak ice winters. Another large increase in variance occurred between 1920 and 1940 (Koslowski and Loewe, 1994). In this case, very strong and extreme ice winters (combined as the very strong group in Figure 4 in Koslowski and Loewe, 1994) as well as weak ice winters have increased since the 1920s, while moderate and strong ice winters have decreased.

5. Discussion

The question of uncertainty when determining ice winter severity types was discussed in detail in section 3.2. It was noted that 7 winters of moderate$_-$ type were perhaps underestimated rather than overestimated because they were determined using only Speerschneider's data which does not permit accurate determination of moderate$_-$ and moderate$_+$ types. Two of these winters fall in the 1701–1720 period characterized by slightly increased ice winter severity. The other five winters belong to the period 1761–1860 (between 1827 and 1850) that is characterized by increased ice winter severity. Even if all 7 winters had been underestimated (the index numerals would increase from 0.1 to 0.3), the slight rise in the smoothed curve of the ice winter index numerals (Figure 5) between 1710 and 1720 as well as between 1820 and 1860 would not influence the variations in ice winter severity on the secular time scale.

It nowadays seems justified to consider ice winter severity in the Western Baltic in the context of winter temperatures between December and February. In numerous central European temperature series covering the 17th/18th centuries, however, March was still viewed as a purely winter month (cf. Figure 21 in Flohn, 1985). While the maximum ice cover this century for the moderate$_+$ to extreme ice winter severity types usually occurred during the last decade of February, in the 17th/18th c. it could be delayed until the second decade in March. Even if ice growth in March was slight due to the higher position of the sun, it is possible that the maximum ice cover lasted longer than today. Caution is therefore required when comparing the ice winter severities of earlier periods with the winter air temperature time series (D J F).

6. Conclusions

Since 1878 the reconstruction of the ice winter severity in the Western Baltic has been based on the accumulated areal ice volume ($V_{A\Sigma}$) along the German Baltic coast; for the period 1701–1877 it is based on the classified accumulated areal ice volume (ice winter severity types). Of the various types of data consulted for the pre-1851 period, Speerschneider's (partly incomplete) data on the duration of ice occurrence and ice cover in the Belts, in the Öresund and in the Western Baltic deserve special mention. Using both these types of ice data from Danish waters, it was possible to reconstruct the four strongest ice winter severity types and the weak type with certainty, because these winter types have typical states of maximum ice cover throughout the Western Baltic. The reconstructed time series of the ice winter severity types is complete and can be regarded as statistically sound.

The Gaussian lowpass-filtered time series of the ice winter index numerals with a 20 year cutoff period indicates temporal variations of ice winter severity. On a secular time scale, 4 periods of different ice winter severity are observed; their length is derived from the mean as the reference value of the 1701–1993 time series.

The present-day ice winter regime has lasted since about 1860. Between about 1760–1860, ice winter severity was much greater with a maximum occurring around 1800. Ice production in the Western Baltic was then three times greater than it is today and even five times greater than that between 1720 and 1760 if the ratio between the number of ice winter severity types producing a lot of ice and the number producing only a little is taken as a measure of the intensity of ice production. Because of their increased ice winter severity, the first two decades of the 18th c. should be assigned to another cooling phase of the 'Little Ice Age' that is believed to have coincided with the Maunder Minimum of sun spot numbers (1645–1715). As this phenomenon is assumed to have occurred in the whole of the northern hemisphere, it seems probable that the ice winter severity in the Western Baltic reflects the cooling phase. It falls to a later investigation to follow up this question in an ice winter severity reconstruction that goes back even further in time.

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