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Sea ice in the Baltic Sea – revisiting BASIS ice, a historical data set covering the period 1960/1961–1978/1979

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BASIS ice data

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Abstract

The Baltic Sea is a seasonally ice-covered, marginal sea, situated in central northern Europe. It is an essential waterway connecting highly industrialised countries. Because ship traffic is intermittently hindered by sea ice, the local weather services have been
5 monitoring sea ice conditions for decades. In the present study we revisit a historical monitoring data set, covering the winters 1960/1961. This data set, dubbed Data Bank for Baltic Sea Ice and Sea Surface Temperatures (BASIS) ice, is based on hand-drawn maps that were collected and then digitised 1981 in a joint project of the Finnish Institute of Marine Research (today Finish Meteorological Institute (FMI)) and the Swedish
10 Meteorological and Hydrological Institute (SMHI). BASIS ice was designed for storage on punch cards and all ice information is encoded by five digits. This makes the data hard to access. Here we present a post-processed product based on the original five-digit code. Specifically, we convert to standard ice quantities (including information on ice types), which we distribute in the current and free Network Common Data
15 Format (NetCDF). Our post-processed data set will help to assess numerical ice models and provide easy-to-access unique historical reference material for sea ice in the Baltic Sea. In addition we provide statistics showcasing the data quality. The website www.baltic-ocean.org hosts the post-prossed data and the conversion code. The data are also archived at the Data Publisher for Earth & Environmental Science PANGEA
20 (doi:10.1594/PANGEA.832353).

1 Introduction

The Baltic Sea is a seasonally ice-covered marginal sea situated in a densely populated and highly industrialised area in northern Europe (Fig. 1). Major shipping routes cross the regularly ice-covered regions. The ice season lasts up to seven months
25 (Vihma and Haapala, 2009) with the maximum ice extent typically reached in late February. Interannual variations are large and range, expressed in terms of ice cover,

between ≈ 10 % and 100 % (e.g. Leppäranta and Myrberg, 2009). The ice can be classified into several types, which obstruct ship traffic to a varying degree: in coastal and archipelagic areas of the Baltic, the dominant ice type is generally (land-)fast-ice, which is solid, even and immobile (apart from very early and very late in the ice season). Further into the basins, as wind fetch increases and the ice cover is repeatedly broken, the ice is forced into motion (Uotila, 2001). Typical conditions there are characterised by an irregular ice coverage comprising floes of variable size, leads (i.e. linear areas of open water) and deformed ice patches (e.g. rafted and ridged ice). Wintertime shipping is challenging in that ships have to find their way through this "drift ice landscape" (Leppäranta and Myrberg, 2009), which can slow down or even stop their progress. Hence, any information on the actual ice state is of benefit to shipping. To this end, it is maybe not surprising that record keeping of sea ice states started as early as more than a thousand years ago (e.g. Ogilvie, 1984). While the information at that time was rather sparse and preserved through oral tradition, the field has, naturally, matured as technology has advanced and traffic has increased.

This paper describes the conversion procedure of a historical ice data set. The original data are based on ice charts from local weather services that were collected and then digitised in 1981 by a joint effort of the Swedish Meteorological and Hydrological Institute (SMHI) and the former Finnish Institute of Marine Research (today Finish Meteorological Institute (FMI)). The original initiative comprised the winters 1963/1964–1978/1979. The winters 1960/1961 and 1961/1962 were added later. The original database was named "Data Bank for **Ba**ltic **S**ea **I**ce and Sea **S**urface Temperatures", abbreviated BASIS. BASIS is a composite of direct ice measurements and estimates from voluntarily observing ships, coast guards, ice breakers, light houses and harbour authorities. Additional information came from overflights operated by FMI, SMHI and the Swedish Air Force (Udin et al., 1981). From the late 60s onwards observations from space became available and were partly included.

A problem related to BASIS is that the underlying ice charts are extrapolated from observations that are irregular as regards space and time. The associated uncertainties

are unclear and are largest when they are at a distance from the major shipping lines. Nevertheless, BASIS is the best available information on historic ice conditions in the Baltic Sea and goes beyond estimates of the historical ice extent (as, e.g., in Omstedt et al., 2004) because it includes unique information on the spatial distribution of ice
5 concentrations, ice thicknesses and, particularly, ice types.

The problem with accessing this data set has been that it was encrypted with a five-digit numerical code, representing the ice conditions in serially numbered grid boxes. Designed for utmost data compression, the encryption rendered storage on cardboard punch cards possible but, at the same time, seriously hindered the accessibility of the
10 data.

This paper describes a post-processing procedure of BASIS developed for utmost accessibility in an age of ever-accelerating storage technology. In the following (Sect. 2), we describe the original data. Section 3 describes the post-processing procedure which necessitated the introduction of ad hoc assumptions. Section 4 presents
15 basic statistical analysis as a means to test the post-processing and bring our product into agreement with previous studies. We close with a summary and download instructions in Sects. 5 and 6, respectively.

2 The original database

The original BASIS ice data set is described in detail by Udin et al. (1981). Both the orig-
20 inal five-digit code and documentation are available at the online portal "Environment Climate Data Sweden" at http://www.smhi.se/ecds. The data there are distributed in the MATLAB® file format containing five-digit coded ice properties for 612 serially numbered grid boxes. The grid boxes are $15'$ in latitude and $30'$ in longitude comprising $\approx 800\,\mathrm{km}^2$ each. They cover Lake Vänern in Sweden and the whole Baltic Sea.
25 The first two digits of the original five-digit code provide information about the dominant ice type, as described in detail in Table 1. Ice thickness, if available, is given by the third digit (Table 2). The fourth and fifth digit describe, if present, the second most

abundant ice type in the respective grid box. If, however, a grid box contains a lead or the ice edge, the third digit does not encode ice thickness but, instead, encodes the fraction of open water in the box (Table 3).

In addition to sea ice properties, sea surface temperature (SST) estimates were also encoded in the original data. According to Udin et al. (1981) all codes containing less than five digits resemble SSTs. However, we were unable to retrieve this information about temperatures because, apparently, the information about the positioning on the punch card has been lost and, hence, leading zeros disappeared.

3 The post-processing

In a first step, we bin the original five-digit coded data on a latitude–longitude, time grid based on metadata provided by Udin et al. (1981) and store it in the current Network Common Data Format (NetCDF) data format (http://www.unidata.ucar.edu/software/netcdf/). All data containing less than five digits were discarded prior to the following analysis because of the leading-zero SST problem (described in the previous section). Subsequently we extract (or derive) the following:

1. pack ice concentration

2. ridged ice concentration

3. fast-ice concentration

4. level ice concentration

5. consolidated ice concentration

6. rafted ice concentration

7. rotten ice concentration

8. belts of slush and shuga

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9. total ice concentration

10. ice thickness.

The unit for (1) to (9) is percentage of ice cover and the unit of (10) is cm. Some of the extractions are straightforward; others are based on assumptions which we explicitly state in the following.

Pack ice and ridged ice concentrations are assigned first, which is straightforward since their concentration is always explicitly expressed in the five-digit code (a convenience which does not apply to all ice types). In a subsequent step, we allocate ice concentrations to all grid boxes at the ice edge and to all grid boxes which contain leads. In those cases, again, concentrations can be assigned without further assumptions since they are directly given by the five-digit code. In the remaining ice interior, away from leads and the ice edge, we base our decryption on the assumption that ice coverage is complete in the presence of fast, level, consolidated, rafted and rotten ice. Without such an assumption percentages could not be assigned. In the following we present a detailed description of respective conversions:

1. Pack ice concentration is originally coded by numbers ranging from 0 to 9, representing the pack ice fraction on a scale of 0 to 1. The five-digit code encrypts ranges with a precision of 0.1. Since we want to assign a representative percentage rather than ranges, we use the respective mean values and subsequently multiply ice fraction with 100 to convert them to percentage values.

2. Ridged ice concentration is coded according to Table 1, resolving the (irregular) intervals 0.1–0.3, 0.4–0.6, 0.7–0.8 and 0.9–1. In those (rare) cases where the original data report "growlers" and "disintegrating" ridges, we set the ridged ice concentration to 0.1. Finally, we multiply it with 100 to convert it to a percentage value.

3.–7. In the presence of leads and at the ice edge, the original code provides open water fraction with a precision of 1/10 (Table 3) and the primary ice type (according to

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Table 1). In this case, we can derive the concentrations of fast, level, consolidated, rafted and rotten ice directly by attributing the entire derived ice concentration to the one dominant ice type. Potential minor occurrence of an additional type might be neglected.

In the absence of leads and away from the ice edge, the original code does not contain information to explicitly derive concentrations of fast, level, consolidated, rafted and rotten ice. In those cases we are restricted to information merely indicating which (maximally two) ice types are most abundant. In order to infer concentrations nevertheless, we introduce ad hoc assumptions: experience suggests, that the ice cover, away from the ice edge and leads, is generally rather complete for fast, level, consolidated, rafted and rotten ice. Hence we assume that the ice coverage here is always 100 % (note that the appearance of belts of slush and shuga is another exceptional case and is described in point 8). If only one primary ice type is given, which does not consist of pack ice or ridged ice, the 100 % are attributed to the primary type. If there is a primary ice type plus a secondary ice type, we assign (ad hoc) 60 % to the primary ice type and 40 % to the secondary ice type, except in those cases where one of the ice types consists of pack ice or ridged ice. In those latter cases we assign the difference between 100 % and the pack or ridged ice concentration to the post-processed data.

8. When the secondary ice type indicates the width of "belts of slush and shuga", the original code provides information about the width but not the length or positioning of the belts. An areal percentage could thus not be computed. Therefore, for the sake of simplicity, we assign a concentration of 10 % for any appearance of shuga (and the primary ice type is determined to 90 %, unless explicitly given) to the post-processed data. Note that shuga does not contribute to the total ice concentration.

9. Total ice concentration is calculated as the sum of the concentrations described above of pack, ridged, fast, level, consolidated, rafted and rotten ice.

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10. Ice thickness is indexed by numbers from 1 to 9 in the original data. We determine the corresponding thickness according to Table 2. A peculiarity is that ice thickness information is intermittently lacking, e.g. in the presence of ice edges or leads. In those cases we assign −9999. Land is marked by -1×10^{34} while zeros denote absence of ice.

4   Basic statistics

Here we show some statistics showcasing the quality of the BASIS data. The time period comprises the winters 1960/1961–1978/1979, a period known to feature high interannual variability, predominantly the effect of some particularly severe winters during the 60s (e.g. Koslowski and Loewe, 1994). Figure 2 confirms the large interannual variability of the basin's ice coverage, which is consistent with previous studies (Leppäranta and Myrberg, 2009): maximum coverage reached during a annual cycle ranges between percentages as low as ≈ 15 up to almost 80 %. Figure 3 features the climatological ice cover during December, January, February and March and, in addition, information on fast-ice and ridges, which is, as far as we know, unique knowledge for the time period under consideration: during December high ice concentrations are restricted to the northernmost Bothnian Bay and the easternmost Gulf of Finland (cf. Fig. 1). The ice builds up further into the season and generally peaks in February, then covering even parts of the Baltic Proper and the Danish Straits. Later in the season the total ice fraction declines but, even so, substantial ridged ice prevails during March in the Bothnian Bay, where it obstructs ship traffic.

The data quality and density of BASIS allows for more elaborate statistics than simply calculating climatological averages. In order to illustrate this, we perform an empirical orthogonal functions (EOF) analysis of the total ice concentration, which captures patterns of major variability. The leading EOF (Fig. 4) explains 60.2 % of the variability of the total ice fraction and thus catches the predominant signal. The analysis of the first principal component (PC, Fig. 4, lower panel) reveals that the major variability in

ice fraction is closely related to changes in the large-scale atmospheric circulation: the leading PC is correlated with 0.66 to the PC-based North Atlantic Oscillation (NAO) index (as applied, e.g., in Hurrell, 1995; Hurrell and Deser, 2009; Löptien and Ruprecht, 2005). This finding is in agreement with previous studies considering the relation be-

5   tween the NAO and ice extent (e.g. Tinz, 1996; Jevrejeva et al., 2003; Koslowski and Loewe, 1994). Note, however, that the relation between the NAO index and the ice extent is nonstationary (Omstedt and Chen, 2001) and consistent; for example, modelling results from Dietze et al. (2014) indicate somewhat stronger correlations in a similar analysis for a later period.

10 When considering the spatial pattern (Fig. 4, upper panel), we find that the leading EOF indicates the largest variations in regions that are often (but not always) ice covered – as is the case in the western part of the Bothnian Bay, the Åland Sea, the north-western Gulf of Finland and the Gulf of Riga. Further north, the amplitude decreases until the leading EOF pattern changes sign at the northernmost tip of the Baltic. Here,

15 it is straightforward to argue that ice concentrations in the Bothnian Bay are always high in winter and thus interannual variability of the ice cover is rather weak. Also, as explained in Löptien et al. (2013), anomalous cold temperatures typically occur in combination with persistent northerly winds which shift the ice further south and trigger the formation of leads.

20 In addition to total ice concentration, BASIS data contain information on the prevailing ice types. Figure 5 shows this by giving a climatological overview (omitting rotten ice because its occurrence is short-lived at the end of the ice season). We find that fast-ice dominates throughout the ice season except for May, when pack ice prevails (Fig. 5a). While the fraction of level ice almost equals the fast-ice fraction in Decem-

25 ber, the relative contribution of level ice decreases strongly throughout the ice season (Fig. 5b). This decrease is plausible because the ice is increasingly forced into motion, breaks up and deforms as the season proceeds.

As concerns interannual variations of the different ice types, we find that they have characteristics that differ substantially from one type to another. For example, fast-ice

is highly correlated with the seasonal basin-average ice cover (0.98) and the typical difference between mild and severe winters in maximum fast-ice coverage is illustrated in Fig. 6. For seasonal mean pack ice and consolidated ice concentrations the correlations with the seasonal basin-average ice cover are lower although still considerable (0.84 and 0.71, resp.). Average ridged ice correlates with a much lower value (0.58, corresponding to only 34 % of explained variance). This is probably related to the impact of local wind effects as explained in Haapala (2000) and Löptien et al. (2013). For rafted ice and the appearance of shuga, correlations with the seasonal mean total ice concentrations are negligible (correlations 0.2 and −0.09).

5 Conclusions

The BASIS ice data set is unique in that it provides comprehensive ice information for the Baltic Sea for the period 1960/1961–1978/1979. However, because the underlying data format was designed for storage on punch cards, its accessibility has always been difficult. This manuscript describes the conversion of the original data to the current and free file format NetCDF. In addition to the original five-digit numerical code, we provide extracted (and derived) prevalent quantities on a latitude–longitude, time grid. Specifically, we provide concentrations of pack ice, ridge ice, fast-ice, level ice, consolidated ice, rotten ice, total ice concentration, ice thickness and a rough indicator of shuga and slush ice. The data set is of value as it sets a reference point in a gradually warming world.

The relevance of the original data and our post-processed product, however, goes beyond that: as the Arctic sea ice declines and waterways such as, e.g., the Northwest Passage become more navigable, the need for sea ice now- and forecasts is increasing. This relates not only to ice concentration and thickness but also to the modeling of ice properties, and in particular ridged ice (such as Funkvist and Kleine, 2007; Haapala, 2000, 2005), because ridges are difficult to break and thus form substantial obstacles. Also, the presence of ridged or deformed ice bears witness to preceding large

ice stresses which can lead to a substantial slowdown and, in the worst case, even cause damage to ships (see, e.g., Suominen and Kujala (2013); Pärn et al. (2007)). Consistently with this, there is a fast-growing body of literature on deformed ice with a major focus on ridges (Haapala, 2000; Kankaanpää, 1988; Lensu, 2003; Leppäranta and Hakala, 1992; Leppäranta et al., 1995; Löptien et al., 2013). We expect that modelling lessons learnt in the Baltic may be applicable elsewhere. To this end, BASIS ice (and the post-processed product presented in this study) may well serve as a unique test bed to assess and develop sea ice models.

6   Data and code repository

The website www.baltic-ocean.org hosts the gridded original five-digit code, the post-processed data and relevant post-processing computer code. The data are provided in NetCDF format. The code is written in MATLAB® (Gilat, 2004). In addition, the post-processed data set is archived at the Data Publisher for Earth & Environmental Science PANGEA, doi:10.1594/PANGAEA.832353.

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Table 1. Ice type allocation according to the original five-digit (C1, C2, . . . C5) BASIS ice punch card coding (Udin et al., 1981). If $9 > C1 > 2$, the primary ice type is coded by C1 and C2 according to this table. If additionally, C4, C5 > 0, a secondary ice type exists and its coding is analogous to C1 and C2 in this table. Ice edge and (generally linear) areas of open water (leads) are coded differently (as described in the text).

Ice type	C1	C2
New ice, level ice	3	0
Rafted ice (< 50 %)	3	1
Rafted ice (> 50 %)	3	2
Fragile spring ice	3	3
Fast ice	3	9
Belts of slush and shuga	4	0–9
Pack ice, small and medium floes, < 1/10	5	0
Pack ice, small and medium floes, 1/10–2/10	5	1
Pack ice, small and medium floes, 2/10–3/10	5	2
Pack ice, small and medium floes, 3/10–4/10	5	3
Pack ice, small and medium floes, 4/10–5/10	5	4
Pack ice, small and medium floes, 5/10–6/10	5	5
Pack ice, small and medium floes, 6/10–7/10	5	6
Pack ice, small and medium floes, 7/10–8/10	5	7
Pack ice, small and medium floes, 8/10–9/10	5	8
Pack ice, small and medium floes, 9/10–10/10	5	9
Pack ice, large floes (> 500 m), < 1/10	5	0
Pack ice, large floes, 1/10–2/10	6	1
Pack ice, large floes, 2/10–3/10	6	2
Pack ice, large floes, 3/10–4/10	6	3
Pack ice, large floes, 4/10–5/10	6	4
Pack ice, large floes, 5/10–6/10	6	5
Pack ice, large floes, 6/10–7/10	6	6
Pack ice, large floes, 7/10–8/10	6	7
Pack ice, large floes, 8/10–9/10	6	8
Pack ice, large floes, 9/10–10/10	6	9
Consolidated ice pack	7	0
Ridged ice, not consolidated 1/10–3/10	8	0
Ridged ice, not consolidated 4/10–6/10	8	1
Ridged ice, not consolidated 7/10–8/10	8	2
Ridged ice, not consolidated 9/10–10/10	8	3
Ridged ice, consolidated 1/10–3/10	8	4
Ridged ice, consolidated 4/10–6/10	8	5
Ridged ice, consolidated 7/10–8/10	8	6
Ridged ice, consolidated 9/10–10/10	8	7
Disintegrating ridges	8	8
Ridged floes, growlers	8	9

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Table 2. Original BASIS ice punch card coding of ice thickness (C3) (Udin et al., 1981). Original thickness bounds and thickness assigned in our post-processed product are listed in columns 2 and 3, respectively. Note, that ice thickness in the presence of leads is not explicitly provided by the original data.

Code (C3)	original bounds [cm]	assigned thickness [cm]
0	missing value	−9999
1	1–2	1.5
2	3–6	4.5
3	7–12	9.5
4	13–20	16.5
5	21–30	25.5
6	31–42	36.5
7	43–56	49.5
8	57–72	64.50
9	> 73	73

Table 3. Original BASIS ice punch card coding of open-water fraction which is given in the presence of leads or at the ice edge (in C3) (Udin et al., 1981). Original open-water fraction and ice concentrations assigned in our post-processed product are listed in columns 2 and 3, respectively.

Code (C3)	original bounds [0–1]	assigned ice concentration [%]
0	0–0.1	95
1	0.1–0.2	85
2	0.2–0.3	75
3	0.3–0.4	65
4	0.4–0.5	55
5	0.5–0.6	45
6	0.6–0.7	35
7	0.7–0.8	25
8	0.8–0.9	15
9	0.9–1	5
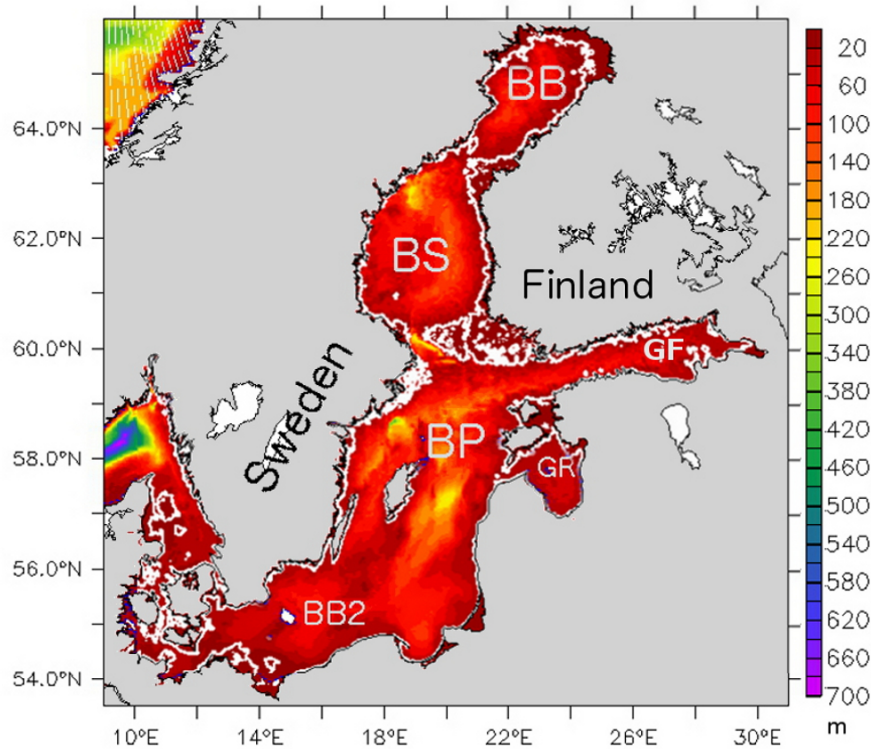
Figure 1. Bathymetry of the Baltic Sea. The colour-coding relates to the unit, i.e. metres. The white line depicts the 10 m isobath. Subbasins are abbreviated as follows: BB = Bothnian Bay; BS = Bothnian Sea; GF = Gulf of Finland; BP = Baltic Proper; GR = Gulf of Riga; BB2 = Bornholm Basin.

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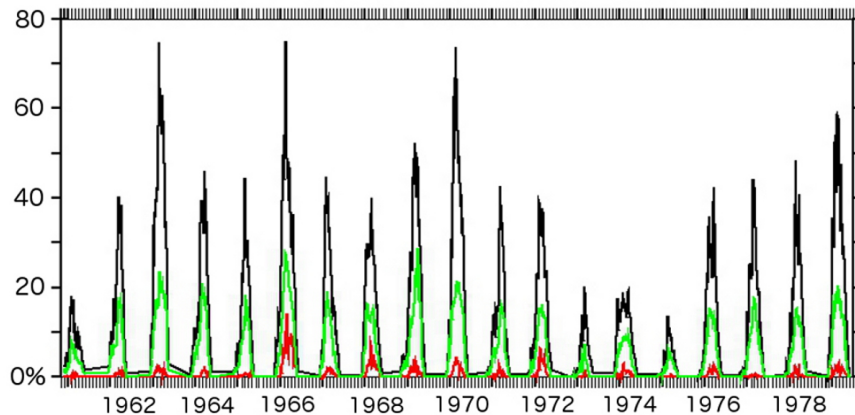
Figure 2. Temporal evolution of basin-averaged ice cover. Total ice cover, deformed ice and fast-ice are denoted by a black, red and green line, respectively.
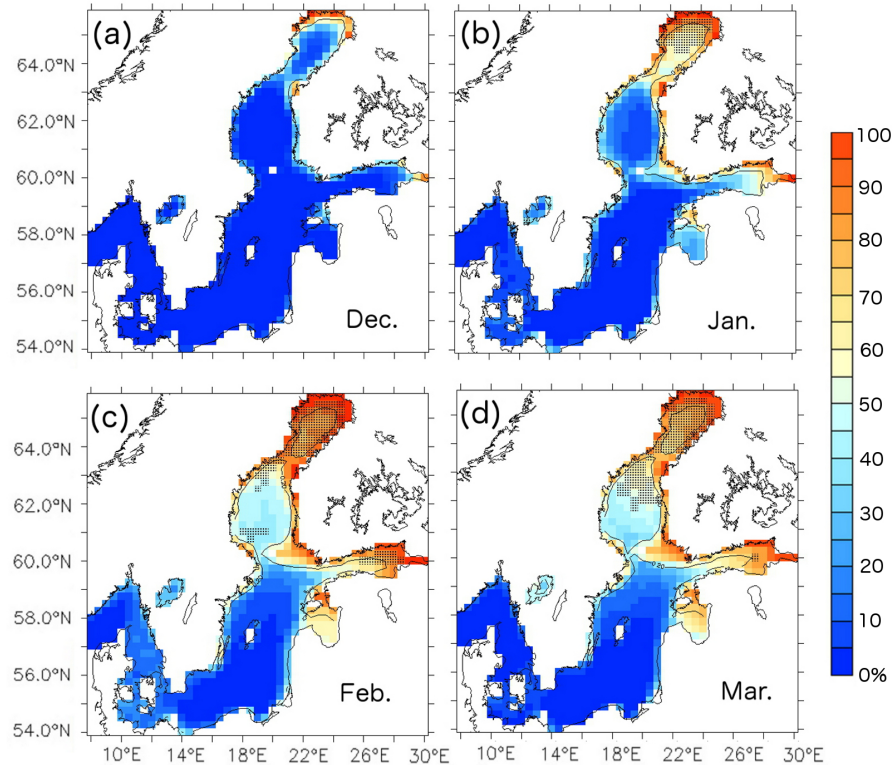
Figure 3. Climatological ice cover for 1960/1961–1978/1979. Panel **(a)**, **(b)**, **(c)** and **(d)** refer to December, January, February and March, respectively. The colour-coding denotes the degree of ice cover. The black line denotes regions where the averaged fast-ice cover exceeds 20 %. The hatched areas indicate more than 5 % of ridges.
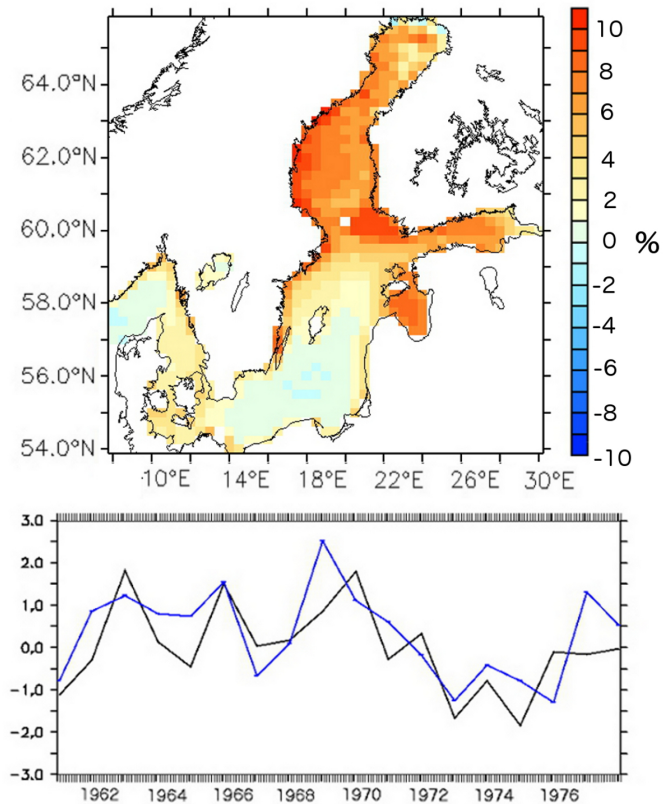
Figure 4. EOF analysis of the total ice concentration. The upper panel shows the leading EOF of the total ice concentration. The lower panel shows the corresponding PC (black line) and the NAO index (blue line; Hurrell, 1995).
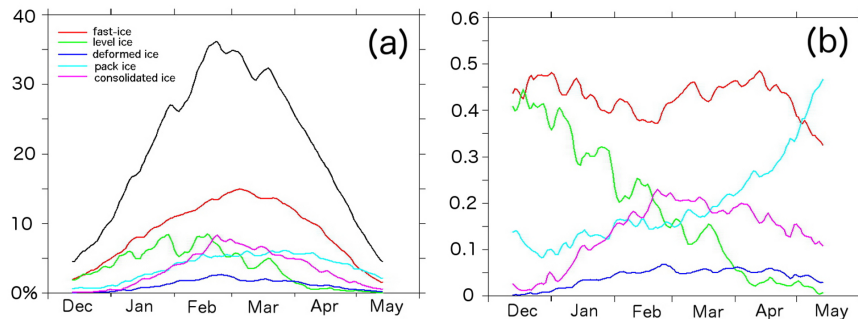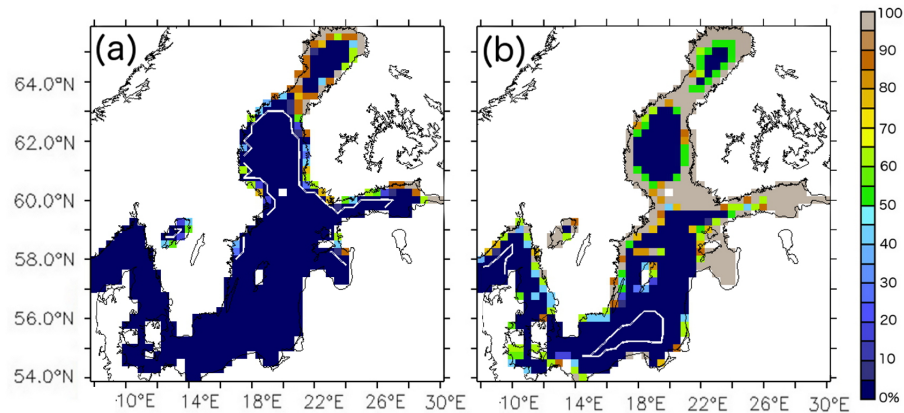
Figure 5. Climatological seasonal ice cycle, weekly resolved, for 1960/1961–1978/1979. **(a)** Basin-averaged cover by different ice types. The total cover is denoted by the black line; ice types as indicated in the legend. **(b)** as in **(a)** but normalised to the total ice cover, which, hence, is omitted.

Figure 6. Fast ice and ice edge in exceptional years: **(a)** the mild winter 1975/1976. **(b)** the exceptionally severe winter 1966/1967. The coloured shading denotes the maximum fast-ice cover occurring in the different years; the white contour line is the corresponding ice edge (here defined as the 1 % isoline of the seasonal maximum total ice concentration).