CLASSIFYING THE ICE SEASONS 1982–2016 USING THE WEIGHTED ICE DAYS NUMBER AS A NEW WINTER SEVERITY CHARACTERISTIC

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Abstract

Sea ice is a key climate factor and it restricts considerably the winter navigation in severe seasons on the Baltic Sea. So determining ice conditions severity and describing ice cover behavior at severe seasons are necessary. The ice seasons severity degree is studied at the years 1982 to 2016. A new integrative characteristic named the weighted ice days number of the season is introduced to determine the ice season severity. The ice concentration data on the Baltic Sea published in the European Copernicus Programme are used to calculate the maximal ice extent and the weighted ice days number of the seasons. Both the ice season severity characteristics are used to classify the winters with respect of severity. The ice seasons 1981/82, 1984/85, 1985/86, 1986/87, 1995/96 and 2002/03 are classified as severe by the weighted ice days number. Only three seasons of this list are severe by both the criteria. We interpret this coincidence as the evidence of enough-during extensive ice cover in these three seasons. In the winter 2010/11 ice cover extended widely for some time, but did not last longer. At 2002/03 and a few other ice seasons the Baltic Sea was ice-covered in moderate extent, but the ice cover stayed long time. For 11 winters (32 % of the period) the relational weighted ice days number differs considerably (>10 %) from the relational maximal ice extent. These winters yield one third of the studied ice seasons. Statistically every 6th winter is severe by the weighted ice days number whereas only statistically every 8th winter is severe by the maximal ice extent on the Baltic. Hence there are more intrinsically severe seasons than the maximal ice extent gives. The maximal ice extent fails to account with the ice cover durability. The weighted ice days number enables to describe the ice cover behavior more representatively. Using the weighted ice days number adds the temporal dimension to the ice season severity study.

Keywords: severity of ice seasons; severity characteristics; winter navigation; Baltic Sea; ice extent; ice days.

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1. Introduction

Sea ice impacts winter navigation on the Baltic. The sea ice varies in form and amount over area and winter season. The shipping on the Baltic Sea embraces important amount of the Baltic countries traffic. Ice-breaking is needed for 3–6 months each winter [1]. When ice conditions in the Baltic Sea are severe, the maritime administrations impose traffic restrictions to certain ports [2].

The severity degree of Baltic ice cover is essential to estimate how seriously the winter navigation is restricted at a particular ice season. Ice season severity is an important factor of climate detection and of its variability. The ice season severity is commonly (HELCOM, European Environment Agency, the ice services) characterized by the maximal ice cover extent at the winter. However the maximal ice extent does not point to all the seasons with severe ice conditions. And this characteristic classifies severe a few seasons when extensive ice cover lasted shortly. So the maximal ice extent does not describe the ice seasons representatively enough as it does not account with the ice cover duration.

For example in 2010/11 ice cover extended maximally at 25th Feb 2011. The maximal extent lasted for 4 days according to the data. Rapid change (more than 15 % in 4 days) preceded and followed the peak. Also a vice versa example is identified [3]. The ice conditions at the winter 2002/03 were hard enough to cause enormous number (98) of vessel damages on the Baltic sea [4]. Then the sum of negative degree days on the Gulf of Finland exceeded twice the average winter value [5]. However this ice season counts only moderate by the maximal ice cover extent.

We identified more such seasons when ice cover stayed longer on a large area but the maximal ice extent did not give value enough to count as severe. The maximal ice extent does not suffice to characterize the ice season severity, as the noted winters and few other winters studied in the present research showed. The example seasons of the present study show that the maximal ice extent does not represent adequately the ice season severity because it does not account with the ice cover lasting time.

A few other definitions are used to determine ice season severity additionally to the maximal ice extent. Both the accumulated areal ice volume [6] and the ice severity index [7] are calculated from the observation stations data. Schmelzer uses the maximal ice extent, the accumulated areal ice volume [8] and the ice severity index [9] to describe ice seasons. Winter severity is described through the time series of ice cover appearance and disappearance dates [10–12].

The ice severity index describes entire ice season, however it provides direct view neither of its specific periods (ice forming, the maximal extent time, breaking up) nor of ice cover behavior trends (extending rate). The accumulated areal ice volume is integrative ice season severity characteristic embracing ice concentration, thickness and ice cover duration. It conceptually precedes to the weighted ice days number of the season.

The ice cover area and duration are taken as ice season severity characteristic properties. In the present study these two properties are assembled in a new season ice severity characteristic. The weighted ice days number of the season is got as each ice day of this season is weighted (multiplied) by the ice concentration on this day and the results are summed over the ice season. This characteristic enables also to consider ice cover behavior at specific periods of the season.

In the present study the Seinä-Palosuo [13] ice season severity criterion is used to classify winters by their relative maximal ice extent (Emax) and the relative weighted ice days number. Here this criterion means that a season when at least 73 % of the Baltic Sea is ice-covered classifies as severe.

The ice seasons severity is studied by both the maximal ice extent and the weighted ice days number in the present research. The remote sensing data on the ice concentration at the Baltic Sea for the seasons 1982–2016 (http://marine.copernicus.eu) are used.

This research had objectives:

– to introduce and use a new characteristic (the weighted ice days number) for ice season severity, to evaluate its validity;

– to identify the severe ice seasons during 1982–2016.

2. Data and methods

2. 1. The basic data and the used quantities

The daily ice concentration values on the Baltic Sea published in the framework of the Copernicus Marine Environment Monitoring Service (CMEMS) are used to calculate the ice cover extents over the Baltic Sea for the ice seasons 1982–2016. They are satellite data from infra-red radiometers for grid resolution 0.03° X 0.03°. The maximal ice extent is determined for each season. The severe ice seasons are determined by the ice cover extent and duration.

There are ice covered and ice-free area on the Baltic Sea. We consider and describe only the ice-covered area. The ice extent is defined as the area of sea with ice concentration at least 10 %. If the ice concentration is less than 10 % then this area is considered as ice-free (open water).

The sea ice extents are calculated on the ice concentration data. All the grid cells with ice presence are summed to get the daily ice extent. Ice is present in the cell if the ice concentration value greater-equals to 10 %.

The seasons are evaluated by the season's relative maximal ice extent and the season's relative weighted ice days number compared to the severity criterion 73 %.

2. 2. The weighted ice days number (WID) of the season

The weighted ice days number of the season accounts with the ice concentration from the ice appearance till the break-up. This characteristic is got weighting each ice day by the ice concentration at this day and summing up weighted ice days over the season.

$$WID = \sum_{t_0}^{n} \sum_{i}^{m} \sum_{j}^{l} d_t \times C_{ijt},$$

where d_t is ice day (d_t =1 day when ice presents). C_{ijt} is the ice concentration weighting the day t in the grid cell (i, j), t_0 is the first ice formation day, n is the length of the season (days). One can calculate this characteristic for a particular station, a wider area, a bay and or whole sea.

The ratios of the values of the maximal ice extent (Emax) and the weighted ice days number at particular season to their superior values within the studied period are taken. The reference season having these superior values is 1986/87, when 97 % of the whole Baltic Sea area was covered by ice. We consider both the weighted ice days number (WID) values and its relative values (RWID).

3. Results

3. 1. Severity classification of the ice seasons

Here the classification results by the season's relative weighted ice days number and by the maximal ice extent for the winters 1981/82 to 2014/15 are presented (**Fig. 1**).

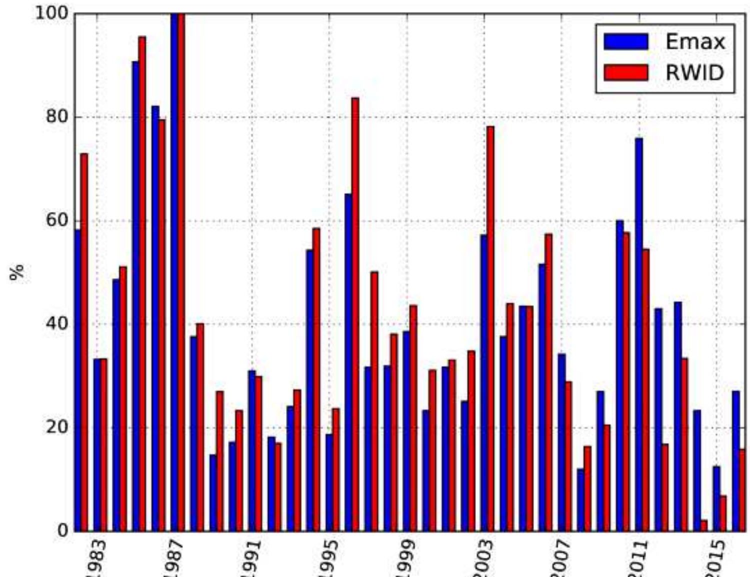

Fig. 1. The relative maximal ice extent (Emax) and
the relative weighted ice days number (RWID) during 1982–2016

The 6 seasons: 1981/82, 1984/85, 1985/86, 1986/87, 1995/96 and 2002/03 are determined as severe by the RWID. Classifying ice seasons by the commonly used maximal ice extent gave 4 winters: 1984/85, 1985/86, 1986/87 and 2010/11. Only the three seasons 1984/85, 1985/86, 1986/87 classified as severe (**Table 1**) by both the measures. The winters consonantly severe by both the criteria (RWID and Emax) had extensive ice cover lasting for a significant time. All these seasons lasted 165 to 190 ice days. Ice cover formed and broke up relatively homogeneously at those seasons. The RWID did not give severity to the season 2010/11. By the maximal ice extent the winters 1981/82, 1995/96, 2002/03 did not count as severe (**Table 1**).

Table 1
The ice seasons classified as severe by both Emax and RWID, only by Emax and only by RWID

Characteristics	Severe seasons
by Emax and RWID	1984/85, 1985/86, 1986/87
only by Emax	2010/11
only by RWID	1981/82, 1995/96, 2002/03

The values of the RWID and the maximal ice extent differ at the ice seasons (**Fig. 1**). To examplify this dissonance, two winters are selected here. The season 2010/11 determined as severe by the maximal extent, but it counted only as moderate by the season weighted ice days number. We compared the ice seasons 2002/03 and 2010/11. To do it, we subtracted the "severe" 2010/11 ice extent values from the values of the "moderate" 2002/03 on the respective dates. **Fig. 2** shows the ice extents of the "moderate" winter generally exceeding the ones of the "severe".

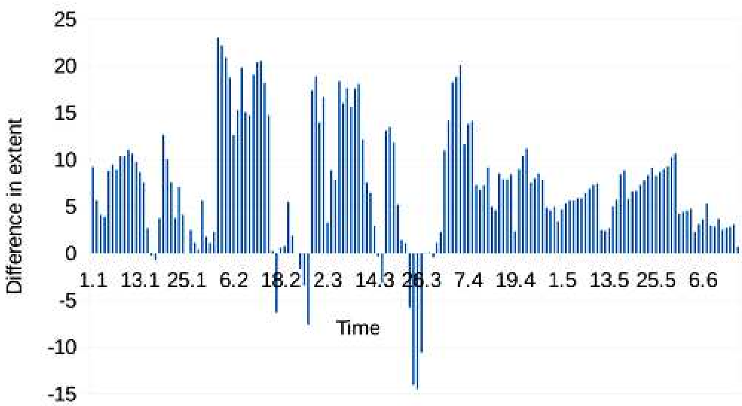

Fig. 2. The ice extents difference for the ice seasons 2003 and 2011. The winter 2010/11 is determined as severe by the maximal ice extent (Emax) whereas 2002/03 is moderate by Emax. However these two seasons classify vice versa (2002/03 as severe and 2010/11 as moderate) by the relative weighted ice days number (RWID)

The ice season 2010/11 lasted for ca 140 ice days. The maximal ice cover extent (74 % of the Baltic) was on the 25th Feb (**Fig. 3**). This extent lasted for 4 days, rapid changes preceded and followed the peak according to the remote sensing data. The Baltic Proper was covered by recently formed nilas at that time [14]. The ice extent decreased soon as the nilas melted. Large sea areas were ice-covered but for a short time. As the season weighted ice days number depends on the ice cover duration, this characteristic did not exceed the severity criterion that winter.

The 2002/03 ice season lasted for ca 190 ice days [15]. The ice cover extended maximally to 62 % on the 5th March (**Fig. 3**) so counting moderate by the maximal ice extent criterion. However the ice cover lasted long on large area then. At most of the ice days of the 2002/03 the ice covered more than on the respective dates of the 2010/11. The authors evaluated this ice season as a severe by the season weighted ice days number.

The results pointed to other severe seasons for which the season relative weighted ice days number exceeded considerably the relative maximal ice extent (RWID>Emax) (**Fig. 1**). This relation between the two severity characteristics pointed to the ice cover lasting for a long time on an extensive sea area. Such tough ice seasons (Table 1) were 1981/82, 1995/96 and 2002/03. All these seasons are long, ca 180 days. However the relative maximal ice extent did not reach the severity criterion (73 % of the Baltic Sea) at these winters.

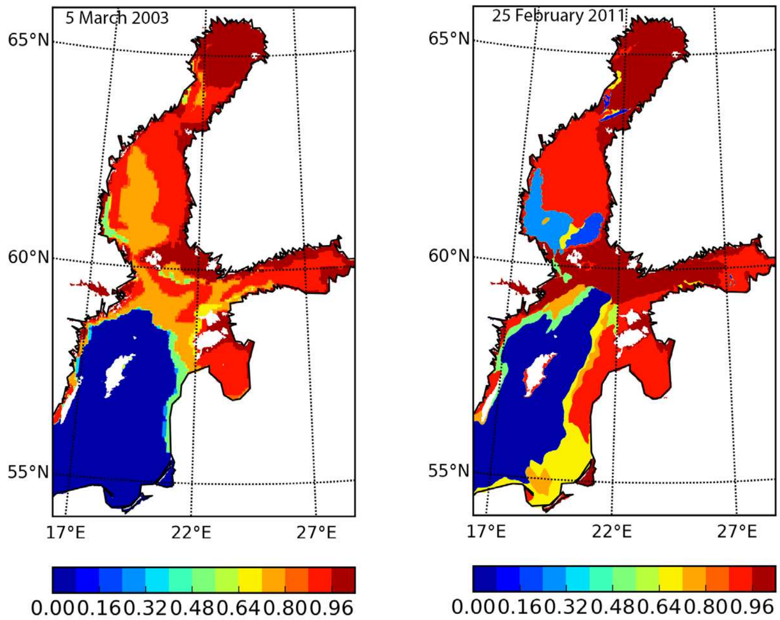

Fig. 3. The ice concentration distributions over the Baltic Sea on the maximal ice extent dates: 5th March 2003 and 25th February 2011. The ice concentration is displayed by the colours

3. 2. Time series analysis

The average values of the relative maximal ice extent and of the season relative weighted ice days number were calculated for the studied ice seasons. The average relative maximal ice extent was 41 % and the average season relative weighted ice days number was 42 %. The sample period was divided to three sub-periods (**Table 2**). The seasons with the relative characteristic values (**Fig. 1**) greater than the averages and less than averages were determined in the scope of each sub-period. The relative maximal ice extent and the season relative weighted ice days number related vice versa to the average at 4 seasons.

Table 2

Ice seasons distribution with respect of the averages Emax and RWID. The values were compared to their respective averages

Time period	Greater (>) or less (<) than average		Controversial winters
A: 1982–1992	>	1982, 1984, 1985, 1986, 1987	–
–	<	1983, 1988, 1989, 1990, 1991, 1992	–
B: 1993–2004	>	1994, 1996, 2003	–
–			1999, 2004
–	<	1993, 1995, 1997, 1998, 2000, 2001, 2002	–
C: 2005–2015	>	2005,2006, 2010, 2011	–
–		–	2012, 2013
–	<	2007, 2008, 2009, 2014, 2015	–

The A sub-period included 5 seasons with both the characteristic values over the averages, 3 such seasons belonged to the B and 4 to the C (**Table 2**). So the A sub-period contained the largest number of the colder ice seasons with the characteristic values over the averages. The least of them belonged to the B. There was no changing trend in the colder winters at these sub-periods.

Both the B and the C included two controversial seasons for which the maximal ice extent and the season relative weighted ice days number related vice versa to the averages (**Table 2**). Both 1998/99 and 2003/04 of the B had the season relative weighted ice days number greater than the relative maximal ice extent. This order of the characteristic values points that the ice season lasts enough but has lack of the days colder than the average air temperature.

The RWID<Emax for 2011/12 and 2012/13 of the C sub-period. This pointed that the season contained a few days colder than the average air temperature causing the ice to extend for some time but the extreme cold lasted shortly so the extensive ice cover did not stay. The C sub-period comprised 7 such winters with extensive ice cover lasting but shortly.

This property of the ice seasons at the last sub-period of the studied time scope characterizes the trend in the Baltic ice climate toward an extensive but short–lasting ice cover.

3. 3. Sum of freezing degree-days

The sum of freezing degree-days indicates the winter severity and correlates to the thermodynamic ice thickness growth. It is got summing negative degree-days under the melting point in a period. This index tells how cold it has been for how long at the winter season. It is calculated from the mean daily air temperature values.

The sums of freezing degree-days (**Fig. 4**) were calculated for three locations: The Bothnian Bay (GoB) near Oulu (65°N; 25°E), the Gulf of Finland (GoF) near Saint Petersburg (60°N; 30°E) and the Baltic Proper (BP) (55°N; 20°E).

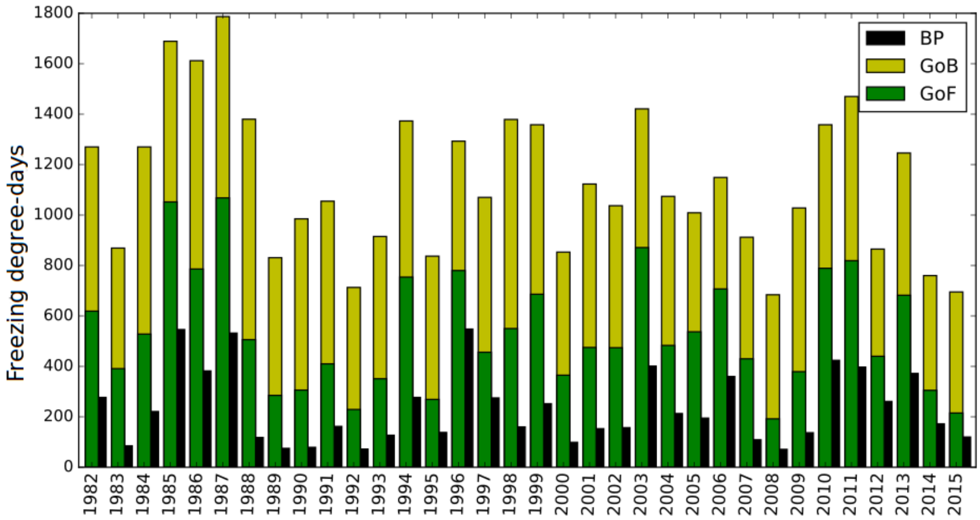

Fig. 4. The sum of freezing degree-days at the 3 locations for 1981–2015.
The daily air temperature data of the NCEP/NCAR Reanalysis are used

The coldest winters with respect of the three locations were ordered ranking by the freezing degree days sum. They were 1986/87, 1984/85, 1985/86, 2002/03, 2010/11 and 1995/96. The first three of this list were ice-severe by both the season weighted ice days number and the maximal ice extent. The 1995/96 and the 2002/03 classified as severe by the season weighted ice days number and not by the maximal ice extent. The 2010/11 classified as severe only by the maximal ice extent.

4. Conclusion

The daily ice extent values are calculated from the ice concentration data for the ice seasons 1981/82 to 2015/16. The maximal ice extent (Emax) was determined for each winter. Also a new ice season characteristic was introduced and its values were calculated for the same seasons. This characteristic is the season weighted ice days number (WID).

The studied winters were classified according to the maximal ice extent and the weighted ice days number. The seasons 1981/82, 1984/85, 1985/86, 1986/87, 1995/96 and 2002/03 were severe by the weighted ice days number. Therefore statistically every 6th winter was severe on the Baltic. There were 4 severe ice seasons by maximal ice extent thus statistically ca every 8th winter is severe. The RWID deviated significantly (>10 %) from the maximal ice extent at 11 ice seasons (ca 32 % of the studied seasons). Hence there are more intrinsically severe seasons than the maximal ice extent gives.

The suitability of two characteristics to specify the ice season severity apart and jointly was evaluated in the present study. The severe ice seasons were divided into three types:

– unambiguously severe – both the characteristics exceed the severity criterion (RWID>73 % and Emax>73 %): 1984/85, 1985/86 and 1986/87 – the three successive winters;

– lasting ice cover – the RWID exceeds the severity criterion (RWID>73 %), but the maximal ice extent does not (Emax<73 %): 1981/82, 1995/96 and 2002/03;

– unstable ice cover – the RWID stays under the severity criterion (RWID<73 %), but the maximal ice extent exceeds it (Emax>73 %): 2010/11.

The studied severity time series pointed that winters are changing more uncertain. For the final part of the studied period, 9 winters had the Emax > RWID and only the 2007/08 had vice versa. This relation of the basic characteristics means that the season near-maximum ice extent lasted for short time. This trend offers subject for a proper study.

5. Discussion

Ice season severity is necessary to determine because ice restricts and endangers navigation. Several characteristics to evaluate ice season severity are defined and a few procedures to obtain these quantities are developed. The ice days number, the maximal ice extent, the ice forming and breaking dates, ice severity indices and the accumulated areal ice volume have been used. Different characteristics enable to describe various aspects of winters nature and changes in their properties.

We respect the maximal ice extent for its simplicity to use. This characteristic enables to reconstruct the time series for the past and to predict on the latent characteristics. It lacks the facility to distinguish a longer lasting ice cover from a shorter. The ice extent includes a new-ice fraction. This fraction covers an extensive area at several seasons. This part of ice cover can rapidly break up contributing to the ice extent variability. If the ice season severity is determined by the maximal ice extent then we get incorrect view of these seasons.

Using the season weighted ice days number together with the maximal ice extent enables to describe the ice season severity more adequately because the RWID accounts with both the ice cover area and duration. Determining ice seasons severity using both the maximal ice extent and the season weighted ice days number enables to classify winters more comprehensively as both the spatial and temporal properties of ice cover are properly considered. Studying the relations between these characteristics can provide diverse description of the ice cover behavior at the season and gives a facility to compare seasons by their properties. Analyzing the time series of the weighted ice days number and the maximal ice extent together enables to determine trends of ice cover properties as a climatic factor.

The weighted ice days number filters out the short–time ice phenomena. This characteristic enables to compare seas, their basins or particular locations. The accumulated areal ice volume is also a two-dimensional ice season severity index. It counts with ice phenomena around the stations. This characteristic inspired to develop an ice season severity index embracing the advantages of the accumulated areal ice volume, the season maximal ice extent and the ice days number.

The weighted ice days number is just such ice season severity index. It is got weighting ice days by the ice concentration on the respective date and then summing up the weighted ice days over the season. It is characteristically similar to the ice days number. It enables to simply determine the ice severity either in a specific location, basin or sea area. The ice severity either of different seasons or of different areas is easy to compare using the weighted ice days number.

Acknowledgement

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