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ORIGINAL RESEARCH ARTICLE

Regime shift in sea-ice characteristics and impact on the spring bloom in the Baltic Sea

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Abstract We evaluated the temporal and spatial trends of the hydrological (temperature and sea ice) and biochemical (chlorophyll-a concentration) characteristics in springtime in the Baltic Sea. Both are strongly affected by climate change, resulting in a decrease in the duration of sea-ice melting in the previous decade. A new regime of sea ice began in 2008 and in all basins of the Baltic Sea, a rapid warming during spring could be detected. Using satellite data, the temporal and spatial variations in spring bloom were analysed during severe and warmer winters. Using a coupled hydrodynamic-biogeochemical model, we tested the response of spring bloom to the changing ice conditions. The results of the modelling indicated that the presence of ice significantly influences the predicted chlorophyll-a concentration values in the Baltic Sea. Therefore, it is necessary that any coupled model system has a realistic ice model to ensure the best simulation results for the lower trophic food web as well.

1. Introduction

The Baltic Sea is a semi-enclosed, brackish regional sea with a unique large-scale gradient from temperate marine to subarctic climate. Located in Northern Europe, the Baltic Sea is seasonally covered with ice (Leppäranta and Myrberg, 2009). Its ecosystem is dominated by a strong salinity gradient (Zettler et al., 2014) and is simultaneously threatened by eutrophication (Norbäck Ivarsson et al., 2019), pollution from hazardous substances and marine litter (Abalansa et al., 2020; HELCOM 2018; Selin and VanDeveer 2004), and climate changes (Murray et al., 2019), which make the sea extremely vulnerable.

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This study aimed to (i) describe the melting season of the Baltic Sea and its spatial and temporal variability, (ii) understand the trends of sea ice melting and variability of the sea surface temperature, (iii) analyse the phytoplankton (chlorophyll-a concentration values) during the melting season, and (iv) test the response of spring blooms (concentration peak values) to changes in the sea ice by using a biogeochemical model.

The ice season lasts up to seven months (Vihma and Haapala, 2009) with the typical maximum ice extent in late February and early March (BACC II Author Team, 2015). The melting season starts in March, but the sea ice is observed in the northernmost Bothnian Bay until June (Leppäranta and Myrberg, 2009). The maximum ice extent observed during the mildest winter (2019/20) was only 37 000 km^2 (~9%), and that in the harshest winter (1986/87) was 407 000 km^2 (97%). Hence, both the ice extent and level of sea ice thickness vary largely (BACC II Author Team, 2015). The sea ice is up to 1.8-m thick (Haas, 2004), and due to the ice drift, ice ridges are typically 5—15 m thick (Leppäranta and Myrberg, 2009), with the maximum drift measured in the Gulf of Finland with 1 m s^{-1} (Lilover, 2018).

Sea ice severely affects turbulent fluxes at the water surface and beyond, influencing the thermodynamics of the ocean and water-mixing. The sea ice and snow cover, which prevent the exchange of heat, CO_2, and other gases among the air, sea and water vaporisation, are good insulators between the ocean and the atmosphere. Furthermore, the sea ice is often covered with snow, which severely influences light attenuation. The albedo of a new snow cover can be up to 0.9, and that of melting bare ice is only 0.4, which is considerably larger than that of the open sea (<0.1) (Vihma and Haapala, 2009). Therefore, a small decrease in the ice or snow cover leads to a large increase in net solar radiations under water.

In early March, the phytoplankton spring bloom starts in the southern parts of the Baltic Sea and extends to the melting sea ice edge of the Gulf of Finland in April (Spilling et al., 2018). Several physical processes drive the spring bloom. First, light availability exhibits a strong impact as the necessary force of primary production (Wasmund et al., 1998). Second, water temperature controls the intensity of most biological and chemical processes (Brierley and Kingsford, 2009). For most fish species, the initial signal of spawning is the crossing of a certain threshold of water temperature. For instance, herring spawning peaks at 5.6°C in the middle Baltic Proper (Jørgensen, 2005). The process rate increases by approximately a factor of 2 per 10°C (Jørgensen, 1994), and climbs up to 2.3 times for zooplankton metabolism (Ivanova, 1985). Thus, changing sea ice conditions not only indicate changing water temperatures but also affect spring bloom timings and phytoplankton species compositions (Klais et al., 2017a, Klais et al., 2017b; Pärn et al., 2021), with further implications on nutrient cycles and ecosystem dynamics (Klais et al., 2013). The presence of sea ice leads to calm conditions under water; thus, most of the heavy plankton (e.g., diatoms) sink below the euphotic zone (~10 m) with velocities, at times, reaching as high as 15 to 30 m d^{-1} (Passow, 1991); while dinoflagellates stay in the euphotic zone and reproduce (Gemmell et al., 2016; Pärn et al., 2021).

Various climate features including temperature, ice phenomena and ecosystem characteristics can be found in relatively stable regimes, which can last for several decades. However, these states can abruptly change to another regime due to several reasons. The shift of the regime in these features in the Baltic Sea was studied by Hagen and Feistel (2005), Keevallik (2011), Neumann et al. (2011), Stips and Lilover (2010). According to Kahru et al. (2016), the water transparency has decreased since 2007 in the central Baltic Sea. Rjazin et al. (2020) analysed the severity characteristics of the ice season, maximum ice extent and ice cover duration of the winter seasons from 1982—2016. They showed that in the winter of 2007, a shift occurred in the ice severity characteristics. Global warming is a driver of this shift and can severely influence the sea ice season and extent. Friedland et al. (2013) estimated that the sea ice extent may decrease by 20% to 40% by the end of the 21st century, depending on the assumed climate change scenario. In the Baltic Sea, the phytoplankton spring bloom accounts for a large part of annual biomass production (Macias et al., 2020) and bloom timing affects carbon recycling, ~50% annual carbon fixation is during spring bloom (Lipsewers, 2020). Spring indicates the beginning of the growth season, and spring bloom is the key to pelagic and benthic (secondary) production (Chiswell, 2015; Griffiths, 2017; Spilling et al., 2018). Climate variations in the Baltic Sea affect plankton communities mostly in the beginning of the production season (Käse and Geuer, 2018; Winder and Sommer, 2012). Global warming affects the timing, composition and magnitude of the phytoplankton spring bloom in the Baltic Sea (Hjerne et al., 2019; Meier et al., 2018). This phenomenon has dramatic implications on the food web dynamics and carbon recycling (Winder and Sommer, 2012). The temporal match with zooplankton consumption is disturbed (Winder, 2004).

Biogeochemical models are one key to understanding potential implications (Eilola et al., 2013; Neumann et al., 2012), if these models are able to reproduce the key features of spring bloom. Therefore, realistic ice models are necessary to be able to simulate the timing, composition and magnitude of the phytoplankton spring bloom. During the melting season, in the Baltic Sea, air temperature exceeds water freezing temperature, even when the water body is covered with ice. Marine ecosystem models, using simplified ice calculations, usually ignore the ice cover during the melting period. Because of the ice cover, the effect of wind on water circulation is eliminated, the sunlight is largely reflected back into the atmosphere, and the warm air does not come in direct contact with the water surface. If these processes are ignored, inaccurate model results are obtained for the timing, composition, and magnitude of spring bloom dynamics. Although few biogeochemical models incorporate ice sub-models (Tedesco et al., 2016), only NEMO Nordic and MOM-ERGOM provide an ice model validated against Baltic Sea observation data (Pemberton et al., 2017; Rjazin, 2019, Neumann et al., 2020). Eilola et al. (2013) investigated the impact of sea ice on Baltic Sea biogeochemistry by using an ice model validated by (Meier, 1999). Neumann (2010) applied MOM-ERGOM to estimate that the sea ice extent may decrease by two-thirds due to climate change by the end of the 21st century, which can lead to an earlier offset of spring bloom up to one month in the Bothnian Sea and Bay.

Climate impact research is important because politicians, decision makers and the society require guidance regarding the environmental effects of global warming. Therefore, sea ice modelling must be corrected to predict spring bloom dynamics to improve biogeochemical models of the Baltic Sea.

2. Material and methods

2.1. Observational data

2.1.1. Sea ice data

The daily ice fractions of the Baltic Sea were provided by the Copernicus Marine Environment Monitoring Service (Von Schuckmann et al., 2018). Ice concentration data was acquired from the Swedish Meteorological and Hydrological Institute (SMHI) at 5.5 km horizontal resolution. Secondly, the ice product (daily ice concentration) of ERA5 was used, which is the latest reanalysis product from the European Centre for Medium-range Weather forecast (ECMWF), covering the 1979—2020 period (Hersbach, 2020). The mean ice extent was determined daily.

This data was used to calculate the ice melting period of the Baltic Sea for the ice seasons of 1982—2020. The ice extent reaches its maximum near the end of February or beginning of March. Therefore, the days before 1st March were not counted to focus purely on the melting period. The average melting time (MT) was computed as follows: 1) calculate the number of days when ice concentration is at least 30% for each grid cell for each year; 2) calculate the spatial average of the number of ice-covered days on the Baltic Sea or sub-basins.

$$MT = \frac{1}{i_{max}} \sum_{1}^{i_{max}} \sum_{d_0}^{n} C_{it} \tag{1}$$

where $C_{it} = 1$; if the ice concentration on the day d in the grid cell i is $>30\%$ and 0 otherwise, t_0 is 01 March, and n is the maximal melting season length (days) in the grid cell (110 days), i_{max} is the number of cells in the Baltic Sea or the sub-basin.

Rjazin (2017) defined the characteristic difference of the ice season, which is the difference between the maximum ice extent (Emax) and the ice extent sum (IES). IES describes the ice cover extent from the starting of ice appearance to its end. In normalised form, the IES can be interpreted as the number of ice days, which, daily, considers the ice-covered area.

$$IES = \sum_{t_0}^{t_n} A_t \tag{2}$$

where A_t is the ice cover extent on the day t, t_0 is the ice appearance date, and t_n is the last day of the ice cover. In the reference winter of 1986/87, the maximum ice extent was 97% of the entire Baltic Sea.

We defined ice season characteristics dch as the ratio of both values:

$$dch = IES \, / \, Emax \tag{3}$$

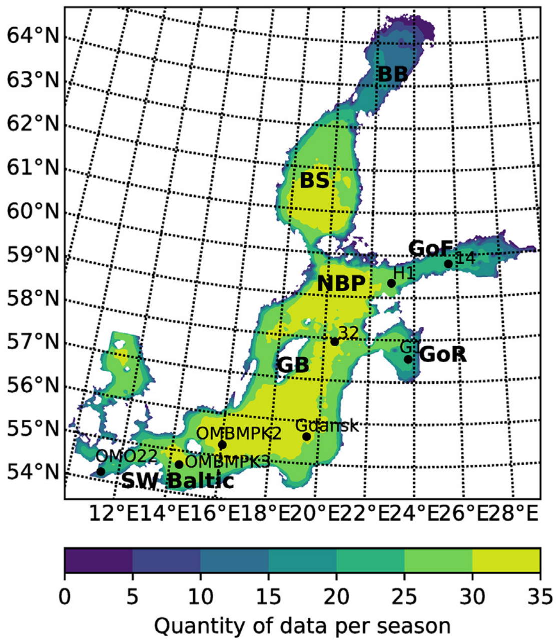

Figure 1 Quantity of chlorophyll data collected during the March, April, and May of 1998—2020 for the stations included in this study.

Emax is the value of the maximal ice extent in a particular season.The regime shift detection method was used to identify regime shifts in the MT time series and dch.

2.1.2. Sea surface temperature (SST) and meteorological data

The Danish Meteorological Institute (DMI) reanalysed the daily sea surface temperature (SST) data on a grid of 0.03° × 0.03° by combining Pathfinder AVHRR satellite data records, along-track scanning radiometer (ATSR) reprocessing for a climate (ARC) dataset, and in situ observations. Validation against an independent set of in situ observations showed a highly stable performance of the reanalysed dataset with the mean deviation and standard deviation (SD) of −0.06 and 0.46°C, respectively, with respect to data from the moored buoys (Von Schuckmann et al., 2018). The meteorological forcing data of the ERA5 reanalysis obtained from the ECMWF for every 6 hours was applied to the model and used for SST.

2.1.3. Chlorophyll-a data

To investigate the annual, monthly, and daily variations in surface chlorophyll-a concentrations, data was used which was provided by the Global Ocean Satellite monitoring and marine ecosystem study group (GOS) of the Italian National Research Council (CNR) with a spatial resolution of 1 km, which was estimated using the BalAlg algorithm (Pitarch et al., 2016). The spring data from March to May for 1998—2020 was extracted. Daily data was unevenly available, especially for the northern part of the Baltic Sea, and only a few observations were available (Figure 1). For 2008 and 2015—2018, we acquired the data of up to 26 days for May for some regions of the Baltic Sea (Figure 2). In March and April 1999, the data of only 8 and 9 days, respectively, were available, and in 2013, the data of 22 days

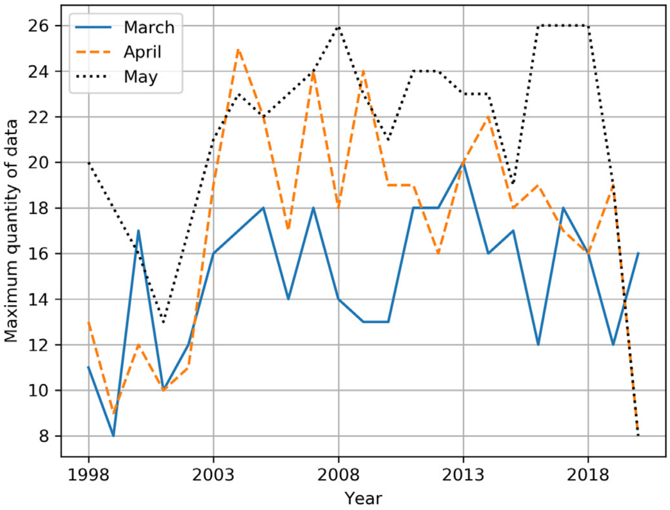

Figure 2 Maximum quantity of satellite data for a single-grid cell during March (solid), April (dashed), and May (dotted).

was available. The rate at which data were recorded fluctuated throughout the study with an increasing trend towards May. There is no day for which satellite data is available for all the 23 years; however, for a minimum of 8 years, data is available for each grid point. On 4 days (16, 22, 23, and 29 May), data was collected for 18 years.

Chlorophyll-a concentration data revealed speckle errors such as large or negative values. Although satellite data was not as accurate as in situ measurement data, this was the only data available for daily measurements covering large parts of the Baltic Sea. The raw satellite data was corrected as follows: (1) only values between 0 and 20 mg m^{-3} were used; (2) the time series was smoothed out with a 5-day moving average to prevent the occurrence of individual high-concentration values; and (3) horizontal smoothing was conducted at each grid point through a weighted average of the grid point and the nearest eight surrounding points. The center point received a weighting of 1, the points on either side and those above and below received a weighting of 0.5, and the corner points received a weighting of 0.3.

2.2. Model description

2.2.1. Setup

Simulations were performed using a coupled three-dimensional model system, comprising a hydrodynamic model GETM (https://getm.eu/; Burchard, 1999; Burchard and Bolding, 2002; Stips, 2004) and a biogeochemical model (ERGOM; www.ergom.net), based on the model described by Neumann (2000). A general ocean turbulence model (GOTM; www.gotm.net) was coupled with the GETM to resolve vertical mixing (Umlauf and Burchard, 2005) and ice existence problems. The default diatom sinking velocity is 0.5 m d^{-1}. Our implementation of the model for the Baltic Sea had a horizontal resolution of 2 × 2 nm and included 25 vertical σ layers with an open boundary in northern Kattegat. Hourly sea level data was interpolated from gauge measurements at Kattegat. The model considers the land-based runoff and nutrient loads that had incorporated into 20 major rivers (Neumann and Schernewski, 2008).

Pärn (2020) provided the main validation for the coupled model. Hydrodynamic features such as salinity, temperature, and surface elevation were well reproduced. The comparison of the modelled SST with satellite data revealed a bias of approximately 0.7°C. The root-mean-square errors (RMSEs) of the sea surface and bottom salinity were 0.3—1.7 PSU. All the modelled eutrophication indicators, chlorophyll-a, oxygen, nitrate, and phosphate followed the dominant seasonal cycles. The simulated chlorophyll-a model was highly suitable to the southern Baltic Sea (RMSE = 0.9), but it was improvable in the ice-covered parts such as the Gulf of Finland.

2.2.2. Model scenarios

The model was applied to study the effects of physical processes on the spring bloom affected by the sea ice. The results of runs A and B were compared and the difference between the two scenarios with respect to the chl-a concentrations was analysed. Six melting seasons, 1986—1987, 1995—1996, 2002—2003, 2009—2010, 2010—2011 and 2012—2013 were modelled, and the biogeochemical model variables had the same initial distributions on 1st March (at the beginning of melting time). Two scenarios were modelled to estimate the ice effect.

In Run (A), we used the ice data obtained from SMHI (section 2.1.1. sea ice data). If the model grid cell was assumed to be ice covered, the water surface temperature was set equal to the freezing point temperature and the wind stress was set to 0. The underwater light conditions were limited due to sea ice. In the case of sea ice, PARi = 0.7*PAR, where PAR is photosynthetically active radiation and PARi is PAR under ice (Lei et al., 2011).

For Run (B), a simple approach was implemented to model ice conditions assuming a minimal thermodynamic ice approximation. When the sea surface temperature (SST) was equal to the freezing temperature, the model grid cell is assumed to be “ice covered”, PARi = 0.7*PAR, and the wind stress was set to 0. When the sea surface temperature (SST) was above freezing temperature, the model grid cell is assumed to be open water. The key difference of this approach compared to Run (A) is that the simple “ice” model in Run (B) did not consider ice during spring even though ice

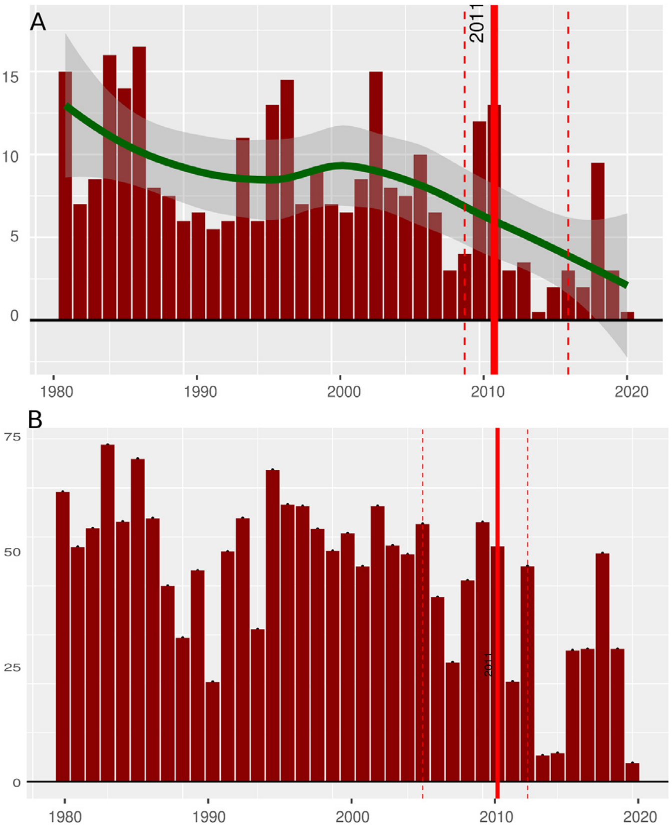

Figure 3 Average ice melting duration (MT) for the Baltic Sea and Bothnian Bay for the years 1982—2020.

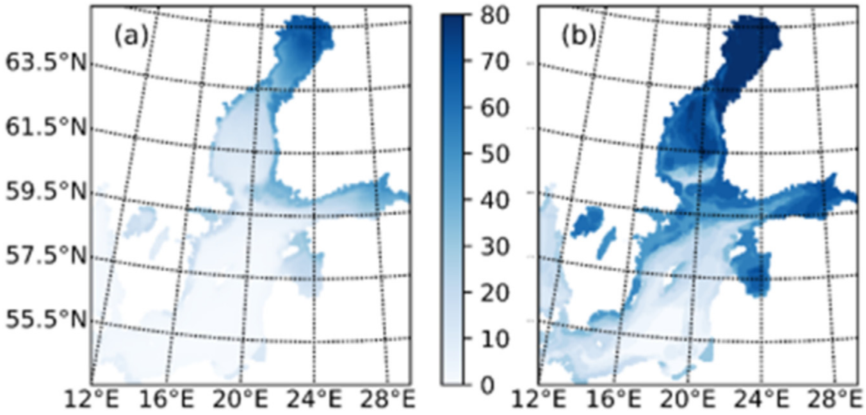

Figure 4 (a) Average number of ice-melting days in the Baltic Sea for 1982—2020 and (b) number of ice-melting days for 1987. SMHI dataset.

cover existed on the sea as seen by satellite data. From this point of view, during the spring bloom, this period is the key issue.

2.3. Regime shift detection methodology

The detection of regime shifts in time series data can be applied to identify points in time when abrupt changes in the data structure occurred. This specific point in time is hereafter referred to as the changepoint.

Several well-documented methods are available for changepoint detection (e.g., (Zeileis, 2003)). These methods are based on solid statistics and can reproducibly identify regime shifts as a significant change in the time series mean. First, Bai (1994, 1997) developed a method that can be used to test the occurrence of a single changepoint in a time series. Bai and Perron (1998) then extended this method to determine multiple changepoints. Rodionov (2004) developed a principally similar method, and other methods are provided in the review by Mantua (2004). We used the method developed by Bai and Perron (2003) and described by (Zeileis, 2003). This method is a widely used technique for the detection of structural changepoints in time series regression models. Their method was implemented in the *strucchange* package of the statistical software **R**, which is freely available on the Comprehensive R Archive Network (CRAN, http://cran.r-project.org/).

The method of Zeileis (2003) is based on a test used to assess deviations from the classical linear regression model. A time series is assumed to have b changepoints, at which the coefficients shift from one stable regression relationship to another. Consequently, b + 1 segments with constant regression coefficients must exist. These optimal segments may be determined through a dynamic programming approach, thereby minimising the residual sum of squares for certain observation intervals. The selected interval search length influences the results. The default value of 0.15 allows a maximum of 5 changepoints to be found in the time series. Therefore, optimising the search interval and maximum number of changepoints searched by using the investigated data is important. The F statistics were used to estimate the optimal number of changepoints, including confidence interval determination. To detect changepoints on an annual time scale, high-frequency contributions (such as seasonal cycles) must be eliminated by applying appropriate filtering or averaging methods before the analysis. Low-frequency oscillations with a period exceeding the selected segment length can lead to changepoint detection. This is especially relevant for the time series with considerable autocorrelations and/or linear trends, which require pre-whitening or even trend removal. All the significance tests were used with respect to a 5% error probability threshold. Corresponding confidence intervals are presented in the figures by using a time range indicated with the dashed vertical lines.

3. Results for the melting period

The ice melting time and characteristics of ice seasons analysed for the Baltic Sea used the SMHI and ERA5 database. As the data correlates well with each other (cross correlation 0.9) and refers to the same trends, we used only SMHI data to describe the results. The following sub-basins were used in the analysis: Bothnian Bay (BB), Bothnian Sea (BS), Northern Baltic Proper (NBP), Gulf of Finland (GoF), Gulf of Riga (GoR), Gotland Basin (GB), Southwest Baltic (SWB) (Figure 1).

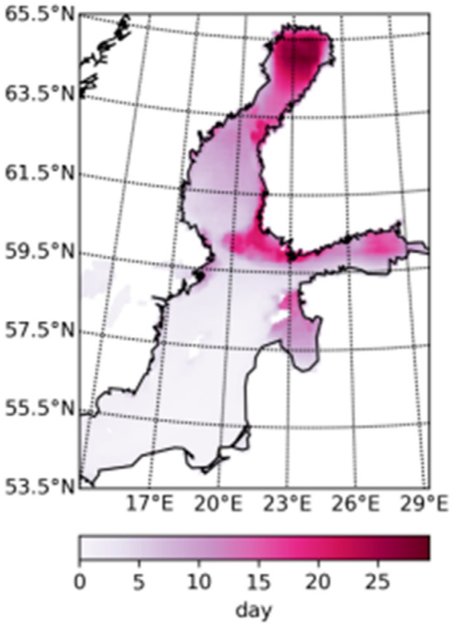

Figure 5 Duration of periods with strong winds (speed > 6 m s^{-1}) in ice-covered areas during the sea-ice melting period. ERA5 wind data of 1982—2020 has been used.

3.1. Duration of the melting time

The sea ice is a prominent feature of the Baltic Sea. The overall Baltic Sea melting time (MT) was acquired for an average of 10.8 days through SMHI data for the studied period (Figure 3). The study period was divided into three parts, 1979—1994, 1995—2007, 2008—2020, the average ice melting time of the period was 14.6 days, 11.6 days and 4.4 days, respectively. Spatial differences were quite large, and thus, the range was from 0 days in the southern and central Baltic

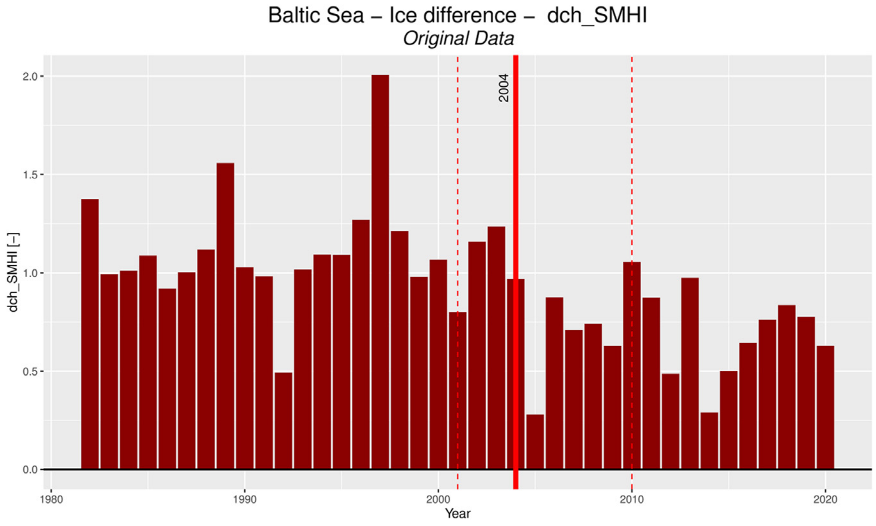

Figure 6 Time series of ice season severity characteristic dch in winter 1982—2020, a statistically significant changepoint (red line) in 2004 in the Baltic Sea.

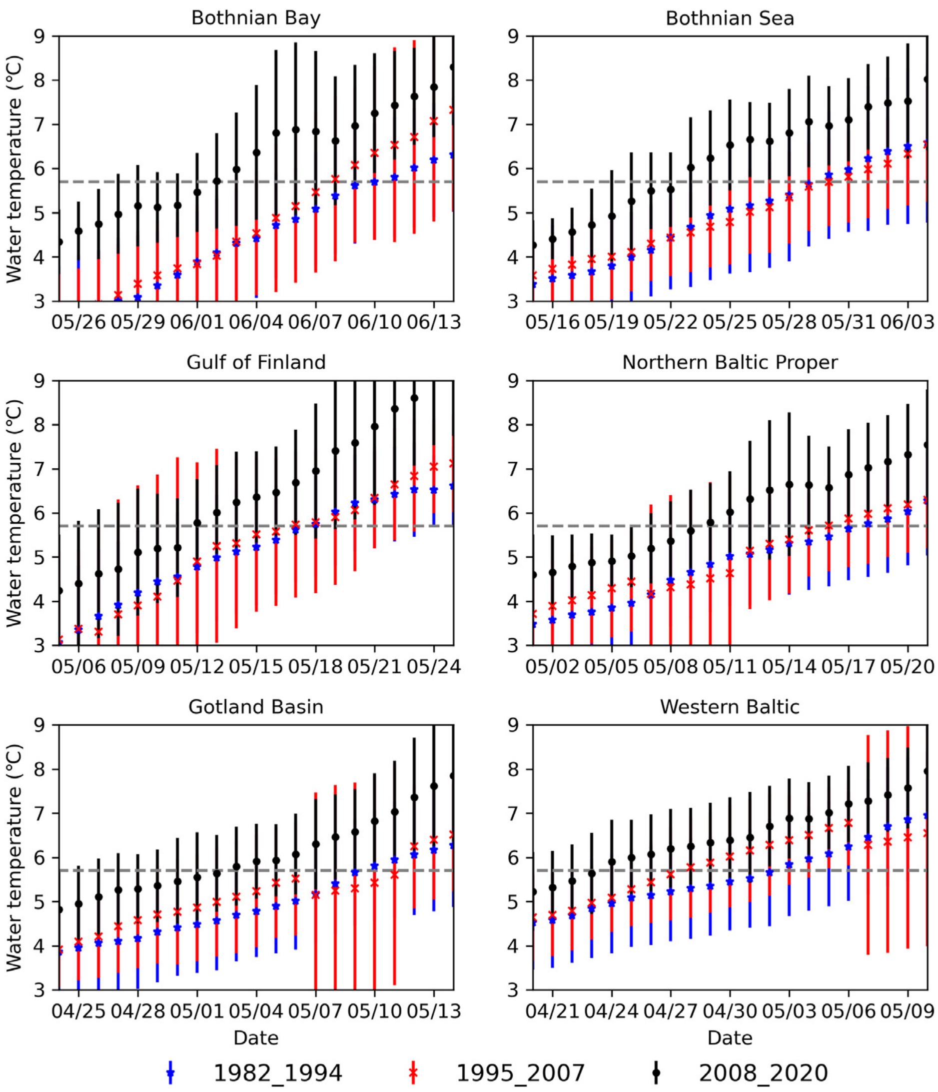

Figure 7 Time series of multiannual daily mean SST over the Baltic Sea basins.

Sea to 70 days in Bothnian Bay (Figure 4a). The most severe winter in the study period occurred in 1987, which resulted in ice formation almost everywhere, except in the southern central Baltic, and melting times of >90 days (Figure 4b). Thus, spatial gradients were relatively less strong because the high ice concentrations led to less mobile ice.

The average ice melting duration for the Baltic Sea showed a statistically significant changepoint in 2013 (Figure 3a). After 2013, the ice melting duration decreased considerably to <4 days (except in 2018). The MT time series data was analysed to determine the occurrence of breakpoints in the different basins of the Baltic Sea (Table 4). For the entire Baltic Sea, GoF and the BB (Figure 3b), statistically significant changepoints were identified.

Because the spring period is characterised by high-speed wind, the existence of ice plays an important role in wind stress hampering. We estimated how long the sea ice led to the elimination of the effects of strong winds (Figure 5). For the area with the longest melting period (Bothnian Bay), it was up to 20 days, and it was lesser in the other basins. On average it was 12 days in the Gulf of Bothnia, 10 days in the Gulf of Finland, 8 days in the Gulf of Riga, 2 days in the North and mid Baltic Proper, and 0.2 days in the southern part of the Baltic Proper.

The ice season severity of the Baltic was classified into three classes: mild (>135 000 km^2), average (135 000 to 180 000 km^2) and severe (<180 000 km^2). Classification is done according to the maximum ice extent. Types of winters in our study: Mild winters occurred during 1988/1989, 1989/1990, 1990/1991, 1991/1992, 1992/1993, 1993/1994, 1999/2000, 2001/2002, 2007/2008, 2008/2009, 2013/2014, 2014/ 2015, 2015/2016, 2016/2017 and 2019/2020; average winters occurred during 1982/1983, 1987/1988, 1997/1998, 1998/1999, 2000/2001, 2003/2004, 2004/2005, 2006/2007, 2011/2012 and 2017/2018; and severe winters occurred during 1981/1982, 1983/1984, 1984/1985, 1985/1986, 1986/1987,1993/1994, 1995/1996, 2002/2003, 2005/2006, 2009/2010, 20010/2011 and 2012/2013.

3.2. Characteristics of ice seasons (dch)

The dch time mean over the Baltic Sea is 0.9. If the value of dch for the respective season is higher than the average,

Table 1 Comparison of the dates when the surface temperature of the water reached 5.6°C.

Basin	a) 1982—1994	b) 1995—2007	c) 2008—2020	a—b(days)	b—c(days)
Bothnian Bay	12 Jun	9 Jun	3 Jun	3	6
Bothnian Sea	31 May	31 May	23 May	0	8
Northern Baltic Proper	19 May	17 May	11 May	2	6
Gulf of Finland	19 May	20 May	13 May	—1	7
Gulf of Riga	9 May	9 May	5 May	0	4
Gotland Basin	11 May	12 MAY	5 May	—1	6
Western Baltic	4 May	31 April	24 April	—4	7

then the ice cover lasts for a relatively long time compared to the maximum ice extent of the same winter. The ice seasons' characteristic dch mainly exhibited higher than average values for 1982—2003 and lower than average values for 2004—2020, except for 2010 (Figure 6). The lower values of dch indicated the seasons (winters) when the ice cover was extensive for some time, but it did not last for a long duration. Before 2004, the ice cover duration was longer than that of the maximum ice extent. The duration of the ice cover of the previous decade decreased compared to the maximum ice extent of the same winter. The time series of 1982—2020 had a statistically significant changepoint in 2004 in the Baltic Sea.

3.3. Shift of Sea Surface Temperature (SST) in spring

We observed that the dates of the water threshold temperature, i.e., 5.6°C, changed during 1982—2020. To find out if the surface temperature of the sea had changed over time (Figure 7), the study period was divided into three periods: 1982—1994, 1995—2007 and 2008—2020. The threshold temperature was observed in the last period, 4 to 8 days earlier compared to the middle interval (Table 1). Between the first and second period, there was not such a clear trend, and only for some basins the threshold temperature was reached earlier.

BB and GoF differed from other basins. The April average SST over BB and GoF had a statistically significant changepoint in 2006 (Table 4). In other basins (BS, NBP, GoR, GB, SWB) the surface temperature was strongly in accordance with the average surface temperature over the Baltic Sea, and the correlation was >0.92. Also, the correlation coefficient between all the sub-basins (except BB) was >0.88, but the mean SST between BB and Baltic was 0.68. The correlation coefficient between MT and mean SST over the Baltic Sea was —0.9.

3.4. Analysis of chlorophyll-a concentrations

Satellite-based chlorophyll-a average (1998—2020) concentrations for the Baltic Proper were 0.6, 0.9, 1.4, 2.3 and 1.6 mg m^{-3} for January, February, March, April and May, respectively. The chlorophyll-a time average concentrations (Figure 8) showed the highest gradient and values of the chlorophyll-a concentration in the Gulf of Finland (up to 8 mg m^{-3}) and the Gulf of Riga (up to 7 mg m^{-3}). However, the northernmost data for the Baltic Sea and easternmost data for the Gulf of Finland must be viewed with some caution because the ice cover lasts longer in these areas. We investigated the pattern of spring bloom according to winter severity (Section 3.1). Figure 9 shows the multiannual daily mean of chlorophyll-a concentration for spring in Baltic Sea basins. The Bothnian Bay and Gulf of Riga were excluded because when they are covered with sea ice from March—May, satellites provide unreliable data or there is a lack of satellite data for these areas. In the SW Baltic, the spring bloom begins on average on March 10—15, and average chlorophyll-a concentration values decrease (<2 mg m^{-3}) in mid-April. In the beginning of spring, chlorophyll-a concentration values are low (up to 2 mg m^{-3}) in all basins except the Gulf of Finland. In other basins, concentrations started to increase in early April, and the peak was reached in late April.

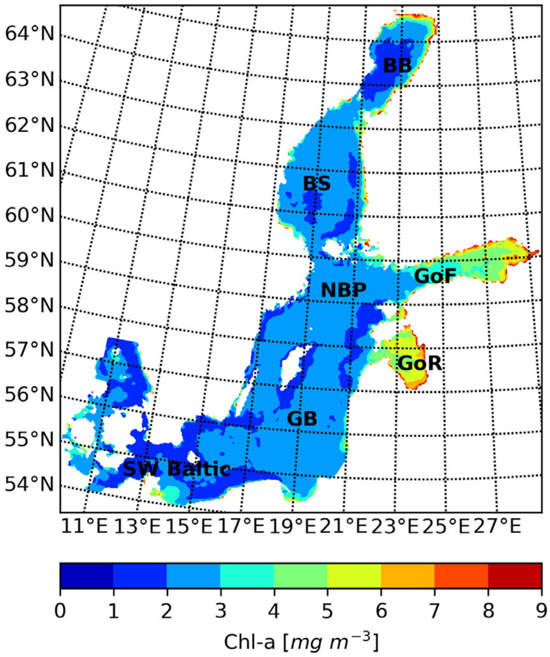

Figure 8 March—May average chlorophyll-a concentration (mg m^{-3}) for 1998—2020 over the Baltic Sea. Satellite-based Chl-a data from Copernicus product.

The peak of chlorophyll-a multiannual daily mean concentration lasted for a shorter duration after severe winters than after average and mild winters (Table 2). In severe winters, peak of concentration only lasts a few days, except in the Gulf of Finland. In all the basins, chlorophyll-a concentration values were lower in severe winters than in average and mild ones, mainly during the whole season (Figure 9). We compared the chlorophyll-a multiannual daily mean con-

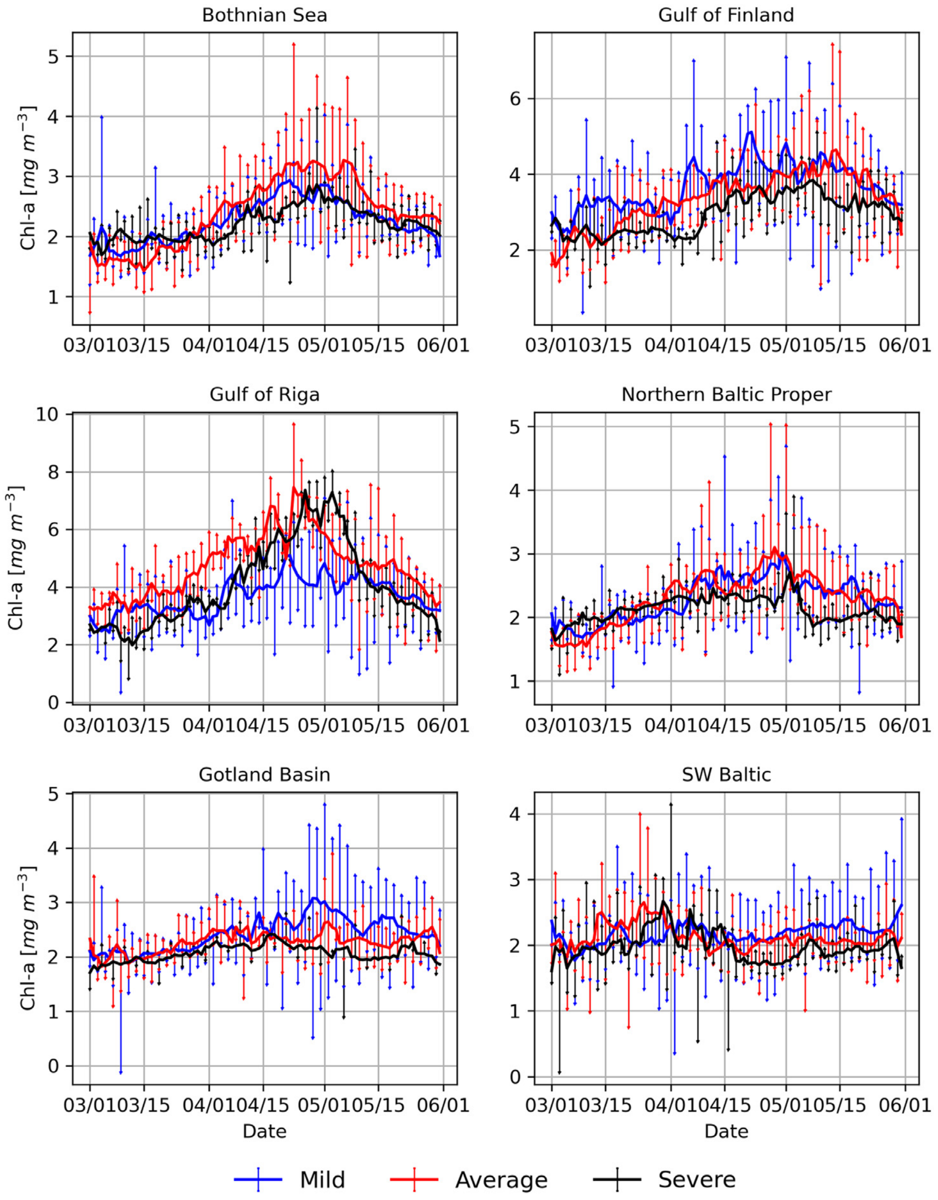

Figure 9 Chlorophyll-a multiannual daily mean concentration over the Baltic Sea basins from March to May for severe, average, and mild winters.

Table 2 Number of days when the daily chlorophyll-a concentration values were higher than the mean.

Basin	Severe (Day)	Average (Day)	Mild (Day)	Before shift (Day)	After shift (Day)
Bothnian Sea	31	56	42	50	22
Northern Baltic Proper	31	58	46	59	31
Gulf of Finland	25	54	56	54	25
Gotland Basin	7	56	57	58	8
SWS Baltic	18	41	60	41	18

centration (1998—2020) in each basin with the daily values of severe, average, and mild winters. We summed up the number of days when the daily values were higher than the mean concentration (Table 2).

The chlorophyll-a data does not correlate with the MT and SST data shown in the previous sections (3.1 and 3.3). The GoF and GoR chlorophyll-a data did not correlate with each other (r=−0.068) or with other basins (Figure 10). The April mean chlorophyll-a concentration from the period 1998—2020 was analysed for the selected sub-basins. The chlorophyll data series is shorter than the ice data, however, the statistically significant changepoint was in 2002 and 2011 in the April mean chlorophyll-a time series in NBP and, in 2011, in the whole Baltic Sea. Statistically significant changepoints were identified for the other basins as shown in Table 4.

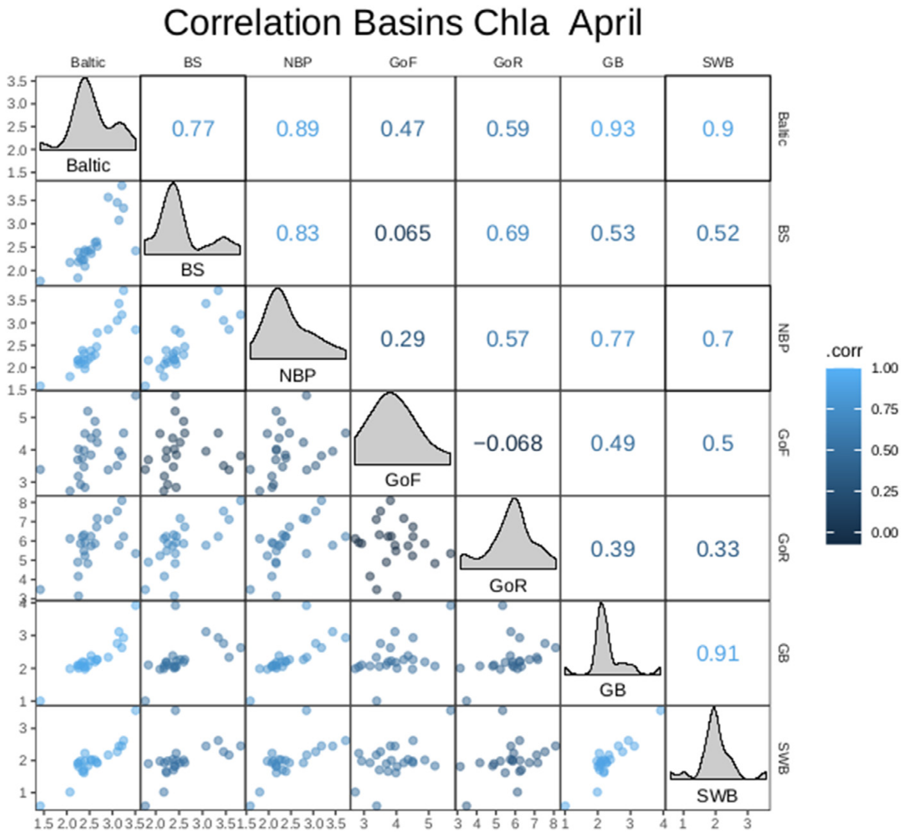

Figure 10 Correlation between April mean chlorophyll-a concentration between the subbasin.

Phytoplankton and chlorophyll-a concentration profiles were rarely measured in the areas covered with the sea ice. No such data are available for the GoF and GoR. An exception is the Bay of Mecklenburg (St. OMO22), for which the measurement data is available for March 2009—2019 in the ICES database. The Bay of Mecklenburg is covered with ice in cold winters (Schmelzer et al., 2014). The number of ice days in Rostock (the nearest port to the station) were: 0, 67, 77, 23, 54, 4, 2, 22, 11, 39, 2, 0 days according to 2009—2020. In severe winters, the chlorophyll-a concentration on the surface (Figure 11) is lower than that for deep underwater (10 m). In mild winters, concentration values are the same, or the surface concentration is high. An exception is 2015, when the surface, a deep layer of 5 m, and a deep layer of 10 m exhibited chlorophyll-a concentrations of 8, 7, and 11 mg m^{-3}, respectively. The day before the measurements, March 17, 2015, the average wind speed was low <5 m s^{-1} (ERA5 data) and the diatom sinking velocity during the spring bloom in the central Baltic Sea is 15 to 30 m d^{-1} (Passow, 1991).

3.5. Impact of the sea ice on the spring bloom in the ecosystem model

A coupled hydrodynamic—biogeochemical model was implemented to analyse the difference between the two scenarios with respect to the chl-a concentrations at stations.

We examined the frequency of the predictions coinciding with the timing of the spring phytoplankton bloom for the two different runs. If both the run results were in the range of ±3 days, we counted the results as coinciding. The dates predicted by the two runs for the spring phytoplankton bloom peak slightly coincided with each other. Stations OMBMPK2 and OMBMPK3 coincided 4 times, station Gdańsk 2 times while stations H1, 14, and G1 did not coincide with any of the considered cases. The prediction difference for the timing of the spring phytoplankton bloom peaks for each station are presented in Table 3. If the bloom peaks of run (A) and run (B) coincided by (±3 days), then we consider the blooming difference to be 0 days. The interval in the southern part of the Baltic Sea (OMBMPK2 and OMBMPK3) was 4 days, and in the Gdańsk Bay, it was 6 days. The correlation of the diatom concentration between runs (A) and (B) was 0.2—0.9 (Figure 11, Table 3). The correlation coefficient is sensitive to the selected time interval. The same period (25.03—5.05) was considered for all the stations. The critical value of the Pearson correlation coefficient is 0.44 ($p = 0.05$). The correlation of the diatom concentration between runs (A) and (B) is not significant at stations H1 and G1. Differences existed in the bloom timing, with the four stations having a timing of >10 days. This shows that the presence of ice significantly influences the values predicted while using the model.

3.6. Influence of sea ice on the dynamics of chlorophyll-a sinking

Sea ice reduces wind-induced turbulence in the euphotic layer even if it is temporary. The effect of the mechanism on chlorophyll-a concentration was tested with the model. The

Table 3 Correlation of the concentration between runs (A) and (B). Correlation of the concentration between runs (A) and (B).

Stations	Correlation (1.03—31.05)	Correlation during bloom (25.03—5.05)	Interval of the spring bloom timing peak (days)
14	0.6	0.4	10.2
32	0.8	0.45	13.7
G1	0.5	0.2	17.8
Gdańsk	0.8	0.75	6
H1	0.57	0.4	13.8
OMBMPK2	0.9	0.8	3.8
OMBMPK3	0.85	0>.7	3.7

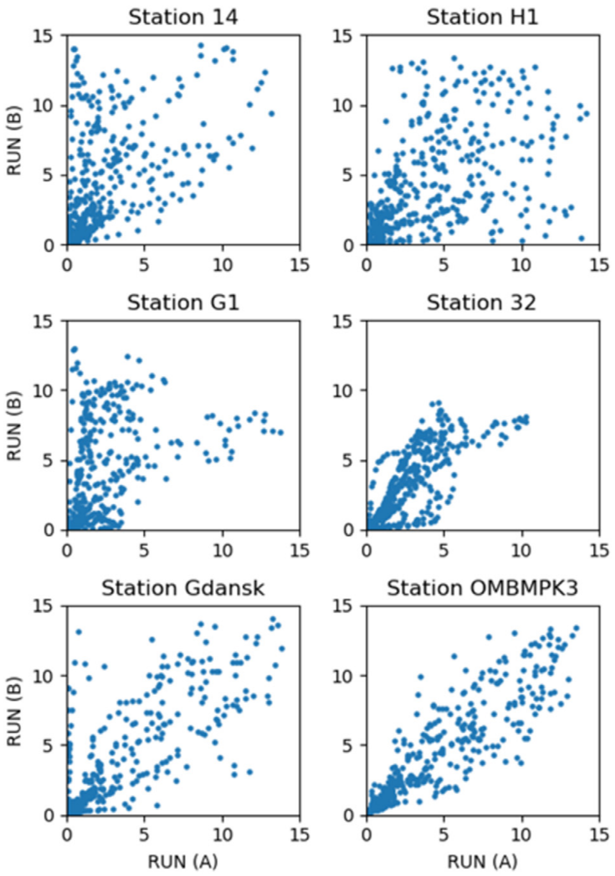

Figure 11 Scatter diagram of the chlorophyll-a concentrations from the two different model simulations, evaluated for stations indicated in Figure 1.

Table 4 Changepoint of the MT, SST and average April clorophyll-a concentration for the Baltic Sea and its parts.

Basin	MT (SMHI)	SST	Chl-April	Chl-May
BB	2013	1992+2006	No data	No data
BS	1987	1988	2002	2002
NBP	No	No	2002+2011	2002+2010
GB	1987	No	2011	No
GoF	2013	2006	No	No
GoR	No	No	2011	2013
SWB	No data	1987	No	No
Baltic	1987+2011	No	2011	2008

conditions for the sinking of chlorophyll-a varied considerably depending on the presence of open water or sea ice. Figure 12 depicts the multiannual daily mean chlorophyll-a concentration in run (A) and run (B) for six modelled spring seasons. The chlorophyll-a concentration started to increase in the middle of March in both the simulations. The chlorophyll-a concentration values were higher at a depth of 10—15 m for run A (Figure 12) which is caused by the diatoms sinking. Therefore, the spring bloom of dinoflagellates appeared only in the sea area with thin ice (or low wind conditions), and thus, the chlorophyll-a concentration values were lower in the upper 5 m layer. For run B, the diatoms dominated in the ice-free water and in the upper 5 m.

4. Discussion

The Baltic Sea is seasonally ice covered with biological activity being the lowest during winter. The average chlorophyll-a concentrations over the Baltic Proper as seen using satellite data were <1 mg m^{-3} before March. The activity of biota during spring depends strongly on the ice cover duration. Climate changes have affected the living environment of the Baltic Sea. The average ice melting time (MT) of the Baltic Sea showed a statistically significant changepoint in 2011.

The average MT in spring decreased over the last decade. Before 2011, the average MT for the Baltic Sea was ~13 days. Since 2012, the MT was ~4 days.

Our study showed a larger change in the northern part of the Baltic Sea, however, Rjazin et al. (2017) reported a larger change in the mean air temperatures over the southwest (compared to the north) of the Baltic Sea. In the southern Baltic region, the average skewness of air temperature distribution shifted from 0.39 to 0.8 (Rjazin et al., 2017).

The generation of sea ice has been episodic after regime shift, and ice has not been able to grow to a large thickness. The ice season characteristic dch shifted from 1.1 to 0.7 in 2004 (Figure 6). Compared to the maximum ice extent of the season, the ice cover lasted longer before 2004. After 2004, the lower values of dch indicated the winters

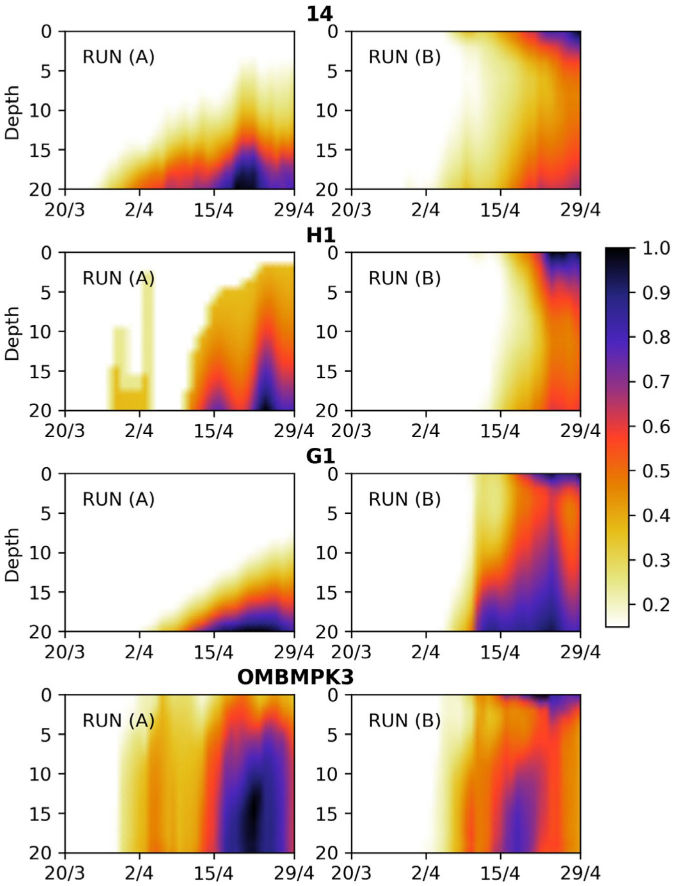

Figure 12 Daily average chlorophyll-a concentration values (normalise scale, values start at 0.2) at the four selected stations (Figure 1) averaged for the severe winters of 1987, 1996, 2003, 2010, 2011, and 2013.

in which the ice cover was extensive for some time but did not last for a long duration. However, considerable strong winds occur during the MT. Wind speeds higher than 6 m s^{-1} occur in some areas for 20 days (Figure 5) during the spring period. This creates conditions for changes in the species composition of phytoplankton.

Changes in the productivity regimes in spring were observed. The April average SST of the Bothnian Bay and the Gulf of Finland showed a statistically significant changepoint in 2006. The water temperature triggered many life processes which have threshold values. It can be concluded that the date of the water threshold temperature of 5.6°C changed during 1982—2020. The threshold temperature dates changed after the changepoint and were on average achieved on 11 May in 1982—2007, and 6 days earlier (05 May) in 2008—20 in the Baltic Proper (Figure 7). The interval 4—8 days between the dates was detected in all the basins in the Baltic Sea (Table 1).

Sub-arctic ecosystems are strongly dependent on environmental factors such as water temperature and changes in it will influence the ecosystem. The spawning temperature of herring is just one example that we took as the threshold value. Phytoplankton cannot compensate for the temporal shift, as the spring bloom is also limited by the available light, shown for the southern Baltic Sea by Friedland et al. (2012). Climate change effects are very quickly identified as a high-risk for herring spawning (Gröger et al. 2014).

The most active period in the sea, the spring bloom, occurs at the end of April (Figure 9), when chlorophyll concentrations were highest in the Baltic Sea, according to satellite data. In the southern parts of the Baltic Sea, the spring bloom starts in early March. The beginning of the spring boom (according to satellite data) did not occur progressively from the south to the north. Chlorophyll-a concentration values in the Gotland Basin, North Baltic Proper and Bothnian Sea started to increase when the spring bloom in the Southwest Baltic was over, i.e., in mid-April, reaching its peak by the end of April (Figure 9). In the Gulf of Finland, chlorophyll-a concentrations started to increase in early April. They were lower in severe winters throughout most of the spring season in all Baltic Sea basins (Figure 9). The Gulf of Finland and the Gulf of Riga are biologically independent basins, chlorophyll-a concentration during spring bloom did not correlate with each other or with the rest of the Baltic Sea sub-basins. The correlation coefficient between GoF and GoR is —0.068, with other sub-basins it is in the range of 0.068—0.69 (Figure 10).

The modelling experiment compared the results of a reference run (A) with observed sea ice with those of a run (B) with underestimated sea ice (imitating a mild and ice-free winter), which confirmed that ecological conditions differed significantly for both the scenarios. It has been found that there are low chlorophyll-a concentrations in the upper 5 m layer in run (A) and the concentration values increased at the surface in run (B). The results of the expeditions in the Bay of Mecklenburg gave a similar result in March 2009—2019. In mild winters, the measured values of chlorophyll-a concentration are the same in the euphotic zone, or the surface concentration is higher (with the exception of 2015); however, in severe winters, the concentration of chlorophyll-a on the surface is lower than in the deeper layer (10 m).

It can be seen from the observations and the model experiment that it is not enough to present the surface values alone to describe spring bloom. The deeper layers of the water column should also be considered. It can therefore be assumed that even in severe winters (shown by satellite data), the concentrations are lower throughout the season (Figure 9) than in mild winters. The presence of ice eliminates the effect of wind, thus creating calm conditions when the heavier particles (diatoms) sink below the euphotic zone (~10 m). The ice conditions during spring are one of the key factors affecting the magnitude, timing and composition of the spring bloom. The correlation of the chlorophyll-a concentration between simulations with sea ice (A) and simulations with the simple ice model (B) was 0.2—0.9. The southern parts of the sea are less affected by sea ice (correlation is higher), and the regions of the central Baltic Sea are more affected.

During ice free conditions in the spring bloom, the diatoms with a higher growth rate were predominant and quickly consumed nutrients. This indicated a faster end of the spring bloom leading to a rapid decrease in the chlorophyll-a concentration. During moderate ice cover and windless springs, the physical conditions were suitable for dinoflagellates. Their nutrient intake was lower than the diatoms allowing the nutrients to be available for longer in the euphotic zone. Diatoms lost their competitive advantage under sea ice and calm wind as these conditions led the diatoms to sink into the deeper layers of water where light was not available. The changes in dominance of these two phytoplankton classes strongly affected the marine food web and showed that they have a role in the net transfer of CO2 to the oceans and then to the sediments.

Extrapolating our results to a future with higher water temperatures and less ice, we can expect an increase in the diatom bloom magnitudes, although this event could potentially not occur in calm winds. This is according to our study, but blooming is the product of complex processes, which need to be investigated more widely to understand the mechanisms behind the underlying change in phytoplankton dynamics. The focus of our study was on the southern and central Baltic Sea. In conditions such as those in the northern part, where ice is thicker and closer along with the presence of snow, there is less light in the sea during spring. This part was not described in our work.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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