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Original article

Influence of Coastal Upwelling on Chlorophyll a Distribution in the Coastal Zone of the Southeastern Baltic Sea in Summer Periods, 2000–2019

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Abstract
Purpose. The study is purposed at obtaining quantitative estimates of coastal upwelling influence on the distribution of chlorophyll a in the coastal zone of the southeastern Baltic Sea during the summer seasons of 2000–2019.
Methods and results. Based on data on the frequency and duration of upwelling events for June–August 2000–2019 and chlorophyll a concentrations from multi-sensor satellite observations in the coastal zone of the southeastern Baltic Sea, long-term and monthly average values of the studied parameters were obtained and the influence of upwelling events on the concentration of chlorophyll a in the surface layer of the sea was assessed. The spatial variability of chlorophyll a in the coastal areas is found to be related to the influence of upwelling events. On average, the chlorophyll a concentration decreases by more than 1 mg/m^3 after an upwelling of any duration and in all summer months. The concentration drop is most significant after the upwelling events lasting more than 6 days.
Conclusions. Reduced chlorophyll a concentrations (as compared to the pre-upwelling values) are observed in the course of a week after a coastal upwelling event in the southeastern Baltic Sea.

Keywords: sea surface temperature, coastal upwelling, chlorophyll a concentration, southeastern Baltic Sea, remote sensing data

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Introduction

Upwelling is a common phenomenon which can be observed for ~ 10% of days in the warm period of the year in shallow water areas of the southeastern Baltic Sea (SEB) according to average long-term estimates [1–3]. On average, four upwellings with a total duration of > 20 days are observed in the water area in the summer seasons of 2000–2019 with the mean upwelling area of ~ 620 km^2. Accordingly, upwelling is undoubtedly an important mechanism for the transport of nutrients into the surface layer [4, 5], which affects bioproductivity of the SEB coastal areas. One of the indicators of bioproductivity is concentration of the main phytoplankton pigment – chlorophyll *a*. Note that its variability can be studied over a wide range of spatial and temporal scales using satellite observation data.

In the first few days of its development, coastal upwelling in the summer drives surface waters away from the shore. Due to this, a decrease in the content of phytoplankton and its main characteristic, chlorophyll a concentration, is observed in the coastal zone [6, 7]. After stabilization of the upwelling, an increase in primary production is observed within several days; it is associated with the development of phytoplankton communities caused by the rise of nutrients into the euphotic zone and temperature increase [8–13]. Further, we noted a primary production decrease associated with the rapid, within one to two weeks, consumption of nutrients raised to the surface [14]. At the same time, the nitrogen-to-phosphorus ratio can vary in the Baltic Sea due to upwelling and it can affect the composition of phytoplankton communities [8, 15]. Sometimes upwelling can lead to the decrease in area productivity, for example, if the raised waters replace the ones coming with the runoff of rivers or lagoons [4, 6], or when upwelling appears persistently and frequently in the same area [16, 17].

The chlorophyll a concentration during an upwelling event is also affected by biotic factors and a seasonal variation of the vertical structure of water associated with changes in the gradient and the thermocline and nutricline position [4, 18]. In June, the summer minimum of phytoplankton biomass begins in the SEB after spring algal blooms and massive development of algae due to nutrient depletion of surface waters. In July, the sea surface temperature (SST) becomes higher, a pronounced subsurface thermocline is formed (provoking massive development of nitrogen-fixing cyanobacteria) and the chlorophyll a concentration reaches peak values. In August, the chlorophyll a concentration decreases in the coastal zone [19].

According to satellite radiometers, the highest chlorophyll a concentrations are observed in the coastal zone from Cape Taran to the Curonian Spit coast, where they reach the eutrophic level (> 4 mg/m^3) [19], which partially overlaps with areas of maximum long-term frequency of upwelling events in the Rybachiy Plateau area and near Cape Taran [2]. At the same time, the works devoted to the issue of assessing the influence of upwelling events on the variability of phytoplankton concentrations in the SEB are based primarily on contact observations that are very rare in space [14] or on consideration of individual cases illustrating the capabilities of satellite research methods [20], although this information (generalized over a long-term period) is important for solving practical problems in the field of recreation and assessing changes in the ecological state of the coastal zone.

The use of remote sensing data enables to conduct large-scale observations of distribution and variability of chlorophyll a concentrations [21], including the ones influenced by upwelling [6, 22, 23]. The main advantages of the latter are instantaneous imaging of vast water areas and high spatial resolution. However, it should be noted that the average annual cloud cover in the Baltic Sea is > 58% [24].

In the presence of clouds, optical satellite data, even those obtained on a regular basis, are very fragmentary. In such conditions, it is advisable to monitor the chlorophyll a concentration not throughout the entire area, but on individual profiles, similar to how it was done in [23, 25].

This study is aimed at obtaining estimates of the coastal upwelling influence on the chlorophyll a distribution in the coastal zone of the southeastern Baltic Sea over the past two decades of the 21st century.

Materials and methods

The initial data for analyzing the relationship between upwelling and chlorophyll a in the SEB were the dates and areas of upwelling events for June – August of 2000–2019 in the SEB coastal zone from [26] and daily data from multisensor satellite observations (combined data from MERIS/ENVISAT, MODIS/AQUA, SeaWiFS/SEASTAR and VIIRS/SUOMI-NPP sensors) of chlorophyll a concentration (mg/m^3) on a regular grid with 1 × 1 km cell size in the surface layer of the Baltic Sea [1].

Analysis of spatial and intra-seasonal variability of upwelling frequency and chlorophyll a in the SEB. Averaged monthly maps and summer maps to describe intra-seasonal spatial variability of upwelling events, SST and chlorophyll a in the SEB were constructed for 2000–2019 in the water area shown in Fig. 1. Chlorophyll a concentrations were calculated monthly and for the summer season in those cells where > 25% of the values were observed over the period under consideration. The upwelling frequency was estimated as the number of days with an observed negative temperature anomaly obtained in a given cell using the method from [2] per month or per season.

Influence of upwelling on chlorophyll a concentration in the SEB. Chlorophyll a variability profiles of ~ 20 km in length were constructed for each identified upwelling using Quantum GIS software. Those profiles approximately corresponded to coastal isobaths from 0 to 30–75 m. A total of 9 profiles were constructed along the coast, located normal to the coast at 7–30 km intervals (depending on the coast configuration) (Fig. 1). The position of profiles was selected considering the areas with the highest frequency of upwelling events from [2, 26]. Chlorophyll a values in the profiles were obtained from daily multi-sensor satellite observations. For each upwelling event, one of the profiles that was best provided with the data on chlorophyll a during the period under consideration was selected for analysis by overlaying both parameters under study on a single geographic basis.

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[1] Copernicus Marine Service, 2012. *Baltic Sea Reprocessed Surface Chlorophyll Concentration from Multi Satellite Observations*. doi:10.48670/moi-00083

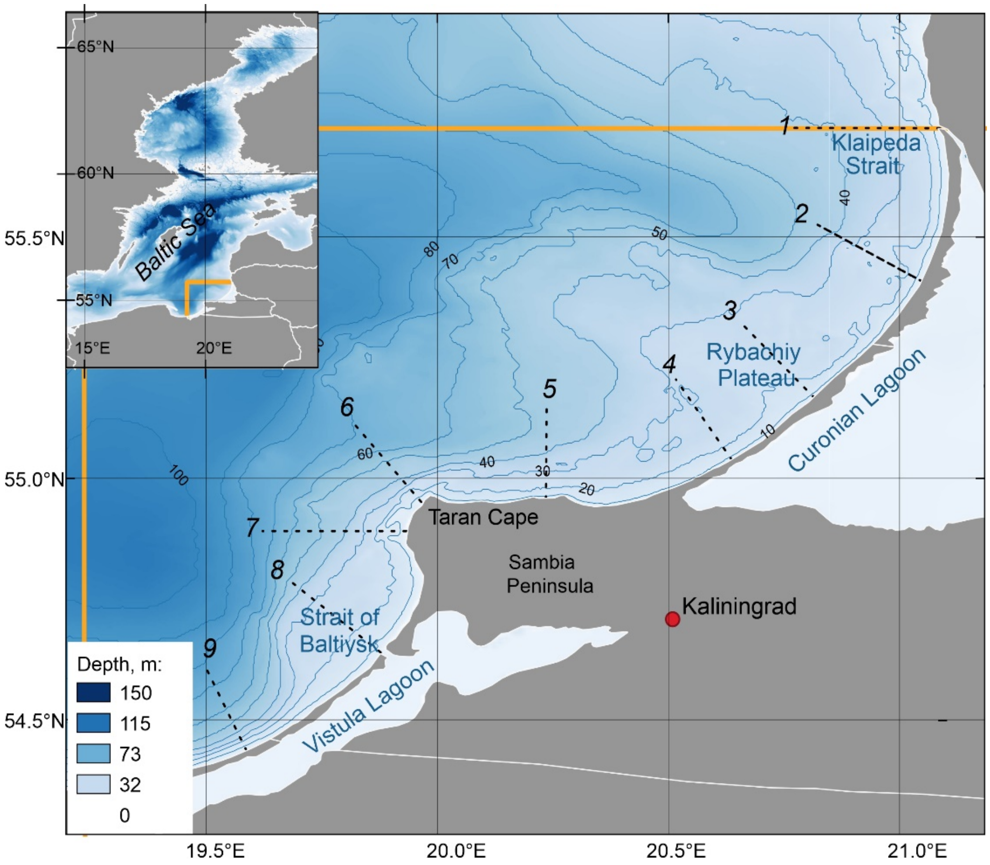

Fig. 1. Study area (yellow box), isobaths in each 10 m (blue curves) [2], and profiles used in the analysis of chlorophyll a variability on the sea surface (dashed black lines)

Upwelling zones from [2, 26] were marked on the selected profile, which made it possible to calculate the values of chlorophyll a concentration (mg/m^3) inside this zone and outside of it. Additionally, the mean values of this characteristic throughout the entire profile before, during and after upwelling were estimated. To obtain a satisfactory amount of data on chlorophyll a before and after upwelling, the analysis included the data from a time interval of up to 7 days, except for the cases when the events went beyond the summer season under consideration or when there were no data. A total of 31 upwelling periods with a total duration of 590 days was studied (for cases lasting 1–42 days). The influence of upwelling duration on changes in chlorophyll a concentration, as well as its contribution to intra-seasonal variation and long-term variability, was assessed.

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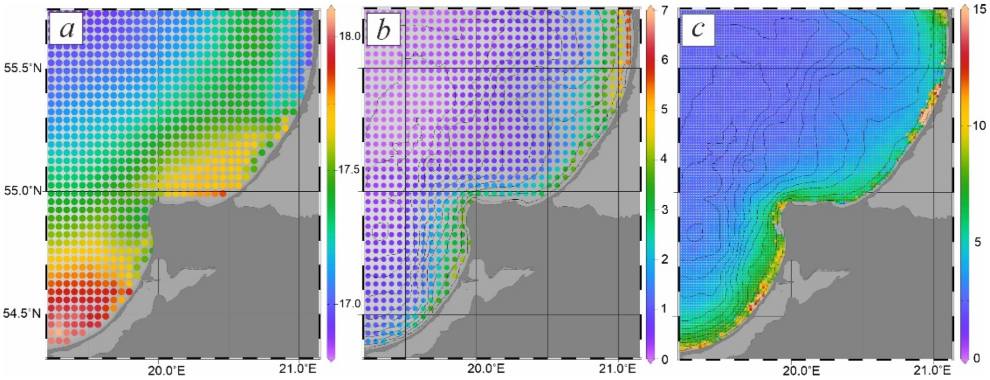
[2] Weatherall, P., Bringensparr, C., Castro, C.F., Dorschel, B., Drennon, H., Ferrini, V.L., Harper, H.A., Hehemann, L., Jakobsson, M. [et al.], 2022. *The GEBCO_2022 Grid – A Continuous Terrain Model of the Global Oceans and Land*. NERC EDS British Oceanographic Data Centre NOC. doi:10.5285/e0f0bb80-ab44-2739-e053-6c86abc0289c

Results

Analysis of intra-seasonal variability of upwelling frequency and chlorophyll a in the SEB. The areas of the northern coast of the Curonian Spit and the western coast of the Sambia Peninsula are clearly distinguished on the SST map by lower temperatures (lower by 0.5–1 °C) than in the coastal zone as a whole (Fig. 2). Depending on the upwelling frequency in the summer, several areas are distinguished in the coastal waters: the northern coast of the Sambia Peninsula and the western part of the Vistula Spit, where upwelling is observed up to 3 days a month; the area near Cape Taran and the southern part of the Curonian Spit, where upwelling is observed 3–4 days a month; the western coast of the Sambia Peninsula and the northern part of the Curonian Spit, where upwelling is observed more than 4 days a month.



F i g. 2. Summer season mean values of SST (°C) (*a*), upwelling frequency (multi-year average number of days with negative temperature anomaly per month or season in a given cell) (*b*), and chlorophyll a concentration (up to 15 mg/m^3) (*c*) in 2000–2019

The mean chlorophyll a concentration in the coastal zone within the 30-meter isobath for the summer seasons of 2000–2019 was 5.3 ± 2.7 mg/m^3, which is generally comparable with the mean multi-year concentration values in the Baltic Sea surface layer obtained both from satellite and *in situ* [3, 4] data [23, 27–30]. However, they have a larger dispersion compared to the estimates obtained from contact observations [31], where the concentration in the 0–10 m layer in the summer seasons of 2003–2007 was ~ 4.3 ± 1.6 mg/m^3.

In general, the chlorophyll a concentration in the Baltic Sea varies within a wide range of 0.3–130 mg/m^3 [32]. In the area under study, local increases in concentrations are observed due to the runoff of the Vistula River, Vistula and Curonian lagoons. A zone with the depths of < 30 m is clearly distinguished in

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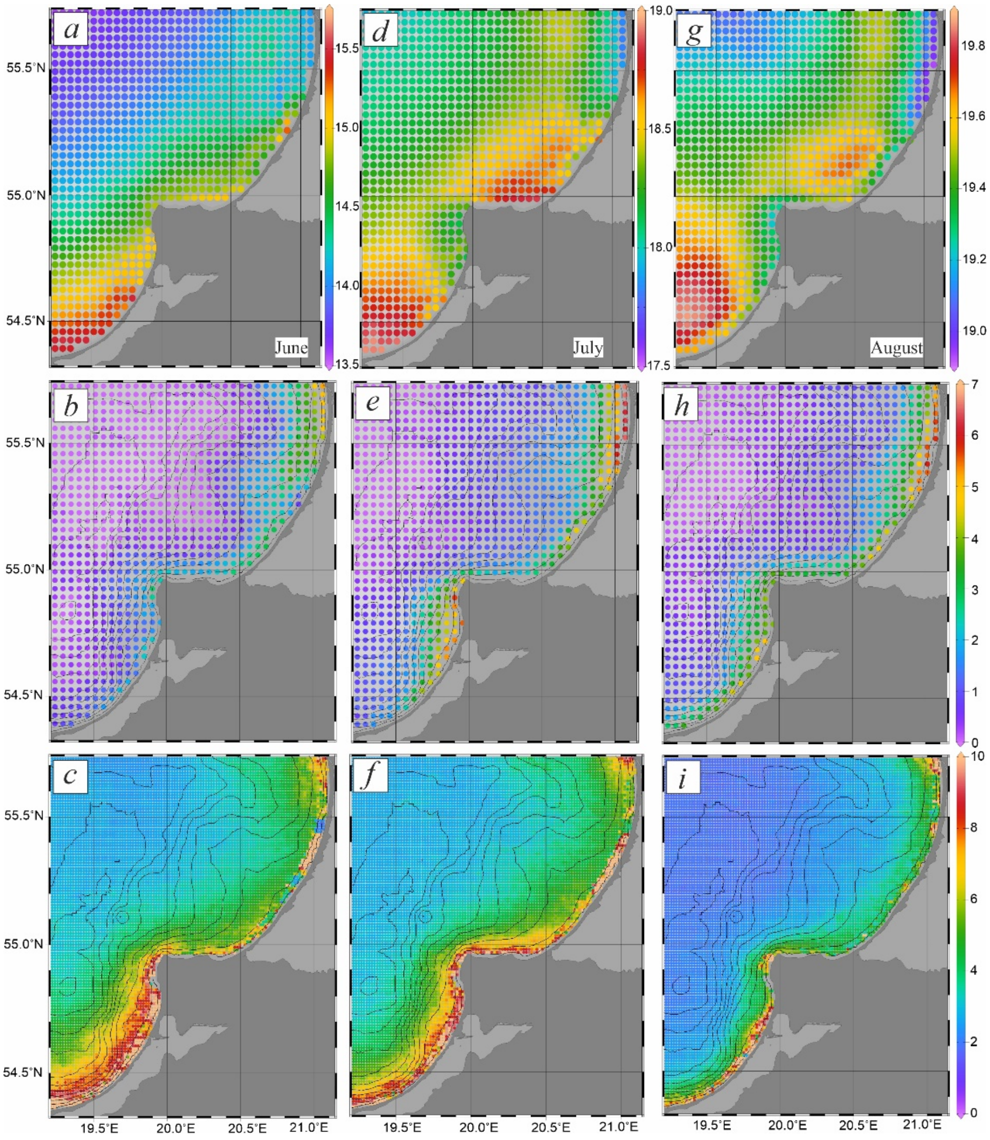
[3] Wasmund, N., Nausch, G., Postel, L., Witek, Z., Zalewski, M., Gromisz, S., Łysiak-Pastuszak, E., Olenina, I., Kavolyte, R., [et al.], 2000. *Trophic Status of Coastal and Open Areas of the South-Eastern Baltic Sea Based on Nutrient and Phytoplankton Data from 1993–1997*. Warnemünde: Institut für Ostseeforschung, 83 p. (Meereswissenschaftliche Berichte; vol. 38). doi:10.12754/msr-2000-0038

[4] Bukanova, T., Nizhnikovskaya, O. and Trushevskiy, A, 2016. Assessment of Eutrophication in the Baltic Sea Coastal Waters from Satellite Imagery. In: *2nd Student Workshop on Ecology and Optics of Coastal Zones: Book of Abstracts*. Kaliningrad, Russia, pp. 1-4.

the water area. An increased upwelling frequency (at least 3 days per month) and chlorophyll a concentration (> 5 mg/m^3) are observed there.

To assess the influence of upwelling intra-seasonal variability on the chlorophyll a concentration, the maps of average monthly values of these parameters were constructed according to the data of 2000–2019, supplemented by SST maps (Fig. 3).



F i g. 3. Intra-seasonal variability of SST (°C) in June (*a*), July (*d*) and August (*g*); upwelling frequency (multi-year average number of the days with negative temperature anomaly per month or season in a given cell) in June (*b*), July (*e*) and August (*h*); chlorophyll a concentration (mg/m^3) in June (*c*), July (*f*) and August (*i*) of 2000–2019

In June, the SST of the coastal zone varied from 13.5°C in the open sea to 15.5 °C in the Vistula Spit western part. Along the northern coast of the region, the temperature was ~ 15 °C. Northwards of the Rybachiy Plateau, a local temperature increase (up to 15.3 °C) was observed, in the Curonian Spit northern part, the temperature was ~ 14.1 °C, which corresponded to the maximum frequency of negative temperature anomalies in this part of the coastal zone (Fig. 3, *a*). In June, upwelling reached its largest area in the Rybachiy Plateau region due to the bottom topography feature – an extensive shallow plateau is observed in this part of the water area. An average upwelling area off the western coast of the Sambia Peninsula in June was significantly less than that off the northern coast, which is associated with a large bottom slope (Fig. 3, *b*). In June, the highest chlorophyll a concentrations were observed northwards of the Rybachiy Plateau. The concentrations were higher near the Vistula Spit than along the Sambia Peninsula northern coast and the Curonian Spit southern part, which is probably due to higher SST in this area (Fig. 3, *c*).

Note that in the Baltic Sea the dominant phytoplankton communities in summer are the cyanobacteria *Nodularia spumigena*, *Anabaena* spp. and *Aphanizomenon* sp. [5] [33]; the first two species are observed at depths of 10 m or less [34], the latter is found at greater depths. Probably, increased chlorophyll a concentrations in the southern part of the area under study in June are associated with optimal conditions for the development of cyanobacteria [35]. On average, within a 30-meter isobath the concentration is ~ 6.88 mg/m^3, which is comparable with previously obtained estimates [3, 4] [27, 28].

The SST spatial variability in July is somewhat different from that in June: the highest temperature is observed in the southern part of the region and along its northern coast (up to 19°C). The minimum temperature can be traced in the northern part of the Curonian Spit and is ~ 17.8 °C, in the open part of the sea – up to 18 °C (Fig. 3, *d*). An increase in the number of negative temperature anomalies is observed from June to July. In July, another area of frequent occurrence of negative anomalies appears at the western coast of the Kaliningrad Oblast (Fig. 3, *e*). In the same month, there is a significantly greater number of upwelling events along the western coast of the region compared to other months (~ 6 days per month in July versus 3–4 days in June and August). An algal bloom observed in July, associated with the massive development of cyanobacteria and water temperature rise in the coastal zone, is reflected in the chlorophyll a concentration increase along the Sambia Peninsula northern coast (Fig. 3. *f*). At the same time, concentration of the parameter under consideration in the southern part of the region decreases compared to June, which may be related to the depletion of nutrient supply in this area due to an earlier algal bloom. On average, the chlorophyll a concentration is ~ 7 mg/m^3 in the coastal zone.

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[5] Neumann, T. and Schernewski, G., 2002. Will Algal Blooms in the Baltic Sea Increase in Future? Model Simulations with Different Eutrophication Combat Strategies. In: Deutches IHP/OHP-Nationalkomittee, 2002. *Low-Lying Coastal Areas – Hydrology and Integrated Coastal Zone Management. International Symposium on Low-Lying Coastal Areas. Hydrology and ICZM*. IHP/OHP-Berichte, Sonderheft 13. Koblenz: Deutches IHP/OHP-Nationalkomittee, pp. 139-145.

In August, the SST up to isobaths of 20–40 m is slightly lower in the coastal zone than in the areas with greater depths (Fig. 3, *g*). The maximum temperature is also observed in the SEB southern part, in the area of 70-meter isobath (up to 19.9 °C), the minimum is observed in the Curonian Spit northern part (up to 19 °C). In August, a slight decrease in the number of upwelling events compared to July (Fig. 3, *h*) takes place. In August, the area of frequent upwelling manifestation along the Curonian Spit coast and the western coast of the region decreases. This is probably due to the warming in the wide strip of shallow waters and an increase in the seasonal thermocline depth. The largest number of upwelling events in August, as well as in June – July, is observed at the exit from the Curonian Lagoon, which is also noted in [20]. In August, the mean values of chlorophyll a concentration are slightly lower than in June and July (< 5 mg/m^3), which is also noted in [36, 37]. The highest values are observed westwards of Cape Taran and at the exits from the lagoons (Fig. 3, *i*).

The increased values of chlorophyll a concentration are naturally observed at the exits from the lagoons. In the area close to the Klaipeda Strait, the zone with increased concentrations in June and July is smaller than in the Strait of Baltiysk area. The increased concentration values in the southern part may be associated with the effect of the Vistula River runoff; in the northern part – with the propagation of the Curonian Lagoon waters to the north. This can probably be explained by the fact that, in general, the Curonian Lagoon is characterized by a higher level of phytoplankton productivity compared to the Vistula Lagoon [38].

The described spatial variability of chlorophyll a in the SEB coastal zone indicates the presence of not only intra-seasonal fluctuations, but also regional distribution features, possibly caused by the influence of mesoscale processes (such as upwelling) developing in the coastal zone.

To quantify the impact of upwelling events on the chlorophyll a concentration in the coastal zone, an analysis of the upwelling events provided by the satellite data was carried out.

Quantitative assessment of upwelling influence on chlorophyll a concentration in the SEB. Table 1 provides the mean values of chlorophyll a concentration on the profile before, during and after the upwelling in 2000–2019. The dashes correspond to the periods with no available data.

It follows from Table 1 that lower chlorophyll a concentrations in the coastal zone after upwelling, compared to the concentration values before it, appear regardless of its duration. Over the entire study period, chlorophyll a drops by 0.4 mg/m^3 after the start of upwelling and by 1.42 mg/m^3 (27%) after its finish. The greatest decrease in concentration (~ 4.5 mg/m^3 or 67%) after upwelling was observed in June 2016. Moreover, in 9 out of 31 cases, the decrease in concentration after upwelling was > 3 mg/m^3 (a drop of 37–67%), in 11 cases – > 1 mg/m^3. The chlorophyll a concentration during upwelling, on average, was often lower on the profile than in the upwelling zone. This is probably due to generally increased concentration values in the coastal zone (see Fig. 2, *c*).

Table 1

Chlorophyll a concentration before, during and after upwelling

Upwelling dates on profile	Profile number	Upwelling duration, days	Mean concentration of chlorophyll *a*, mg/m^3		
			before upwelling	during upwelling	after upwelling
04–10.07.2001	*3*	7	6.26	5.22	2.57
23–31.07.2001	*3*	9	2.72	3.27	5.70
23–26.08.2001	*3*	4	3.22	4.33	3.03
17–19.07.2002	*4*	3	6.12	5.67	2.84
04–31.08.2002	*4*	27	5.19	4.51	–
02–05.06.2003	*6*	4	1.22	1.98	1.67
16.07–14.08.2003	*1*	30	4.34	7.31	4.52
07–15.08.2004	*4*	9	4.55	3.59	3.83
09–13.07.2005	*9*	5	8.95	7.56	5.66
03–09.07.2006	*4*	7	6.36	3.92	3.35
12.07–22.08.2006	*4*	42	3.35	3.78	1.52
07–12.06.2007	*6*	6	9.59	7.27	–
15–16.06.2007	*6*	1	–	7.66	6.96
01–10.06.2008	*7*	10	–	3.78	5.31
13–15.07.2008	*8*	3	7.62	8.50	7.57
27.07–03.08.2008	*8*	8	7.50	6.88	3.54
30.06–05.07.2009	*8*	6	–	5.76	6.72
30.06–08.07.2009	*2*	9	5.13	4.52	4.85
08–11.08.2009	*8*	4	6.18	8.68	2.05
15–20.07.2010	*8*	6	9.66	8.92	8.79
04–06.08.2011	*4*	3	3.79	5.36	3.07
23–27.07.2014	*2*	5	6.63	3.46	2.57
23–29.07.2014	*4*	7	5.39	3.78	2.74
09.08.2014	*2*	1	2.54	2.76	2.53
15–25.08.2015	*9*	11	5.78	4.70	2.69
05–09.06.2016	*5*	5	6.70	4.57	2.21
01–05.07.2018	*6*	5	3.33	5.26	3.86
16–21.07.2018	*6*	6	4.45	2.76	5.27
25–29.07.2018	*6*	5	5.27	3.12	–
31.07.2018	*6*	1	–	2.67	2.72
01–08.08.2019	*4*	8	3.32	2.46	2.51
Mean value for 2000–2009			5.52	5.48	4.22
Mean value for 2010–2019			5.17	4.15	3.54
Mean value for 2000–2019			5.38	4.97	3.95

Within the period of 2000–2009, the chlorophyll a increase after upwelling was noted three times: at the end of July 2001, beginning of June 2003 and in mid-July – August 2003 (see Table 1); within the period of 2010–2019, the increase after upwelling was observed only in July 2018.

The average decrease in chlorophyll a concentration after upwelling in the second decade is slightly greater than in the first one. This may be due both to the changes in characteristics of the studied upwelling events (changes in their duration and frequency by month) and to the influence of seasonal variation in the chlorophyll a concentration: in the second half of July – August a natural decrease takes place, which may be due to the depletion of nutrient supply in this area; in the second decade, the largest share of all considered upwelling events were the upwellings of July and August.

Most of the studied (see Table 1) upwelling events lasted up to 5 days (14 out of 31). Moreover, in the first decade the duration of upwelling events included in the analysis is ~ 10 days; in the second decade – slightly more than 5. After short upwelling events (5 days or less), the chlorophyll a concentration drops by an average of 1.24 mg/m^3, after longer ones – by 1.89 mg/m^3.

To illustrate the upwelling effect on the chlorophyll a concentration in the coastal zone, the maps of its changes in June 2007 are demonstrated in Fig. 4.

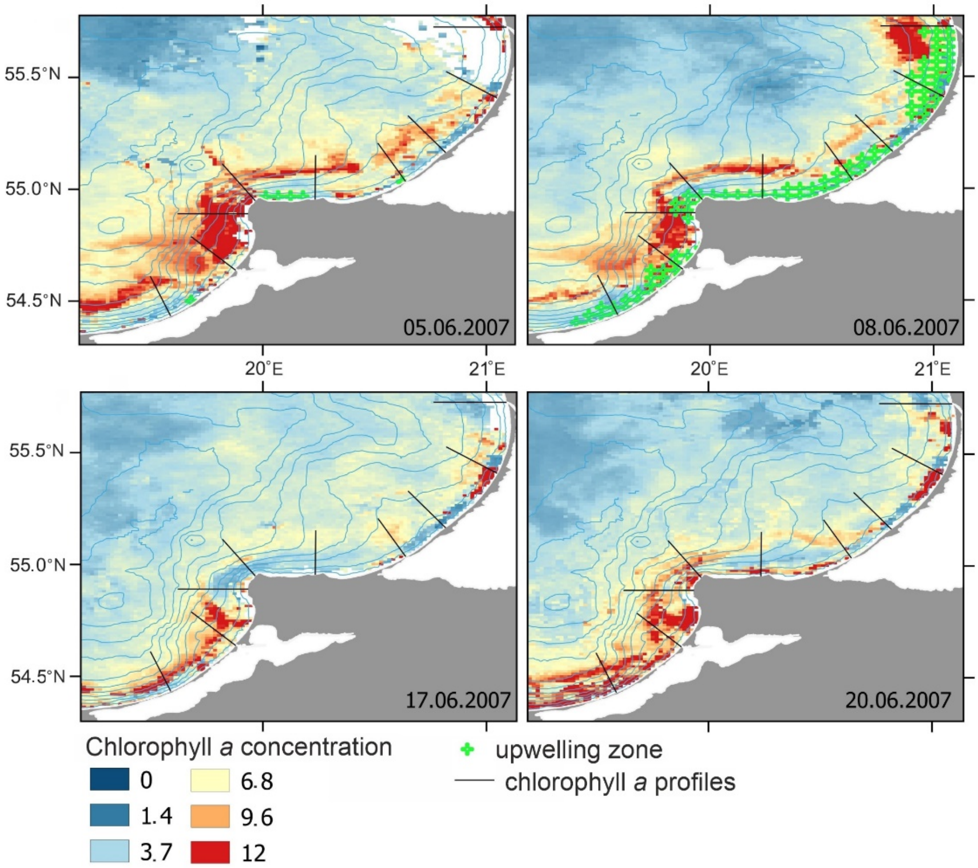

Fig. 4. Changes in chlorophyll a concentration during and after the upwelling event on June 4–16, 2007

The upwelling observed on 4–16 June 2007 led to the following change in the chlorophyll a concentration: on the first day (June 5), its mean value in the upwelling zone decreased to ~ 3 mg/m^3, while outside the upwelling zones it was ~ 10 mg/m^3 (Fig. 4). A chlorophyll a front, characterized by a two-fold drop in concentration (from 7–8 to 4 mg/m^3), was noted on profile *6* (Fig. 1, Cape Taran area) on 8 June at the upwelling boundary at ~ 9 km from the coast. A concentration drop of 40–50% was demonstrated in [25]. After the end of the upwelling (June 17), the concentration in the coastal zone of ~ 7 km wide was still reduced; its increase in the coastal zone was noted only since June 20, on the fourth day after the end of the upwelling.

Previously, it was shown for the Baltic Sea that in coastal areas there is a time delay between phytoplankton growth and the nutrient supply to the surface layer as a result of upwelling [8, 23, 39]. For example, in the Gulf of Finland and off the island of Gotland, the increase in phytoplankton biomass occurred with a 2–3-week delay after the upwelling. In [11], no growth of phytoplankton was noted after the upwelling; the authors attribute this to the fact that 10 days after the end of one upwelling, the next one began. In this case, the time interval between nutrient supply and phytoplankton growth depends not only on the upwelling characteristics, but also on the species composition of phytoplankton in its upwelling area, as well as on the ratio of nutrients and the temperature of the water raised to the surface layer. An important factor is also the length of an adaptation period of phytoplankton communities raised to the surface layer to temperature, light, and nutrient concentrations [7].

In addition, due to the presence of a seasonal variation in the chlorophyll a concentration, associated with abiotic factors and succession of the phytoplankton community, it is also important to know the quantitative contribution of upwelling events to the variability of its concentration during the summer season on the profiles under study (see Fig. 1). The changes in concentration are presented in Table 2.

Table 2

Changes in mean chlorophyll a concentration in summer months due to upwelling

Month	Mean concentration of chlorophyll *a*, mg/m^3	Upwelling mean duration, days	Mean concentration of chlorophyll *a*, mg/m^3	
			before upwelling	after upwelling
June	5.27	5.20	5.84	4.04
July	5.33	7.18	5.98	4.58
August	3.78	12.11	4.21	2.65

Chlorophyll a mean values on the profiles are approximately equal in June and July with the highest weighted mean concentration observed in June. This difference probably reflects intra-seasonal variation of the upwelling influence on concentrations. Moreover, their average duration amounted to 5.2–7.18 days in June–July and increased significantly by August. Within the week after the upwelling, the chlorophyll a concentration demonstrates reduced values in all months and amounts to ~ 1.4–1.8 mg/m^3. Compared to the long-term average data, its greatest decrease is observed in June. Moreover, July had the greatest number of significant concentration decreases after the upwelling (6 times out of 9 within the entire study period – by more than 3 mg/m^3 and 8 times out of 11 – by more than 1 mg/m^3).

A joint analysis of chlorophyll a and SST satellite data shows that a decrease in its concentration caused by upwelling leads to a positive effect on water quality in the coastal zone [39]. It is worth noting that in the works studying algal blooms , it is indicated that in most cases blooms are observed already at a distance from the coast and it is comparable to the upwelling width [40].

The performed analysis confirms the need to take into account the intra-seasonal variation of chlorophyll a concentration when considering the influence of upwelling events, which is important for correct assessments of changes in the ecological state of the coastal zone.

Conclusion

According to the data on the frequency and duration of upwelling events in June – August 2000–2019 and multisensor satellite observations of chlorophyll a concentration in the coastal zone of the southeastern Baltic Sea, long-term and monthly average values of the studied parameters were obtained. High concentrations were observed in the area of exits from the Vistula and the Curonian lagoons, the highest concentrations were found northwards of the Rybachiy Plateau. Moreover, in the Curonian Spit northern part, in the area of the highest frequency of upwelling events, the zone with increased chlorophyll a concentrations had a smaller area than in the Strait of Baltiysk. In June, the upwelling zone had the largest area in the Rybachiy Plateau region, while the chlorophyll a concentration there was lower than northwards and southwards of the plateau. This indicated a possible relationship between the chlorophyll a spatial variability and the frequency of upwelling events.

In the study area, nine 20-kilometer profiles from the coast towards the sea were analyzed, on which the chlorophyll a concentrations were calculated for a week before, during and after the upwelling. This provided the assessment of their influence on concentration. It was demonstrated that a decrease in concentration was observed after an upwelling event of any duration and in all months; on average, after an upwelling event the concentration dropped by more than 1 mg/m^3 (27%). After short upwelling events (lasting less than 5 days), the chlorophyll a concentration decreased, on average, by 1.24 mg/m^3, after longer ones – by 1.89 mg/m^3. On average, in June–August, the concentration dropped by approximately 1.4–1.8 mg/m^3 after upwelling; in July, a significant decrease was observed most often. The noted difference reflects the presence of an intra-seasonal variation in the upwelling influence on the chlorophyll a concentration in the considered water area associated with both abiotic factors and succession of the phytoplankton community.

The analysis of temporal variability of chlorophyll a concentration revealed that a few days after the upwelling its growth begins, which is probably associated with the development of phytoplankton communities caused by nutrient supply to the photic layer and is often stimulated by the water temperature increase.

The decrease in chlorophyll a concentration after upwelling in the second decade of the current century is slightly greater than in the first one, which is likely due to the changes in the characteristics of the events included in the analysis. In the second decade, a decrease in the duration of upwelling was observed, most significant – in July and August. On average, in 2000–2009, upwelling throughout the SEB lasted about a week (7.1 days), in 2010–2019 – 4.66 days. Most of those studied occurred during upwelling events lasting less than 5 days (14 out of 31, 7 in each decade) and 6–10 days (13 upwellings). Moreover, in the first decade of the 21st century the duration of upwelling events is ~ 10 days, in the second – ~ 5.

In the future, some targeted observations are required in upwelling zones and beyond them in order to analyze the species composition of phytoplankton communities. This will enable us to identify the influence of upwelling on the ecological state of the Baltic Sea waters, including algal blooms with a massive development of potentially toxic cyanobacteria.

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