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Original article

Variability of Upwelling Characteristics in the Southeastern Baltic Sea in the First Two Decades of the 21st Century

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Abstract
Purpose. The study is purposed at systematizing the regional features of coastal upwelling in the southeastern part of the Baltic Sea (SEB) during the summer seasons of 2000–2019 in a changing climate.
Methods and Results. The results of the identification of upwelling events in the southeastern Baltic Sea are presented as a negative anomaly of the coastal sea surface temperature relative to the selected area of the open sea. The estimates of influence of the local and global atmospheric processes (based on the data on wind characteristics and *SCAND* and *NAO* teleconnection indices) upon the upwelling event characteristics (frequency, duration and area) were obtained. On average, 4 upwelling events with a total duration exceeding 20 days were observed at the upwelling zone average area of about 620 km^2. The upwelling frequency in the area under study was the highest along the northern part of the Curonian Spit and the Sambia Peninsula western coast. In comparison to 2000–2009, the upwelling durations in the summer seasons of 2010–2019 were recorded to decrease by about 8 days at the decline of frequency of the winds favorable for their development by 4–5%. The correlation between the number of upwelling days in the southeastern Baltic Sea and the *SCAND* index is established (the correlation coefficient was 0.65) that allows further attempts on obtaining the long-term forecasts of the probability of coastal upwelling development in the southeastern Baltic Sea.
Conclusions. It is shown that a steady decrease in the upwelling frequency in the SEB in recent decades is related to a declining frequency of the upwelling-favorable winds largely conditioned by the anticyclogenesis development over the Scandinavian Peninsula.

Keywords: coastal upwelling, upwelling type, interannual variability, large-scale atmospheric circulation, southeastern Baltic Sea

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Introduction

Regional features of upwelling in the southeastern Baltic Sea (SEB) are well described based on the results of modeling and generalization of the long-term data [1–4]. It has been shown that coastal upwellings of the Baltic Sea have two main mechanisms of occurrence [5–8]: Ekman transport of surface waters from the coast under the alongshore wind influence [8] (classical, or Ekman upwellings) and upwelling induced by the stress of normal to coastal seaward winds (offshore-wind-driven upwelling, so-called “Leewirkung”) [7, 9]. It is known [10] that upwellings can be caused by other reasons, for example, the impact of alongshore currents, but in the Baltic Sea the main factors influencing the short-term variability of surface currents are the local wind and the associated Ekman transport [11].

It is believed that atmospheric transport variability over the Baltic region noted by many researchers in the 21st century [12, 13] should be reflected in the intensity of upwellings in the water area under consideration [14–16]. However, the existing studies of upwellings in the SEB make it impossible to describe their spatial dynamic features over a long-time interval (several decades) and to systematize the data on the area of temperature anomalies as well as to obtain estimates of the relationship of these anomalies with atmospheric circulation characteristics to determine the possibilities of forecasting upwelling events. To obtain and clarify this information is important in understanding the way that ongoing global climate changes affect the characteristics of waters off the coast of the Kaliningrad region, actively used for recreational purposes. The results of upwelling variability research can also be used to study local dynamics of coastal zone waters associated with pollution, nutrients, and phytoplankton transport. In addition, the information obtained can be used to develop science-based monitoring strategies and coastal zone management.

Therefore, the present paper is aimed at studying regional features of coastal upwelling in the SEB in the first two decades of the 21st century in changing climate. The objectives of the paper are identifying events of surface manifestations of upwellings in the SEB waters, estimating their spatiotemporal variability for 2000–2019, analyzing the influence of local weather conditions and large-scale atmospheric circulation on the characteristics of upwellings in the coastal zone of the SEB.

Materials and methods

An estimation of the spatial variability and quantitative characteristics of the frequency of temperature anomalies, identified as the surface indicators of upwellings, was carried out using average daily water temperature data with a spatial resolution of 4 km at the 1.5 m depth from June to August 2000–2019. The data were obtained from the Baltic Sea Physics Reanalysis product (CMEMS) [1]. Coastal water areas with the temperature of 1 °C below the background values for the selected open sea area were marked as upwelling zones (the method is described in more detail in [2]). The presence of negative temperature anomaly cells in the coastal area lasting from one day with an area of one cell was taken as an upwelling event. Using this technique, upwelling dates and areas were identified for the SEB water area limited by coordinates 19.236–21.200°E, 54.300–55.725°N (Fig. 1) for two subregions: western (western coast of the Kaliningrad region and the coast of the Vistula Spit) and northern (northern coast of the Kaliningrad region and the coast of the Curonian Spit).

The frequency of upwellings was obtained in days and events. The average daily area (km^2) of each upwelling was calculated as the sum of the areas of cells where

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[1] Copernicus Marine Service. *Baltic Sea Physics Reanalysis*. doi:10.48670/moi-00013

a negative anomaly, divided by the upwelling duration, was observed. The average upwelling areas for each month and season were defined as the average of the upwelling areas observed in that month and season. Vertical velocities in the upwelling zone were estimated from the vertical change in the position of isotherms at the reanalysis grid nodes in the coastal zone during upwelling observation (m/day).

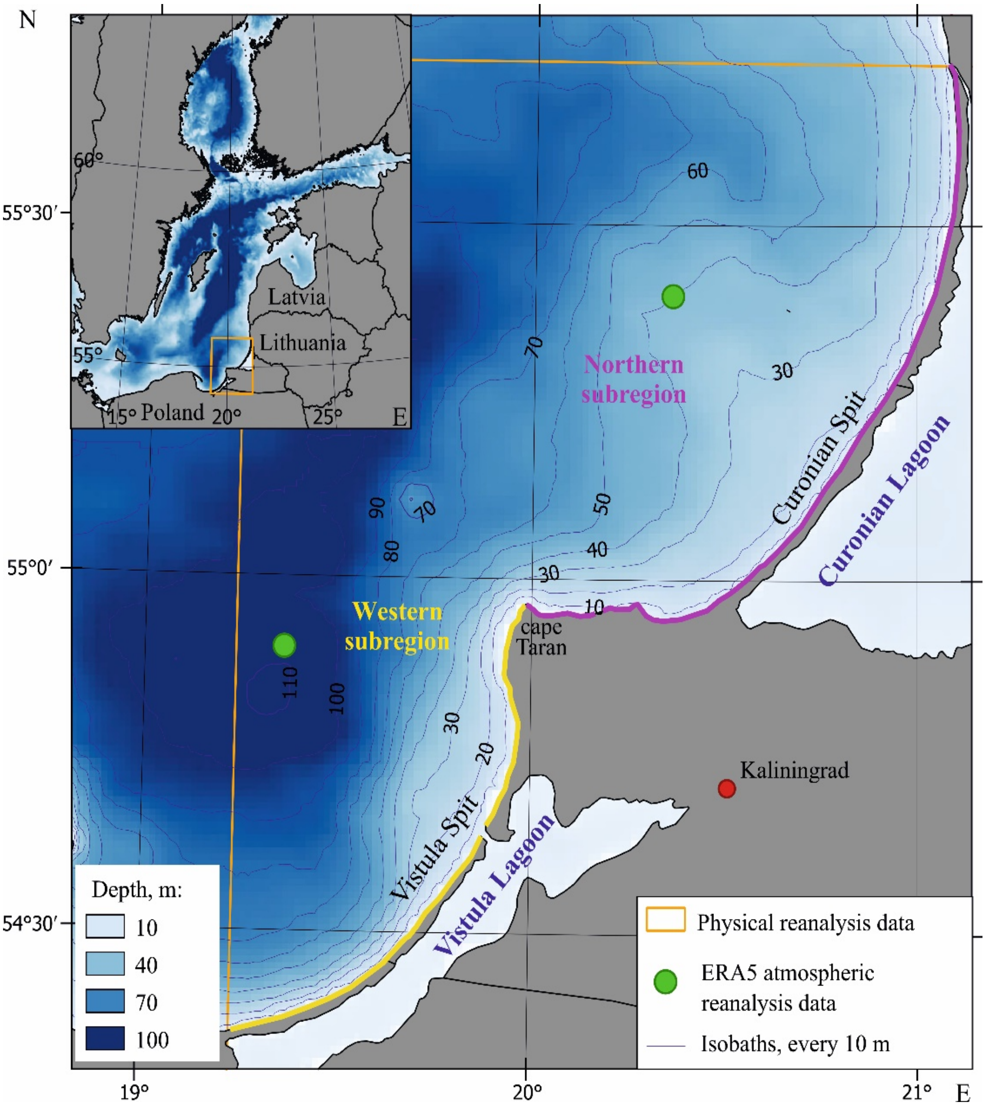

Fig. 1. Area under study. The coast is divided into the northern and western subareas (purple and yellow colors of coastlines, respectively)

The frequency of wind directions at 16 points and its velocity for 2000–2019 were calculated using hourly data on wind components from the ERA5 reanalysis [2] at the 10 m height (similar to [17, 18] in squares with 55.40°N, 20.36°E (northern subregion) and 54.90°N, 19.36°E (western subregion)) coordinates. In addition, for each identified upwelling lasting more than two days, wind direction frequencies were obtained at 16 directions three days before the event started. They were used to determine the winds favorable for upwelling development and for the subsequent determination of the upwelling type: classical (or Ekman) upwelling; upwelling, caused by offshore winds; or mixed upwelling. It is worth noting that for the Baltic Sea there are several duration and wind speed estimates sufficient for classical upwelling development: in [10] it was shown that to raise water from the 5 m depth, the 10 m/s wind blowing parallel to the shore for one day is sufficient; in [18], the 3.5 m/s wind, blowing for at least 2 days, was accepted as favorable; in [17], the case of the upwelling development after a 42-hour exposure to wind velocities of up to 10 m/s was studied. In the present paper, it was assumed that classical, or Ekman, upwelling was formed under the alongshore wind influence; offshore-wind-driven upwelling was formed under the influence of the wind directed from the coast towards the sea. Moreover, in [19], the Ekman layer depth for the Baltic Sea for a wind speed of 10 m/s was estimated at 25 m, i.e., Ekman upwellings even with favorable winds will develop at depths ~ 20–30 m. At the same time, the northern and western SEB subregions differ significantly in bathymetric characteristics: near the Curonian Spit, the 30 m isobath moves away from the coast at a distance of ~ 20 km, near the Vistula Spit it approaches the values of ~ 3 km. Accordingly, the ratio of sea depth to Ekman layer depth in these waters varies in the range of 0.1–2 at an equal 10 km distance from the coast.

The coast direction was taken to be the tangent along the coastline of the subregions for those parts of the coast where upwellings are observed more often than the average for the region under study. If the total duration of one type of the winds exceeded significantly the duration of another type of the winds, the upwelling was considered to be caused by alongshore or offshore winds. If the difference in the duration of winds of different types was < 10%, the upwelling was recorded as mixed.

Analysis of the influence of atmospheric circulation parameters on the characteristics of upwellings was carried out by calculating linear correlation coefficients (the average monthly number of days with upwelling (June – August)) with the average monthly (May – August) values of large-scale atmospheric circulation indices: SCAND (the Scandinavia teleconnection pattern characterizing the pressure gradient between Scandinavian peninsula and south of Europe) and NAO (North Atlantic Oscillation characterizing variability of the meridional pressure gradient in the northern Atlantic Ocean) [3]. The obtained coefficients were

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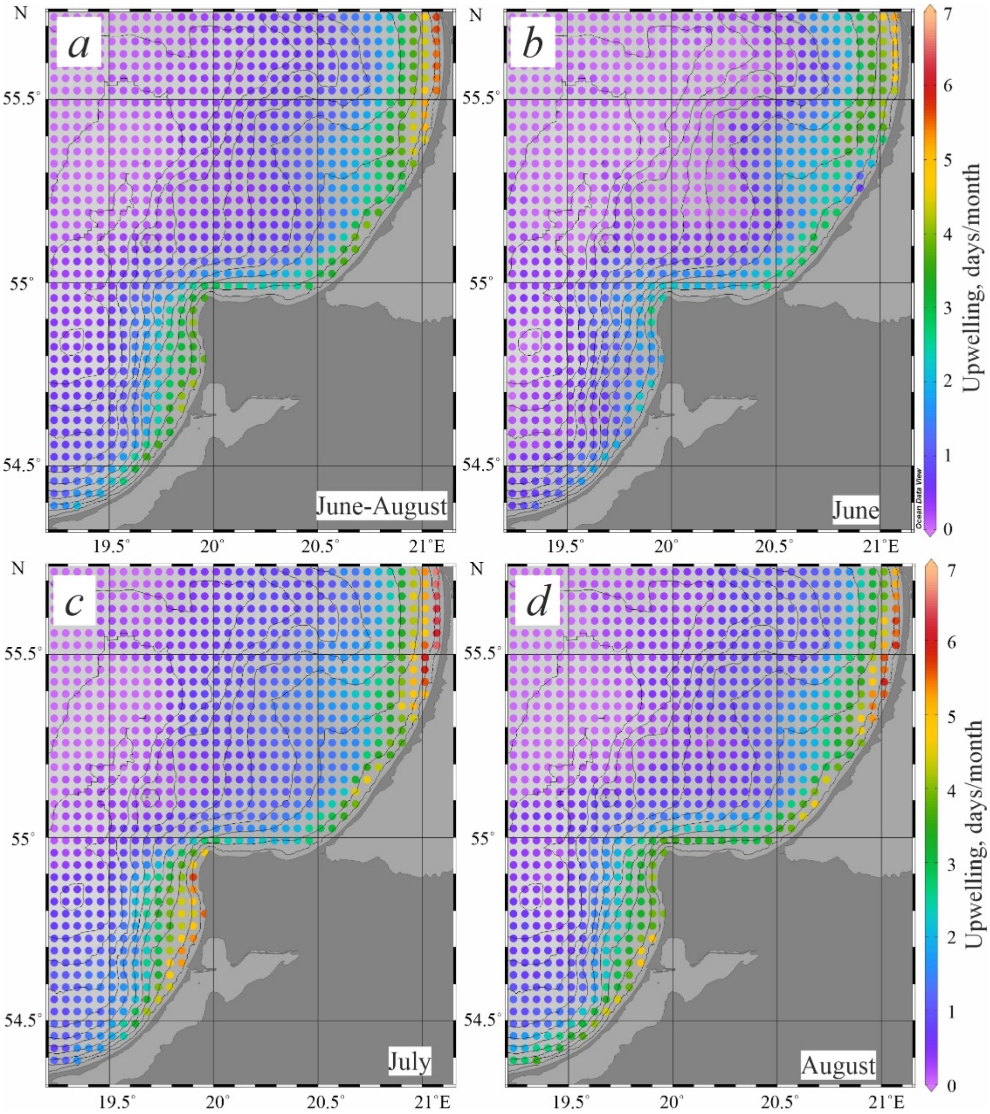
[2] Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R. [et al.], 2023. *ERA5 Hourly Data on Pressure Levels from 1940 to Present.* Copernicus Climate Change Service (C3S); Climate Data Store (CDS). doi:10.24381/cds.bd0915c6

[3] National Weather Service. Climate Prediction Center. *Northern Hemisphere Teleconnection Patterns*. [online] Available at: https://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml [Accessed: 10 June 2020].

estimated at the significance level of α = 0.05; those not corresponding to this level were not presented in the study.

Results

The analysis carried out permitted to reveal 82 upwellings with a total duration of 546 days for the summers of 2000–2019 in the SEB. The spatial variability of the negative temperature anomalies, identified as indicators of upwellings, over the entire summer season and by month is shown in Fig. 2, which reflects a well-defined intraseasonal variation in the frequency of upwellings.



F i g. 2. Long-term average annual number of days with a negative temperature anomaly per month over a season and per month in a given cell in 2000–2019

On average for summer period (Fig. 2, *a*), an area with depths of < 30 m is clearly visible in the water area, where negative temperature anomalies take place at least three days a month. The largest number of upwellings is observed at the exit from the Curonian Lagoon; a high frequency of upwellings in this area is also noted in [20]. According to the frequency of upwellings in summer, the coastal waters can be divided into several areas: the first includes the northern coast of the Sambia Peninsula and the western part of the Vistula Spit (two or fewer days of observation of upwellings per month), the second includes the area near Cape Taran and the southern part of the Curonian Spit (3–4 days of observation of upwellings per month), the third includes the western coast of the Kaliningrad region and the northern part of the Curonian Spit (upwellings are observed > 4 days per month).

In June, the maximum number of negative temperature anomalies can be observed in the northern part of the Curonian Spit (Fig. 2, *b*). At this time, upwellings reach their largest area near the Rybachy Plateau, which is due to the bottom topography peculiarities (there is an extensive shallow plateau in this part of the water area). The average upwelling area in June off the western coast is smaller than off the northern one, which can probably be explained by the topography features (a significant bottom slope).

In July (Fig. 2, *c*), an increase in the frequency of upwelling events is observed in the water area. There is a significantly greater number of upwellings along the western coast of the region than in other months studied. According to the maximum frequency of upwellings, two subregions are clearly distinguished. These are the Curonian Spit and the western coast of the Kaliningrad region with the northern part of the Vistula Spit, while the northern coast of the region, as well as the southern part of the Vistula Spit, are distinguished by low frequency of upwellings, which is probably due to the wind regime peculiarities.

In August (Fig. 2, *d*), the area of upwellings along the Curonian Spit coast and the western coast of the Sambia Peninsula decreases. This is probably due to the development of a warming area in wide shallow water. At the same time, the maximum decrease in the frequency of negative anomalies is observed in the western subregion.

Table 1

Frequency and area of upwellings of different duration in SEB in June – August, 2000–2019

Upwelling duration, day	Number of upwellings, total (June/July/August)	Average daily area of upwellings (range of variation), km^2
1–5	52 (20/16/16)	181 (1139)
6–10	14 (2/6/6)	761 (1876)
11 and more	16 (5/8/3)	1949 (4487)

In the SEB, the highest frequency of upwellings is up to 5 days (Table 1), their average area is an order of magnitude lower than that of long-lasting upwellings (> 11 days). At the same time, the area variability relative to the average estimates is maximum for the shortest (lasting up to 5 days) of the events under consideration. Short upwellings are more often observed in June, long ones – in July.

Table 2

Main upwelling characteristics in SEB in June – August, 2000–2019

Year	Number of upwellings	S_{max} in SEB, km^2	Number of upwelling days (June, July, August)		Average daily area km^2	
			Subregions			
			northern	western	northern	western
2000	6	720	8 (0, 0, 8)	8 (0, 2, 6)	195	89
2001	4	4992	30 (1, 19, 10)	33 (0, 27, 6)	819	791
2002	4	6560	51 (12, 8, 31)	47 (11, 5, 31)	1330	453
2003	2	3760	34 (4, 16, 14)	24 (4, 16, 4)	595	566
2004	2	2528	19 (0, 5, 14)	13 (0, 3, 10)	830	411
2005	5	2912	20 (4, 10, 6)	10 (1, 9, 0)	223	292
2006	2	9584	62 (2, 30, 30)	56 (0, 26, 30)	2045	1053
2007	4	3136	21 (14, 0, 7)	18 (10, 0, 8)	303	227
2008	5	8016	26 (12, 10, 4)	31 (11, 11, 9)	1307	522
2009	5	3648	28 (2, 9, 17)	24 (7, 8, 9)	378	168
2010	6	6640	24 (9, 14, 1)	19 (3, 16, 0)	282	249
2011	2	528	9 (0, 3, 6)	4 (0, 1, 3)	219	64
2012	6	112	6 (4, 0, 2)	4 (2, 2, 0)	42	40
2013	6	1920	14 (10, 4, 0)	11 (8, 3, 0)	228	253
2014	6	4528	36 (12, 16, 8)	32 (3, 17, 12)	632	409
2015	3	1904	14 (0, 1, 13)	14 (0, 2, 12)	128	181
2016	5	5104	21 (18, 3, 0)	16 (12, 4, 0)	690	292
2017	1	16	0 (0, 0, 0)	1 (1, 0, 0)	0	16
2018	3	4992	45 (15, 28, 2)	33 (13, 19, 1)	1738	512
2019	5	896	17 (5, 4, 8)	6 (1, 1, 4)	278	41

The interannual variability of upwelling characteristics is shown in Table 2. On average, over the entire period, 4 upwellings were observed in the SEB water area in summer with a total duration of > 20 days. At the same time, the average daily area of the upwelling zone in the SEB was ~ 620 km^2. A greater number of days with upwellings and their larger area are characteristic of the northern subregion (see Fig. 1): there, during the summer season, an average of 24 days with upwellings per year were observed, their average daily area was ~ 560 km^2; in the western subregion – ~ 20 days with an average daily area of ~ 315 km^2.

In the SEB, from one (in 2017) to 6 (in 2000, 2010, 2012–2014) upwellings were observed during summer season. The average duration of one upwelling was < 7 days, but most often they lasted for one to two days. The longest duration of upwellings was observed in 2006 (60 days) and 2002 (32 days). Similar estimates for the eastern coast of the Baltic Sea were obtained in [20]. The smallest number of upwelling days was observed in 2017 (one day).

The largest areas of upwelling (up to 80% of the subregion water area) were observed in 2002 (in the northern subregion), 2006, 2008 and 2014 (in the western subregion); the smallest – in 2000, 2011–2012 and 2017. The maximum areas (> 5000 km^2) were recorded during the observation of upwellings in June 2008 and 2016, in July 2010 and in July – August 2002 and 2006.

The rate of isotherm rise in the area north of the Rybachy Plateau was ~ 4 m/day at the reanalysis grid node at 9 m depth during upwelling of medium intensity (July 13–14, 2018). In the coastal zone at a station with a depth of > 30 m west of Cape Taran, the rate of isotherm rise on July 15–16, 2006 was ~ 8 m/day during intense upwelling, which was accompanied by a significant decrease in temperature.

There is a high degree of correlation between the number of days with a thermal anomaly in summer and the average (correlation coefficient 0.85) and maximum area of upwellings (correlation coefficient 0.87), while no significant correlation can be observed between the number of events, their duration and area. In the SEB waters, a greater number of days with upwelling as well as larger areas were observed in the northern subregion, which is associated both with a larger area of shallow water in this subregion and the total length of the coastline and, possibly, with its orientation relative to the most recurring winds.

We should note the change by year in the intraseasonal frequency of upwellings: in 2000–2006 a greater number of days with upwelling was observed in July–August; since 2006 the distribution of days with upwelling has been more evenly distributed throughout summer season. In the northern subregion, an increase in the number of days with upwelling was observed in summer (from 6.2 days in June to 9 days in July–August). In the western subregion, the smallest number of days with upwelling was observed in June (4.4 days), the largest was observed in July (8.6 days), and in August there was a decrease to 7.3 days. Intraseasonal variability of the average daily area of the upwelling zone in the SEB in two regions shows an increase from June to July and a decrease by August.

An increase in the number of upwellings was recorded in 2010–2019 with a general decrease in their duration: in the first decade – 39 upwellings with a total duration of 327 days, in the second – 43 upwellings with a total duration of 221 days. The average daily area of upwellings in two regions in the second decade also decreased (by more than a half), which could be reflected in a change in the ecological state of coastal waters: coastal upwelling is an important mechanism for the transport of nutrients into the surface layer and the transfer of pollutants from the coastal zone to the open sea area.

In general, the frequency of upwellings in the summer of 2000–2019 in the SEB can be divided into three 6-year periods: an increase in frequency in 2006, a decrease in 2012 and a subsequent growth. Moreover, in 2000–2009 upwellings occurred significantly more often than in 2010–2019: on average > 30 days with upwelling in the summer of the first decade and 22 days in the summer of the second decade. A significant decrease in 2010–2019 both in the number of days and the area of upwelling was observed in July and August (Table 3). In addition, a sharp decrease in the variability of upwelling areas was observed in the second decade, especially in the northern subregion. In June, the number of days with upwelling decreased slightly in the western subregion, while in the northern subregion their increase was recorded. The noted intraseasonal variations in upwelling characteristics may be caused by changes in the nature of large-scale atmospheric circulation, which are reflected in the region, among other things, in the seasonal shift in the frequency of maximum winds [21].

Table 3

Average annual upwelling duration and frequency in SEB in June – August, 2000–2019 by decades

Month	Years	Number of upwellings			Number of upwelling days			Area (range of variation), thousand km^2		
		Regions and subregions								
		SEB	western	northern	SEB	western	northern	SEB	western	northern
June	2000 – 2009	1.00	0.70	0.90	5.7	4.4	5.1	0.9 (4.04)	0.33 (1.57)	0.61 (2.59)
	2010 – 2019	**1.90**	**1.30**	**1.50**	8.2	4.3	7.3	0.72 (3.01)	0.21 (0.57)	0.64 (2.58)
July	2000 – 2009	1.40	**1.30**	1.10	12.1	10.7	10.7	**1.32 (5.16)**	0.45 (1.17)	**1.08 (4.35)**
	2010 – 2019	1.70	**1.30**	1.40	8.7	6.5	7.3	0.45 (1.55)	0.22 (0.92)	0.29 (1.03)
August	2000 – 2009	1.50	1.10	1.20	**14.9**	**11.3**	**14.1**	1.23 (4,64)	**0.48 (1.05)**	0.92 (3.48)
	2010 – 2019	0.70	0.50	0.50	5	3.2	4	0.27 (1.43)	0.17 (1.19)	0.15 (0.54)

* the minimum parameter values are underlined, the maximum ones are in bold.

In most cases, a temperature decrease (interpreted as a indicators of upwelling) took place in each of the selected zones independently of each other under certain wind conditions. The greatest frequency in a three-day period before upwelling is demonstrated by the north-northeast (NE) wind for the western subregion and the north (N) wind for the northern subregion (Fig. 3). The lowest frequency in these subregions during the specified period is shown by western and southern winds. Wind directions that showed frequency above average (6.25%) are as follows: wind sectors from N to E for the western subregion and wind sectors from NNW to E for the northern one. More than 70% of upwellings in the western subregion and ~ 80% in the northern one are caused by winds of these directions; the remaining share of upwellings is caused by southern winds, which are driven by the northern coast of the Sambia Peninsula and the southern part of the Vistula Spit.

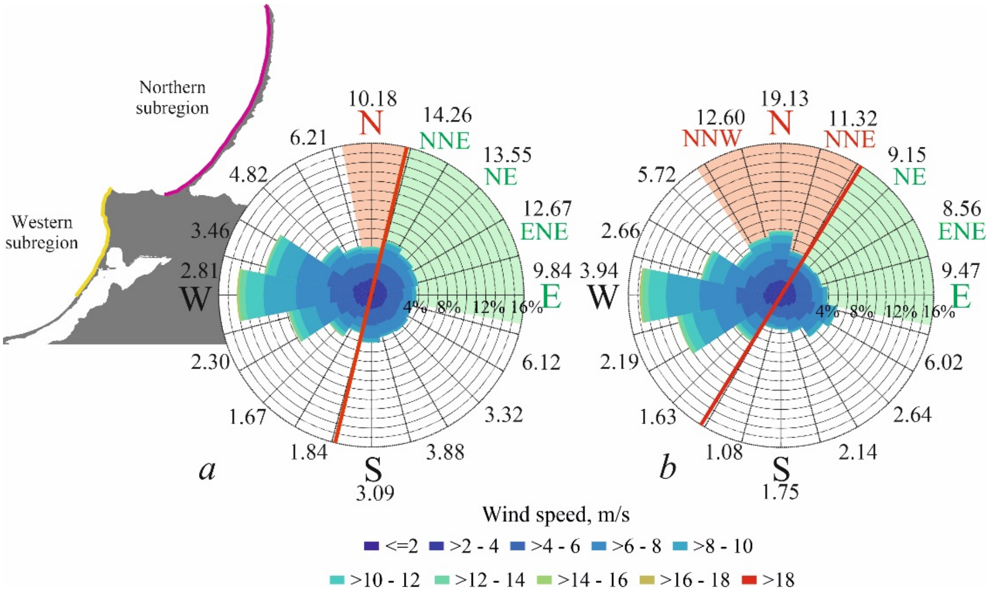
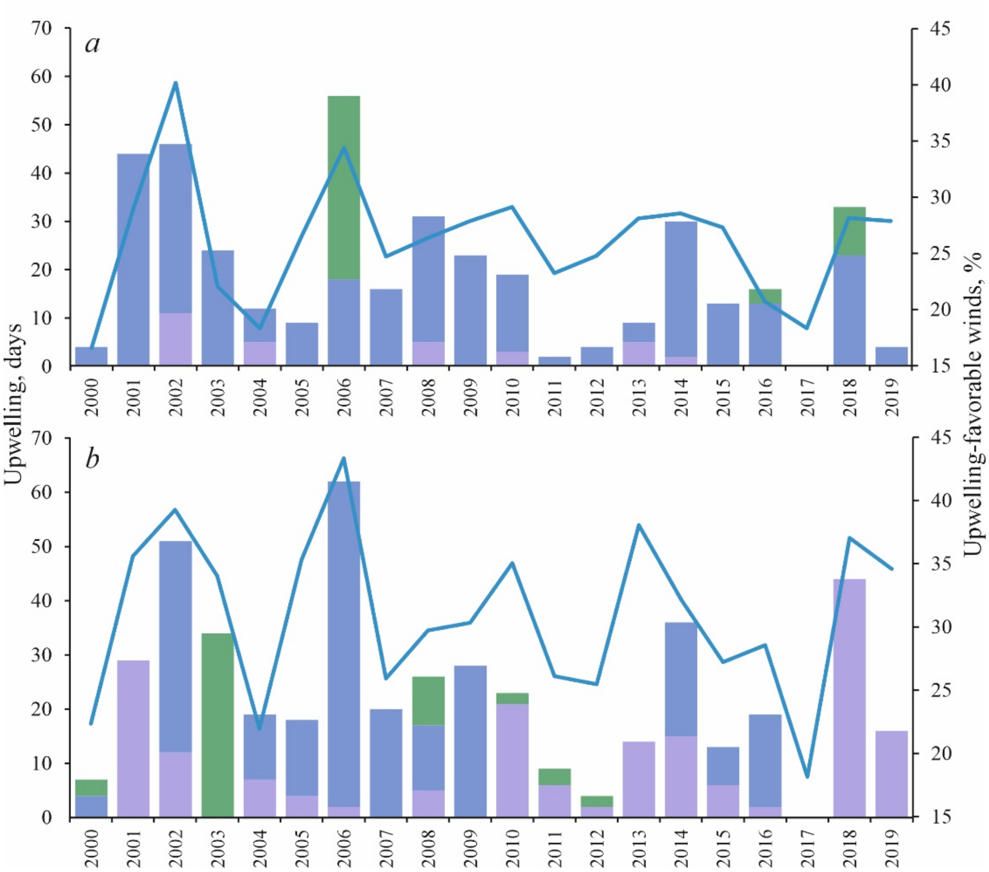


Fig. 3. Wind regime in the western (*a*) and northern (*b*) subregions of SEB in 2000–2019. Pink shading indicates alongshore wind directions leading to an upwelling, light green one – offshore wind directions leading to an upwelling. Red straight lines show the coastline average direction in the region of the highest upwelling frequency (coastline parts are given in the inset). Numbers on the direction points indicate the average frequency of winds three days before the upwellings occurred

A significant interannual variability of upwellings (Fig. 4) is associated with variability of winds favorable for their development. There has been a decrease in both the average annual number of days with upwelling and the frequency of favorable winds over the period. In 2000–2009 the share of favorable winds averaged 26.6% for the western subregion and 31.8% for the northern; in the second decade it decreased to 25.6% and 30.2%, respectively. The number of days with upwelling decreased in the second decade by 47% in the western subregion and by 38% in the northern one.

According to Fig. 4, the highest number of days with upwelling in the western subregion in 2002 and 2006 is associated with a smaller share (< 40%) of the frequency of unfavorable winds in the SW-W-NW directions. At the same time, the high frequency of winds in these directions noted in 2000 and 2017 (~ 60%) was reflected in fewer days with upwelling. In some years, for example, in 2013 despite the high frequency of favorable winds in July, the number of days with upwelling did not exceed the long-term average. A significant interannual variability in the frequency of upwellings is also noted in other works [18, 20, 22].



F i g. 4. Interannual variability in frequency of the upwellings, produced by alongshore winds (lilac columns); upwellings, produced by offshore winds (blue columns); and mixed (green columns) upwellings, and favorable winds (blue curve) in the western (*a*) and northern (*b*) subregions

Upwellings, produced by offshore winds, the prevailing type in the western subregion (~ 80% of all cases), lasted on average 8 days, in the northern subregion they lasted > 11 days. Upwellings, occurring during the influence both of alongshore and offshore winds, were observed equally often in the northern subregion – in 45% of cases, the remaining 10% of upwellings were of a mixed type. In [9], based on the data on wind regime 5–7 days before the beginning of upwelling, it was shown that upwellings, caused by offshore winds, in the SEB are observed in 4–6% of cases, and Ekman upwellings – in 93–96%.

Furthermore, the division of upwellings on types depends not only on the weather conditions that are considered favorable for the development of those types, but also on the topographic characteristics of the study area. The depth of the coastal zone, where upwellings are observed most often, extends to 30–50 m in the northern subregion and to 20–30 m in the western subregion (see Fig. 2). Thus, the ratio between total water depth and Ekman layer depth changes in areas of frequent occurrence of negative temperature anomalies in the range of 0.1–1.5, which confirms the possibility of the development of different types of upwelling.

The observed interannual variability of upwelling characteristics is also noted in decadal averaging: in the first decade there are more days with upwelling; in the second decade, there is a larger proportion of Ekman upwellings due to a significant increase in their frequency in the northern subregion – 71% in the second decade versus 20% in the first. In the western subregion, the share of Ekman upwellings did not change, the share of upwellings brought about by the stress of offshore winds increased slightly and the share of mixed upwellings decreased. Within the summer season, the decadal variability in the western subregion is presented as follows: in June, there was an increase in the share of mixed upwellings and a decrease in the share of upwellings, produced by an offshore winds; in July, vise versa; no changes were observed in August. In the northern subregion, in June and July there is a significant increase in the share of Ekman and a decrease in the share of upwellings caused by an offshore winds; in August, there is an increase in the share of Ekman and mixed upwellings.

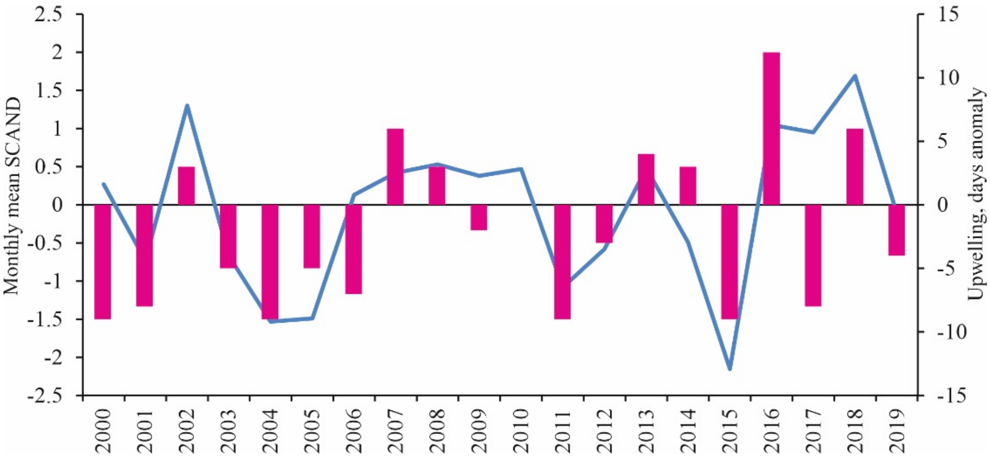
Intraseasonal variability is also noted for favorable winds: in the western subregion, alongshore wind is observed more often in June – July than in August of the first decade, in addition, it is observed much less frequently (3–4 times) than offshore wind. In August, offshore winds are observed more often than in other months. A shift to July in the maximum frequency of offshore winds was noted in the second decade. In the northern subregion, in the first decade, alongshore winds predominate in June – July and offshore winds – in August; in the second decade, a shift to July in the maximum frequency of offshore winds was also noted. The decadal variability within the summer season in the western subregion is presented as follows: in June there is a decrease in the frequency of offshore winds and an increase in alongshore winds, in July there is an increase in the frequency of winds of both types, in August there is a general decrease and a significant decrease in offshore winds. In the northern subregion, a decrease in the frequency of both favorable winds was noted in June and August and an increase in their frequency in July.

A significant increase in the share of upwelling-favorable winds in July is associated with very high frequency of directions in certain years: for example, in the northern subregion in July 2013, alongshore winds (NNW – N) accounted for 34%; in 2014, ENE – E winds accounted for > 25%; in July 2018 and 2019 there were > 30% of alongshore winds and ~ 30% of offshore winds. At the same time, the upwelling frequency in July decreased.

As noted earlier [12], wind regime changes in the Baltic Sea region may be associated with variability in large-scale circulation indices. In particular, the SCAND index reflects the intensity of anticyclonic activity development over the Scandinavian Peninsula blocking zonal transport, which in its positive phase leads to increased northerly winds over the Baltic Sea and, accordingly, to an increase in the number of upwellings in the SEB. During 2000–2019 the index varies within – 2.33...2.48, while in 2010–2019 its negative phase is observed more often.

The NAO index is an indicator of zonal circulation intensity in the extratropical zone of Eurasia and in its positive phase, an increase in westerly winds over the water area is observed. This index for 2000–2019 varies within – 3.14 ... 2.55. During the period under study, a positive index is most often observed in June (in half of the cases), least often – in August.

The estimates of correlation coefficients showed that a relationship of medium strength was observed in the upwelling frequency in the southeastern part of the Baltic Sea in June with the SCAND index in May (r = 0.65 for the SEB and r = 0.62 for the northern subregion); at the same time, a strong relation can be seen for the western subregion (r = 0.72). The relationship between the SCAND index in May and the number of days with upwelling in June is shown in the graph (Fig. 5).



F i g. 5. Temporal variability of the SCAND index values in May (blue curve) and the anomalies of the upwelling days in June 2000–2019 (pink columns)

The frequency of upwellings in July did not have clearly defined relationships with atmospheric transport. The maximum correlations were noted between the June NAO index and the anomaly of days with upwelling (the correlation coefficient was 0.46). Probably, this relationship occurring during the positive NAO phase is caused by an increase in the number of cyclones (forming over the Atlantic Ocean) over the Baltic Sea, in the rear part of which northerly winds intensify and lead to the upwelling frequency increase.

In August, the correlation coefficient between the anomaly of days with upwelling and the SCAND index was 0.6 (for the SEB and the northern subregion) and 0.66 (for the western subregion) characterizing a relationship of medium strength.

In [3], a weak but statistically significant relationship between the frequency of upwellings and the SCAND index on the Polish coast for April – September

1982–2010 was previously noted, and in [6], based on the data for June – August 1982–2017 this index was shown to have the strongest influence of all others indices on the upwelling in the Southern Baltic Sea. The difference in the estimation of the relationship between the SCAND index and the characteristics of upwellings in the Southern Baltic Sea may indicate that the role of the processes described by this index changes over time, which may be associated with climate change [23]. Accordingly, a large-scale circulation affects the frequency of upwellings in the SEB. An important factor influencing the intensity of upwellings in June and August is the frequency of anticyclones blocking western transport, which confirms the assumption of a significant role of global processes in the development of temperature anomalies in the SEB.

Conclusion

In general, 82 upwellings with a total duration of 546 days were identified in the SEB for the summer period of 2000–2019: from one day in 2017 to 60 days in 2006. Most often (~ 70%) upwellings last up to 5 days, while short upwellings are more often observed in June – July. On the whole, period there was a decrease in both the average annual number of days with upwelling and its average daily area. The number of days with upwelling decreased in 2010–2019 compared to 2000–2009 by 47% in the western subregion and by 38% in the northern; the average daily area of upwellings decreased by more than a half in two subregions.

An intraseasonal variability in the frequency of upwellings was observed on an interdecadal scale. The largest number of days with upwelling was observed in July and August 2000–2009. In the second decade, a significant (2–3 times) decrease in both the duration and the area of upwellings was noted during these months, while the decrease in the frequency of favorable winds amounted to ~ 4–5%.

On average, in 2000–2009, ~ 50% of upwellings were observed with offshore winds, 25% with alongshore winds and 25% with the winds of both alongshore and offshore directions. The connection was shown between upwelling days in June and August with the SCAND index, which describes the blocking zonal transport dynamics and in the positive phase leads to an increase in the frequency of northern winds. In 2010–2019, the negative phase of the SCAND index is observed more often, which possibly causes a decrease in the frequency of upwellings.

Subsequent work will be aimed at an expanded analysis of the relationship between the frequency of upwellings and indices of large-scale atmospheric circulation, which will give a further possibility to obtain important practical predictive relationships to estimate future characteristics of upwellings.

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