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Baltica

BALTICA Volume 31 Number 1 June 2018: 73–85
https://doi.org/10.5200/baltica.2018.31.07

Atmospheric forcing of upwelling along the south-eastern Baltic coast

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Bednorz, E. Czernecki, B., Półrolniczak, M., Tomczyk, A.M., 2018. Atmospheric forcing of upwelling along the south-eastern Baltic coast. *Baltica, 31 (1), 73–85.* Vilnius. ISSN 0067-3064.
Manuscript submitted 12 February 2018 / Accepted 05 June 2018 / Published online 28 June 2018.

Abstract The meteorological forcing on the occurrence of upwelling along the south-eastern Baltic Sea coast (Lithuanian-Latvian sector) is analysed in this study. The sea level pressure patterns and the locations of pressure centres inducing and inhibiting upwelling were identified. The research was performed for the years 1982–2017, for the months of May–September, when the sea waters are thermally stratified and the phenomenon is detectable. The frequency of upwelling is the highest in June (approximately 15%), July and August (11–13%) and the lowest in September (7%). The central and northern part of the Lithuanian–Latvian coast is most favourable for upwelling occurrence (frequency up to 20% in summer months). The main features of the sea level pressure patterns that induce upwelling in the research area are positive pressure anomalies spreading over Northern Europe and the Norwegian Sea, while negative anomalies encompass Southern Europe. Airflow around the anticyclonic centres gives a north-eastern component to the wind direction over the Lithuanian-Latvian shore. Two circulation types were recognized as inducing the occurrence of upwelling along the Lithuanian–Latvian coast. Both of them are characterized by the anticyclonic centres located west or northwest of the study area and intensify the northerly or north-easterly airflow over the research area. Different pressure patterns with the negative anomalies of sea level pressure spreading over the North Sea and the positive anomalies underlying Central Europe inhibit upwelling along the Lithuanian–Latvian coast. Such pressure conditions, bring about the western airflow component. More constant western winds restrain the upwelling process and bring about normal thermal stratification of coastal waters. A detailed analysis allowed the recognition of two circulation types inhibiting coastal upwelling in the study area. They reveal dipole patterns of sea level pressure anomalies, but the two inhibiting patterns differ substantially in the intensities and locations of the pressure centres and in wind conditions.

Keywords *• coastal upwelling • atmospheric circulation • south-eastern Baltic Sea • Lithuanian–Latvian coast*

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INTRODUCTION

Upwelling is defined as an ascending motion of subsurface water by which water from deeper layers is brought into the surface and is distributed from the area of upwelling by divergent horizontal flow (AMS Glossary of Meteorology 2017). It is an oceanic and seawater phenomenon, but is driven mainly by atmospheric conditions. Coastal upwelling appears along coastlines where an alongshore blowing wind has the coast on its left in the Northern Hemisphere or on its right in the Southern Hemisphere. The relationship between the surface wind direction and sea surface currents is explained by Ekman's theory, which describes the spiral structure of currents or winds in which the flow direction rotates while changing level and moving away from the boundary. An Ekman spiral is an effect of frictional forces and, mainly, of the Earth's rotation and Coriolis effect, which compels the surface water current to turn 90° to the right of the wind direction in the Northern Hemisphere (Lehman, Myrberg 2008).

The role of Ekman transport in inducing upwelling in a small sea basin is discussed, but in most research papers concerning coastal upwelling in the Baltic Sea it is generally assumed that it is an essential factor forcing the upwelling phenomenon in the Baltic Sea (e.g., Lehmann, Myrberg 2008; Lehman *et al.* 2012; Kowlewski, Ostrowski 2005; Zhurbas *et al.* 2008; Zhurbas *et al.* 2004; Sproson *et al.* 2014; Myrberg, Andrejev 2003; Jankowski 2002; Gurova *et al.* 2013). However, Omsted *et al.* (2014) emphasize that Ekman-transport caused by alongshore winds is the most effective at generating upwelling in large basins. Lehmann and Myrberg (2008) claim that although observed transports fairly well correspond with the Ekman transport, it should be remembered that the Ekman spiral is only a theoretical consideration and that there are no direct measurements of its existence in the wind-driven surface mixed layer. Myberg and Andrejev (2003) and Karsten *et al.* (2014) mention that upwelling could also be brought about – apart from Ekman forces – by the stress of seaward winds (normal to the coast), particularly in shallow waters. Krężel *et al.* (2005) affirm that upwelling in general is generated in line with Ekman's classic theory, but they mention a certain departure from this rule (the occurrence of upwelling when winds blow from other directions) observed only in the Hel upwelling region (eastern Polish coast). Esiukova *et al.* (2017) claim that in the south-eastern Baltic, coastal upwelling is "Ekman upwelling" in almost 93–96% of cases and only 4–6% are of another type.

When wind-driven surface currents are deflected offshore, the surface water is drawn away from the coast, causing the colder water from deeper layers to upwell (Urbański 1995; AMS Glossary of Meteorology 2017). Therefore, in the moderate climate zone, the phenomenon is best recognized in summer, when the strongest stratification is found and warm surface waters overlay colder deeper water masses. During upwelling events in summer, cold waters from deeper layers – usually from below the thermocline – rise to the surface, substantially lowering the sea surface temperature along the shore (Choiński 2011; Gurova *et al.* 2013; Karstensen *et al*. 2014). This makes summer upwelling events easy to detect as cold anomalies of surface coastal waters.

Vertical water displacements and substituting warm surface water by colder water from below the thermocline, which is caused by upwelling in summer, have important environmental impacts. They increase the concentration of nutrients necessary for biological productivity and influences phytoplankton growth (Vahtera *et al*. 2005; Zalewski *et al*. 2005; Kowalewski 2005; Lehmann, Myrberg 2008; Omstedt *et al*. 2014). A decrease in sea surface temperature also influences local boundary climate by modifying the surface-atmosphere heat exchange, i.e. increasing the atmospheric heat loss and changing the stability of the marine boundary layer (Omstedt *et al*. 2014).

In the Baltic Sea, which is a semi-enclosed basin of a relatively small size located in the moderate climate zone, upwelling is considered to be a frequent warm season phenomenon (Myrberg, Andrejev 2003; Lehmann, Myrberg 2008; Lehmann *et al*. 2012). Less attention has been paid to the atmospheric forcing triggering and suppression of this phenomenon in different regions of the Baltic Sea. Lehmann *et al*. (2002) used a local circulation index to parametrize the influence of the western flow intensity on the occurrence of up- and downwelling in different coastal regions. Furthermore, upwelling-favourable wind conditions have been identified along the Baltic Sea coast (Lehmann *et al*. 2012). Bychkova *et al*. (1988) identified synoptic situations associated with upwelling in different parts of the Baltic Sea coast. Their findings for the southern coast of the Baltic Sea were verified and discussed by Bednorz *et al*. (2013).

This study is meant as a contribution to research on sea-atmosphere coupling; our aim is to confirm the atmospheric forcing of sea water circulation and sea surface temperature along the meridionally oriented south-eastern Baltic coast (the Lithuanian–Latvian section). The atmospheric circulation forced by the air pressure pattern is recognized as the main factor conducive to the upwelling process. The pressure patterns and surface wind fields that trigger the upwelling events as well as pressure and surface wind patterns suppressing the phenomenon are determined in the study. In addition, quantitative characteristics of upwelling occurrence along the Lithuanian–Latvian Baltic coast are provided in the study.

AREA, DATA AND METHODS

The occurrence of coastal upwelling was investigated in the south-eastern part of the basin, i.e. along the Lithuanian–Latvian coast line, which is meridionally oriented and extends between 55°N and 57.5°N (Fig. 1). Upwelling cases were detected based on the mean daily sea surface temperature (SST) data derived from the NOAA OI SST V2 High Resolution Dataset provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, (available at: http://www.esrl.noaa.gov/psd). This dataset uses the satellite SST data from the Advanced Very High Resolution Radiometer (AVHRR) and Advanced Microwave Scanning Radiometer (AMSR) on the NASA Earth Observing System. The optimum interpolation (OI) method was utilized on both infrared and microwave data and in situ data from ships and buoys to improve data series resolution. The final product has a spatial grid resolution of 0.25° × 0.25° and a temporal resolution of 1 day (Reynolds *et al*. 2007). This implies

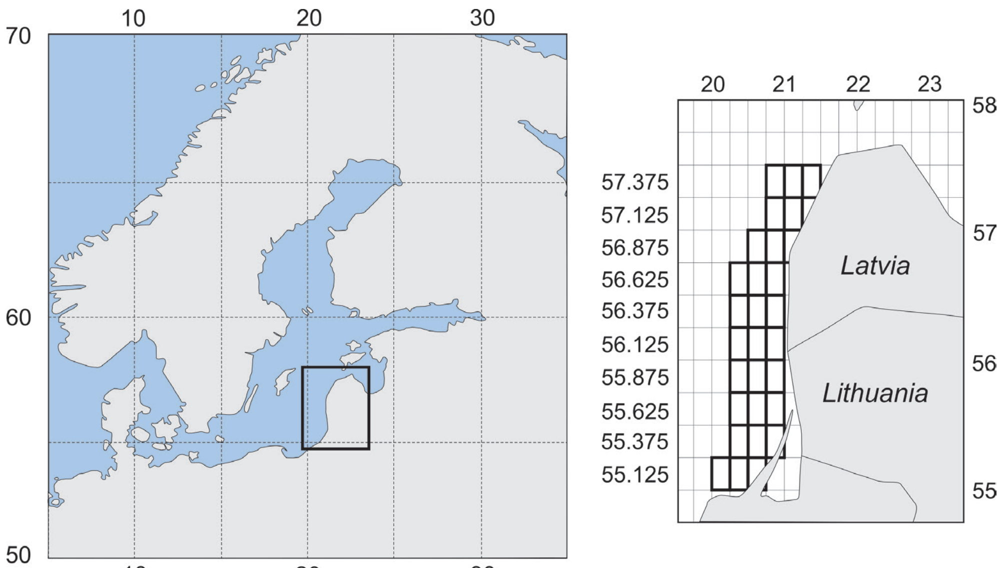

Fig. 1 Location of the research area (left) and grids (with latitudes) taken to the analysis (right). The size of the grids is 0.25°× 0.25° (Authors: Ewa Bednorz and Hanna Forycka Ławniczak, who provided technical support)

a ca.15–16 km resolution along parallels 55–57.5°N and 27.8 km resolution along the meridians.

According to Lehmann and Myrberg (2008), the length-scale of upwelling at the Lithuanian and Latvian coasts is typically approximately 250 km and the width is between 5 and 20 km, and the resolution of the SST data derived from the NOAA OI SST V2 dataset employed in this study is apparently sufficient to recognize upwelling events, but one must remember that smaller upwellings close to the coast may be undetectable, especially due to the internal Rossby radius which is approximately 2–10 km in the Baltic Sea (Lehman, Myrberg 2008).

Most of the contemporary studies on upwelling in the Baltic Sea are based on in situ measurements, satellite imagery and numerical modelling (e.g. Woźniak *et al.* 2011; Kozlov *et al.* 2012; Lehmann *et al.* 2012; Łysiak-Pastuszak *et al.* 2012; Mingelaite *et al.* 2014). One of the most important advantages of the reanalysis SST product chosen in this study is the over 30-year length of the dataset, which is a necessary condition in climatological analyses. The main disadvantage is the low temporal resolution of 1 day, which means that the mean daily SST averages are available. However, as was proved in a previous study concerning the occurrence of upwelling on the Polish coast, both the spatial and temporal resolutions appeared to be sufficient for detecting the upwelling signals in the Baltic Sea (Bednorz *et al*. 2013). Three grids on each of the 10 profiles along the coast were taken for analysis and the SST difference between the grid closest to the coast and the two farther ones was computed (Fig. 1).

A threshold value of the SST difference < –0.2°C between the grids closest to the coastline was adopted, and that condition when fulfilled along at least three parallels (83 km along the coast) was considered to be an upwelling event. This criterion was adopted at the basis of the preliminary visual analysis of SST daily maps produced automatically as plots from the NOAA OI SST V2 dataset. The phenomenon was recognized by a drop of SST towards the coastline by at least 0.2°C in at least three pairs of grids along the coast, with SST isotherms bent towards the sea. The recognition of all weak upwelling cases (SST difference between grids close to –0.2°C) was supported by the visual analysis of the SST maps (examples in Fig. 2). Using this method the experiences from a previous study concerning atmospheric conditions governing upwelling along the Polish Baltic coast, also employing the NOAA OI SST V2 High Resolution Data, were followed (Bednorz *et al.* 2013). Only upwelling periods of two and more days duration were considered for further analysis. The research was performed for the years 1982–2017 in the months of May–September, when the sea waters are thermally stratified and upwelling is detectable. Earlier in spring and, particularly, later in autumn colder waters beside the coast may result not from the upwelling process but from differential cooling in the shallow waters over the gentle continental slopes (Esiukova *et al*. 2017; Rukšėnienė *et al*. 2017) After this basic recognition some quantitative characteristics of upwelling occurrence along the Lithuanian–Latvian coast such as frequency and duration were computed.

Atmospheric forcing, namely, pressure patterns and airflows, governing the occurrence of upwelling along the south-eastern Baltic shore, was identified using ERA-Interim data obtained from the European Centre for Medium-Range Weather Forecasts (ECM-

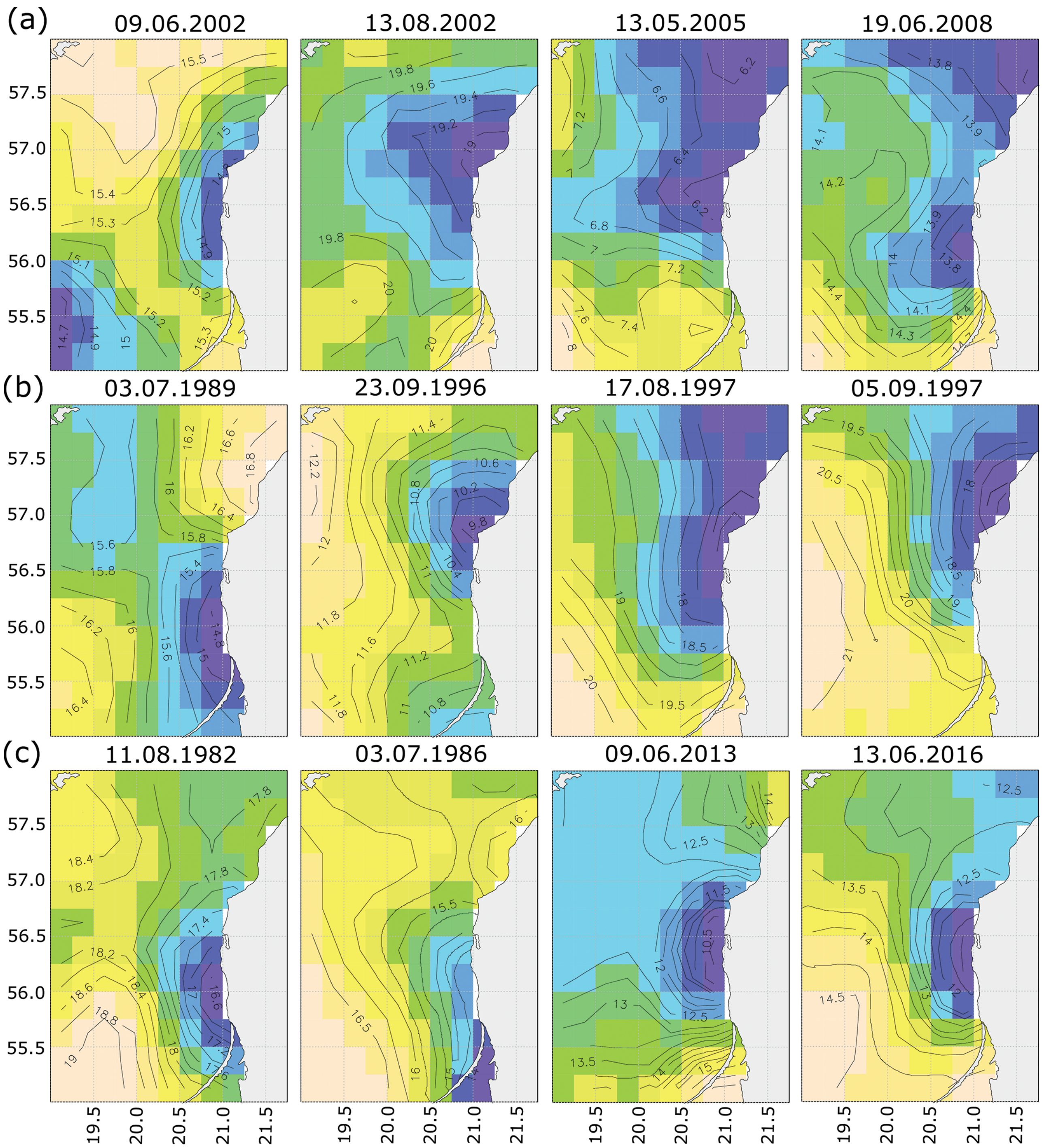

Fig. 2 Examples of the SST field in the days with upwelling along the Lithuanian–Latvian shore; SST difference between the pair of grids closest to the coastline 0.2–0.5°C (a), 0.51–1.0°C (b), and >1.0°C (c) (Authors: Marek Półrolniczak and Ewa Bednorz)

WF) supplies (available at http://apps.ecmwf.int/datasets/; Dee *et al*. 2011). ERA-Interim is a reanalysis of the global atmosphere that produces data with 0.75°× 0.75° resolution. From those resources, the daily mean sea level pressure (SLP) data were acquired in order to create maps of the pressure fields and to identify circulation patterns. Additionally, surface wind speed and wind direction data were used to recognize the main airflow directions and intensity.

Assuming that the upwelling-favourable wind conditions must appear first and the response of sea water circulation is delayed, the days preceding the upwelling signals appearing in at least three grids were selected. To determine the circulation pattern triggering upwelling along the Lithuanian–Latvian coast, a SLP composite anomaly map for the days preluding the upwelling periods was constructed. Anomalies were computed as the differences between the composite values for the selected days preluding upwelling and the multiannual averages (1982–2017) of the warm part of the year (May–September). The composite anomaly map shows specific features of the pressure pattern that induce upwelling along the Lithuanian–Latvian coast, namely, the areas where the SLP is higher/lower than the multiannual norm in the warm season. In the same way a map of wind speed and direction was composed. An analogous procedure was applied to recognize atmospheric conditions that suppress upwelling. In such case, only the last days of upwelling periods were considered.

The composite analysis applied in this study and the 'environment to circulation' approach have been used previously to identify the atmospheric circulation patterns associated with different environmental or weather phenomena (Yarnal 1993; Yarnal *et al*. 2001; Dayan *et al*. 2012). This method classifies atmospheric conditions according to a specific set of environment-based criteria for a particular environmental process, in this case inducing or inhibiting the upwelling events along the south-eastern Baltic Sea coast.

Assumptions of the composite analysis applied to the SLP data consist of assembling pressure fields that may differ substantially. Therefore, an attempt was made to distinguish some different types within the composites. To that end, Ward's (1963) minimum variance method was used to determine the circulation types inducing/inhibiting upwelling along the Lithuanian–Latvian coast. Ward's method is a hierarchical clustering technique most frequently used for climatic classification (method description in Kalkstein *et al*. 1987; Wilks 1995; used in e.g. Esteban *et al*. 2005; Bednorz *et al*. 2013; Tomczyk, Bednorz 2014; Tomczyk *et al*. 2016). In the case of classifying the pressure fields, the clustering was based on the standardized daily SLP data. The main idea of the clustering of objects (daily pressure patterns in this case) is to consider the minimal distance between them in the multidimensional space of the data vectors (standardized SLP). The obtained types of circulation patterns were shown on composite anomaly maps and interpreted as various atmospheric conditions inducing/inhibiting the upwelling process.

RESULTS

Frequency and duration of upwelling

The total number of days with upwelling in the analysed period 1982–2017 (May–September), identified according to assumptions described in the previous section varied from a total of more than 700 days (approximately 20 days per year) in the central part of the Lithuanian–Latvian coast to less than 300 days (less than 10 days per year) in the southern part, along the Curonian Spit. Most of the upwelling events were of short duration (2–3 days); the longest durations (over 1 week or even over 2 weeks) were observed between latitudes 56.375°N and 57.125°N.

On the average, more than 20 days per year with upwelling appear during the warm season in the central part of the Lithuanian-Latvian coast (latitudes 56.125°–56.875°) and less than 10 days per year occur in the southernmost part. This results in an average frequency of upwelling days in the warm period of the year (May–September) ranging from 17.6% to 6.2% in different parts of the research area. However, the number of days with upwelling varies considerably from year to year; while the average number of upwelling cases detected in at least one latitude equals 47 per year, it can sometimes exceed 70 days (as in 1983, 1994, 1997 and 2014) or drop below 15 days (as in 1987, 1998, 2007 and 2010), and upwelling may even not appear at all, as in 1991. While a large year-to-year variability is observed, the multiannual course of days with upwelling along the Lithuanian–Latvian coast does not reveal any significant trend of changes.

Seasonally, the frequency of upwelling along the south-eastern Baltic shore is the highest in June (approximately 15%) and lower in August (13%) and July (11%) (Fig. 3). The phenomenon is much rarer in the beginning of the warm season (approximately 8% in May) as well as at the end (approximately 5% in September).

Spatially, upwelling conditions with colder temperature alongside the shore than in the open sea appear most often in the central part of the research area (Fig. 4, pixels between latitudes 56.125°N and 56.875°N; for latitudes see Fig. 1). In summer months (June–August) the frequency of upwelling exceeds 15% or even 20% (June). The phenomenon was also

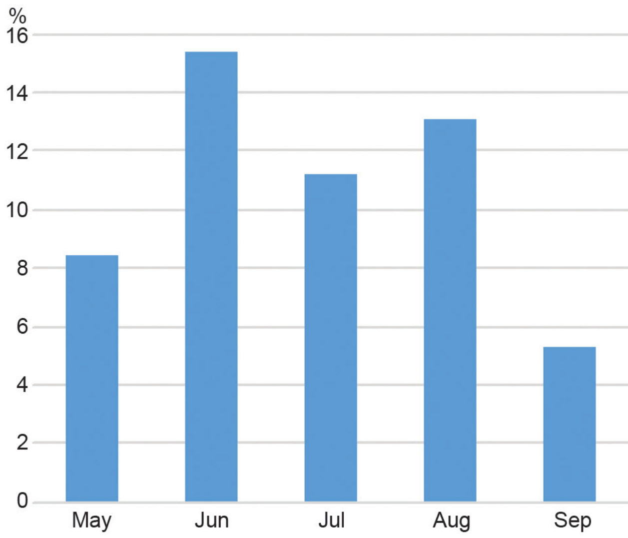

Fig. 3 Mean monthly frequency of the days with upwelling in the period 1982–2017 along the Lithuanian–Latvian coast (Author Ewa Bednorz)

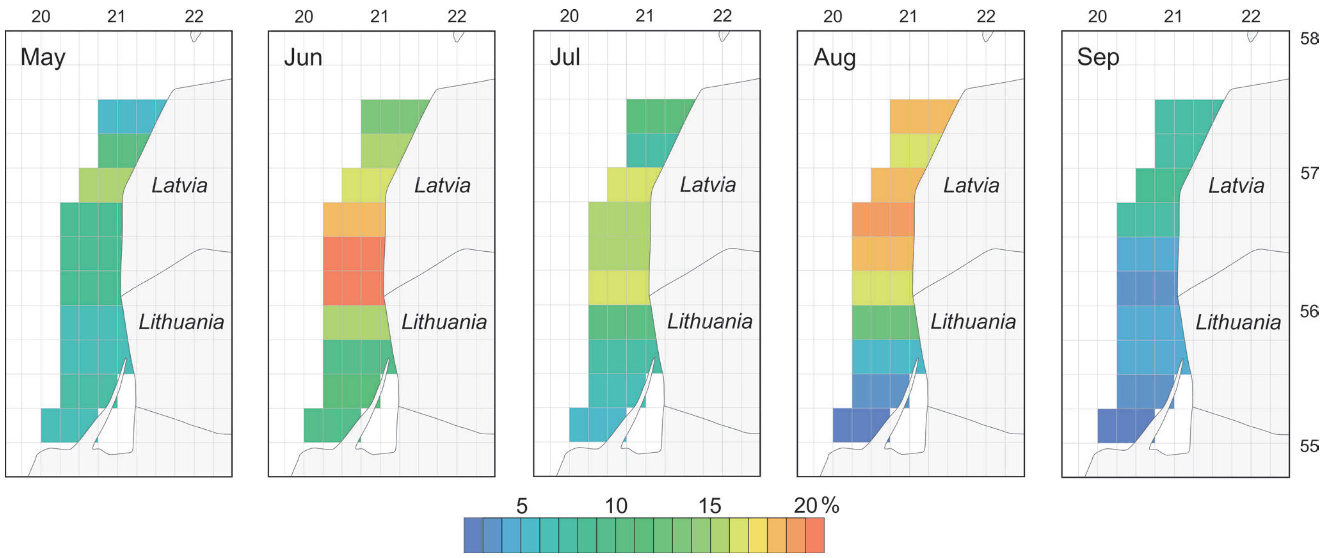

Fig. 4 Frequency of upwelling along the Lithuanian–Latvian shore in the period 1982–2017 based on the mean daily SST values (Authors: Ewa Bednorz and Hanna Forycka Ławniczak, who provided technical support)

recognized quite often within the northernmost grids (frequency exceeding 18% in August). In the southern part of the Lithuanian–Latvian coast, upwelling was much rarer and south of 55.875° its frequency dropped below 13% in June and below 8% in other months. Along the Curonian Spit (two southernmost latitudes) the upwelling frequency was lowest in every month.

Similar spatial and temporal variabilities in upwelling frequency in this part of the Baltic basin were found by Lehmann *et al*. (2012).

Atmospheric conditions inducing upwelling

The mean SLP field over the study area during the warm season from May to September averaged for the period 1982–2017 reveals a high pressure area in the southwest, with SLP exceeding 1018 hPa. A wedge of high pressure extends to the northeast, encompassing Western and Central Europe. SLP decreases gradually eastwards and northwards, where low pressure centres are located over northern Scandinavia, the Norwegian Sea and westward of it. In the warm half of the year, small pressure gradients are observed over the continent and larger gradients over the North Atlantic (Fig. 5A). Due to the association of the pressure gradient and Coriolis force, dominant airflow is generally in a clockwise direction around the high pressure centres and in a counterclockwise direction around low pressure centres. Therefore, the described pressure pattern results in the predominance of the

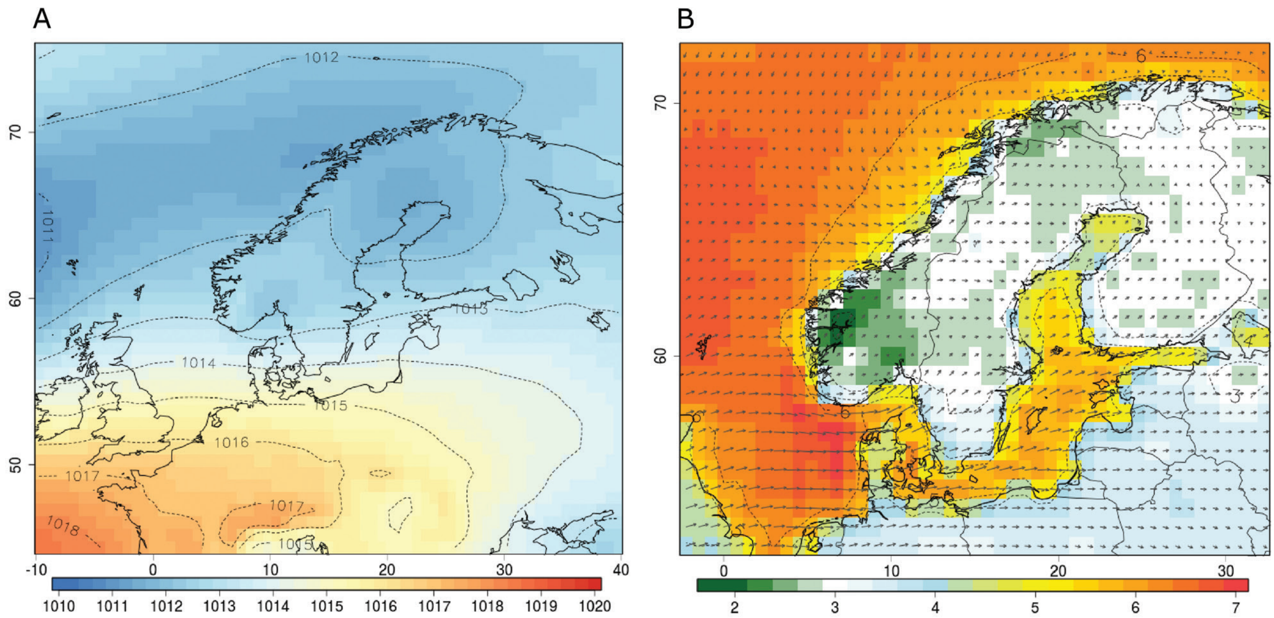

Fig. 5 A – mean sea level pressure (hPa) in the period from May to September in the years 1982–2017; B – mean wind direction (arrows) and wind speed (m s^{-1}) (colour shades) (Author Bartosz Czernecki)

western airflow direction in the research area during the warm season. The averaged wind speed along the southern Baltic shore amounts to 4–5 m s^{-1}, exceeds 5 m s^{-1} over the Baltic basin, and drops below 4 m s^{-1} over land (Fig. 5B).

Upwelling is driven by the dynamics of the surface atmosphere, and the strongest offshore sea-water surface currents, which allow upwelling of colder waters from below the thermocline, are expected where the northern winds blow along the Lithuanian–Latvian shore (see the first section). Assuming that the upwelling-favourable wind conditions must appear first and the response of sea water circulation is delayed, the days preceding the upwelling signals appearing in at least three grids were selected. Composite anomaly weather maps for those days were constructed and besides wind conditions, i.e. speed and direction, SLP anomalies were shown (Fig. 6). Composite anomaly maps show differences between selected weather situations (days preceding upwelling in this case) and climatic means for the months from May to September. The created SLP anomaly field allows the recognition of the pressure patterns (i.e. location and intensity of the pressure centres) conducive to upwelling events along the south-eastern Baltic shore.

The main features of the SLP pattern that induces upwelling along the Lithuanian-Latvian shore are the positive SLP anomalies that spread over Northern Europe and the Norwegian Sea, while negative anomalies of low value encompass Southern Europe. The centre of the high pressure area with anomalies exceeding 4.5 hPa is located northeast of the Shetland Islands, and the isanomalous lines over the research area, i.e. the south-eastern Baltic Sea, are oriented from southwest to northeast (Fig. 6A). Airflow around the anticyclonic centres in the Northern Hemisphere has a clockwise direction, more or less parallel to the isobars, so that the wind direction over the Lithuanian–Latvian shore has a strong north-eastern component (Fig. 6B).

The composite anomaly maps shown in Figure 6 were prepared on the basis of data from 103 days that were recognized as preceding upwelling periods in at least three grids. However, while interpreting composite maps it has to be kept in mind that they show only a generalized idea of synoptic conditions favourable to particular environmental or weather phenomena and – possibly – the patterns that are put together may differ substantially. Therefore, an attempt was made to distinguish some different types within the composites, using Ward's minimum variance method, which allowed the circulation types causing upwelling along the Lithuanian–Latvian coast to be classified. Based on the standardized mean daily SLP values, the 103 days were clustered into the two most relevant groups that were interpreted as two different types of circulation patterns. Composite anomaly maps of both types were constructed using both SLP and wind data (Fig. 7). The obtained two types differ mainly by the positions of the high pressure centres.

In type 1, which consists of 73 days, the anticyclonic centre with SLP anomalies exceeding 5 hPa is located over the northern British Islands (Fig. 7A). On the ridge of positive SLP anomalies the isanomalies are placed close to each other, which indicates a large pressure gradient and means stronger than normal winds, and the direction of airflow reveals a substantial northern component (Fig. 7B). In type 1, a weak centre of negative SLP anomalies is located over Eastern Europe.

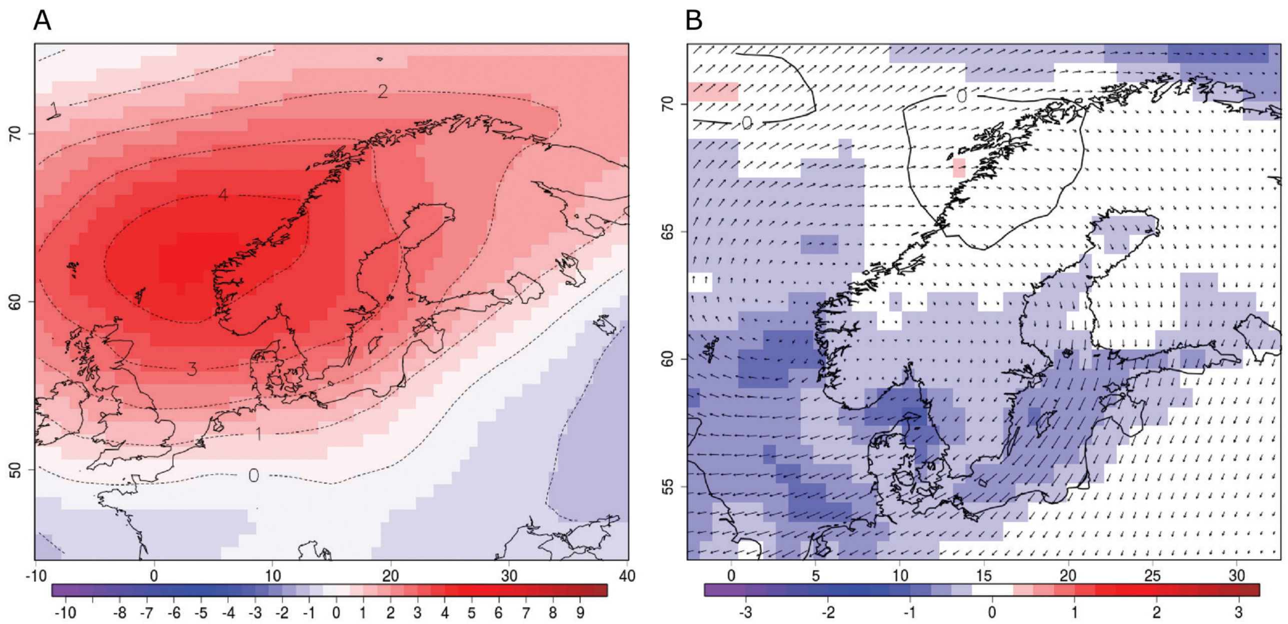

Fig. 6 A– anomalies of sea level pressure (hPa); B – anomalies of wind direction (arrows) and wind speed (m s^{-1}) (colour shades) in the days preceding upwelling periods along the Lithuanian–Latvian coast (Author Bartosz Czernecki)

In type 2, which consists of 30 days, SLP anomalies are much stronger and the positive centre is shifted northeast (Fig. 7C). The highest values, which exceed 8 hPa, spread over the Norwegian Sea close to the central part of the Norwegian coast. Such anticyclone locations intensify the eastern and north-eastern component of the wind direction (Fig. 7D).

The idea of determining synoptic conditions, particularly the pressure patterns conducive to the coastal upwelling in different parts of the Baltic Sea was taken mainly from Bychkova *et al*. (1988). They recognized 22 regions of coastal upwelling in the Baltic basin and then described 11 different synoptic situations favourable to upwelling in various regions. Four of them were indicated as being favourable for upwelling along the Lithuanian–Latvian coast, which was recognized as a homogenous region number 3 (Bychkova, Viktorov, 1987; Bychkova *et al*., 1988) (Fig. 8). Although the occurrence of the four synoptic situations is coincident with the occurrence of upwelling, it does not mean that all of the distinguished circulation types trigger the upwelling process in the analysed area, as is proved in this study.

Circulation types recognized in this study as inducing the occurrence of upwelling along the Lithuanian–Latvian coast are similar to two synoptic patterns indicated by Bychkova *et al*. (1988) as related to upwelling in region 3. Our type 1 with anticyclonic centre located over the northern British Islands (Fig. 7A) reveals the synoptic situation I recognized by Bychkova *et al*. (1988), where the high pressure centre is located over the North Sea; on both maps

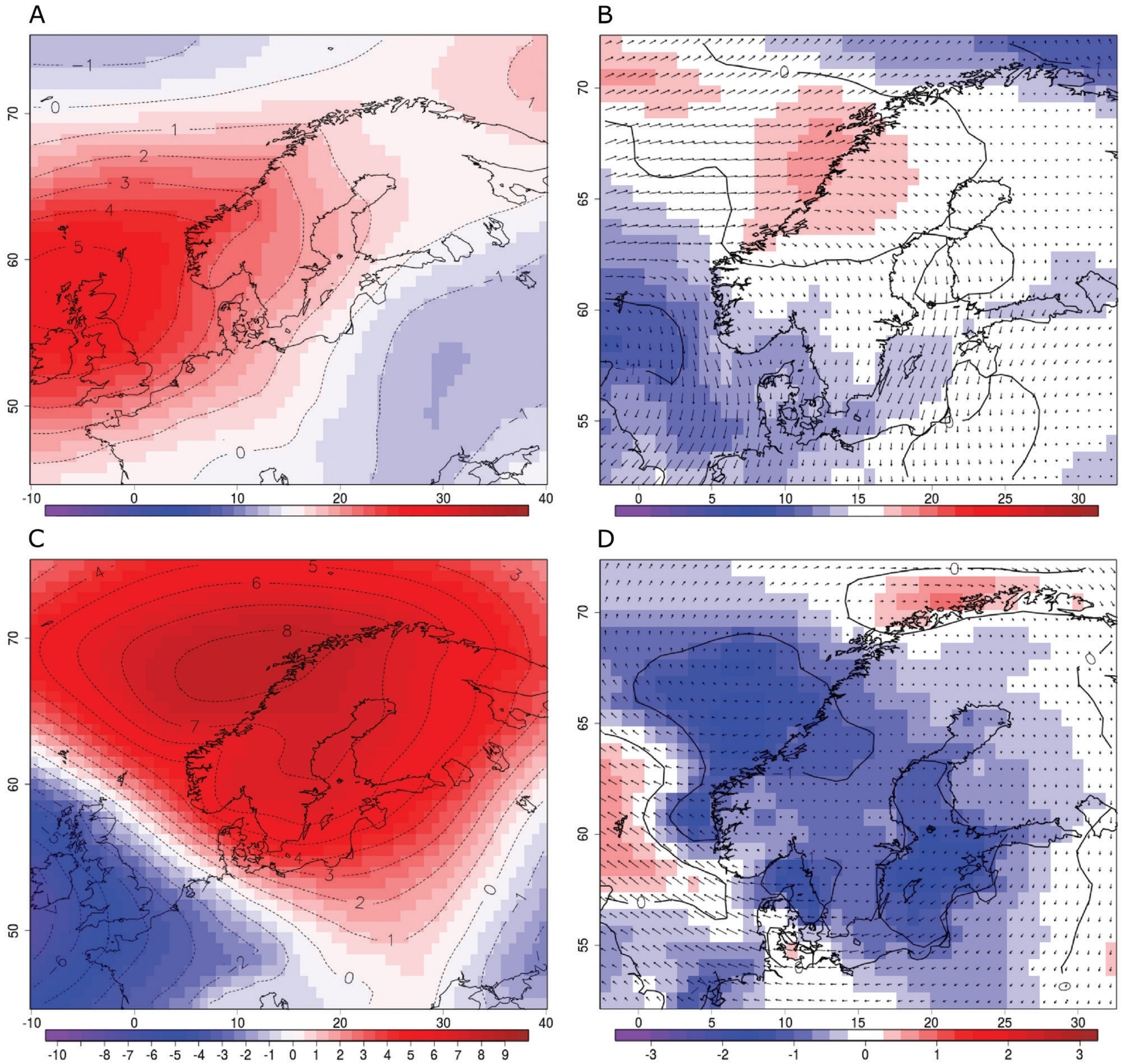

Fig. 7 Types of circulation patterns inducing upwelling along the Lithuanian–Latvian coast (A, B for type 1; C, D for type 2). Left (A, C) – anomalies of sea level pressure (hPa); right (B, D) – anomalies of wind direction (arrows) and wind speed ($m\ s^{-1}$) (colour shades) (Author Bartosz Czernecki)

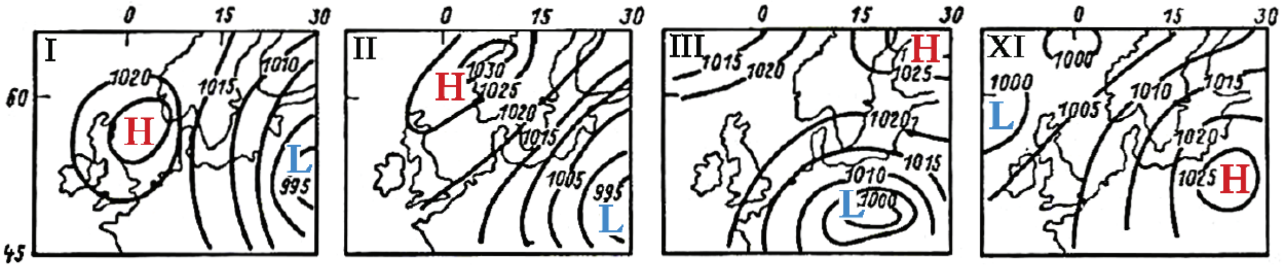

Fig. 8 Types of synoptic situations related to upwelling in the region of the Lithuanian–Latvian coast (redrawn from Bychkova *et al*. 1988 by Hanna Forycka Ławniczak)

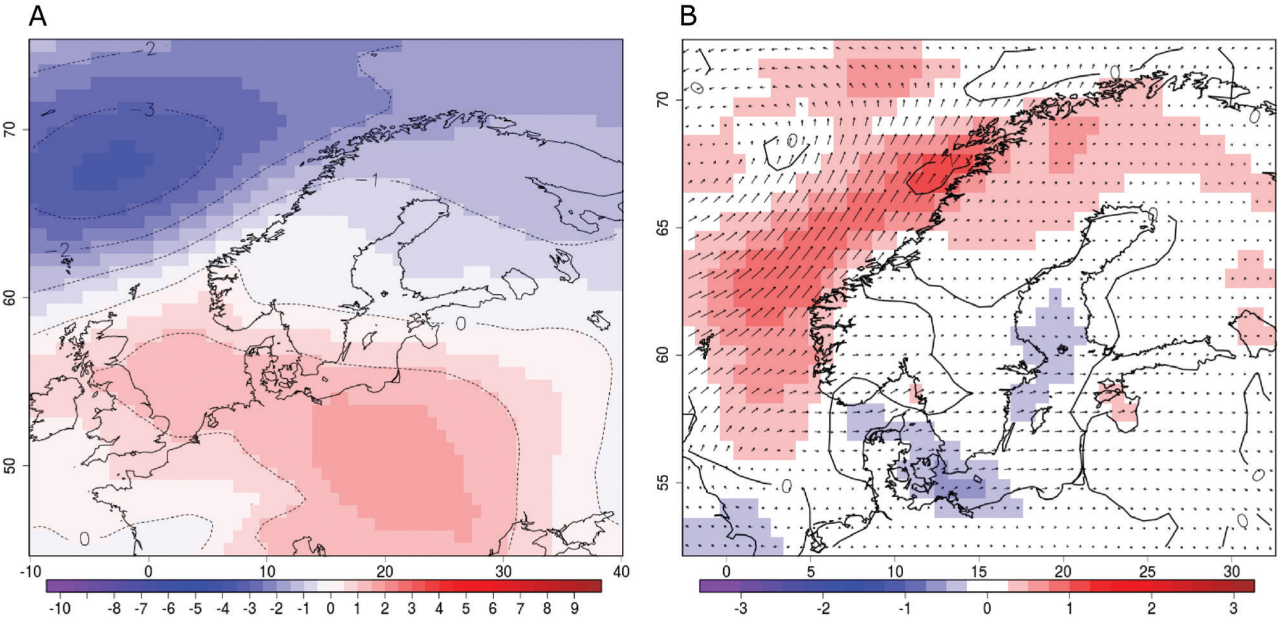

Fig. 9 A – anomalies of sea level pressure (hPa); B – anomalies of wind direction (arrows) and wind speed (m s^{-1}) (colour shades) in the last days of upwelling periods along the Lithuanian–Latvian coast (Author Bartosz Czernecki)

isolines represent more or less meridional directions, indicating northern airflow along the Lithuanian–Latvian coast. The second type of inducing upwelling recognized in this study (Fig. 7C) corresponds to Bychkova's synoptic situation II; both patterns show high pressure area spreading along the Norwegian coast, which intensifies north-eastern airflow over the area of the study. Other weather patterns, defined by Bychkova *et al*. (1988) as related to upwelling on the south-eastern Baltic coast, were not recognized in this study as triggering the analysed phenomenon.

Atmospheric conditions suppressing upwelling

As stated previously, coastal upwelling is a phenomenon of a rather short duration and usually lasting several days. To fully accomplish the research on the atmospheric forcing of the occurrence of coastal upwelling in the south-eastern Baltic Sea, atmospheric conditions inhibiting upwelling were investigated. To that end, the last days of upwelling periods were selected, consequently applying the thresholds adopted in the previous chapter. Composite anomaly maps for the selected 46 days ending upwelling periods in at least three grids were constructed (Fig. 9). When the SLP anomaly field in Figure 9A and the respective map in Figure 6A are collated, an opposite pressure pattern is revealed. In the days ending upwelling periods, the negative SLP anomalies (up to –4.0 hPa) spread over the North Sea, while weak positive anomalies (up to 2 hPa) underlie Central Europe. Such a pressure pattern brings about the western airflow component over the south-eastern part of the Baltic basin (Fig. 9B). More constant western winds occurring at the end of the upwelling periods restrain the upwelling process and bring about normal thermal stratification of the coastal waters.

Complementarily to investigations of the atmospheric conditions inducing upwelling, circulation types inhibiting upwelling along the Lithuanian–Latvian coast were distinguished. The clustering method allowed two types to be set apart, which differ substantially by the intensities and locations of the pressure centres and the wind conditions (Fig. 10).

The first distinguished type reveals a dipole pattern of SLP anomalies. A cyclonic centre with negative anomalies exceeding –4 hPa spreads over the Barents

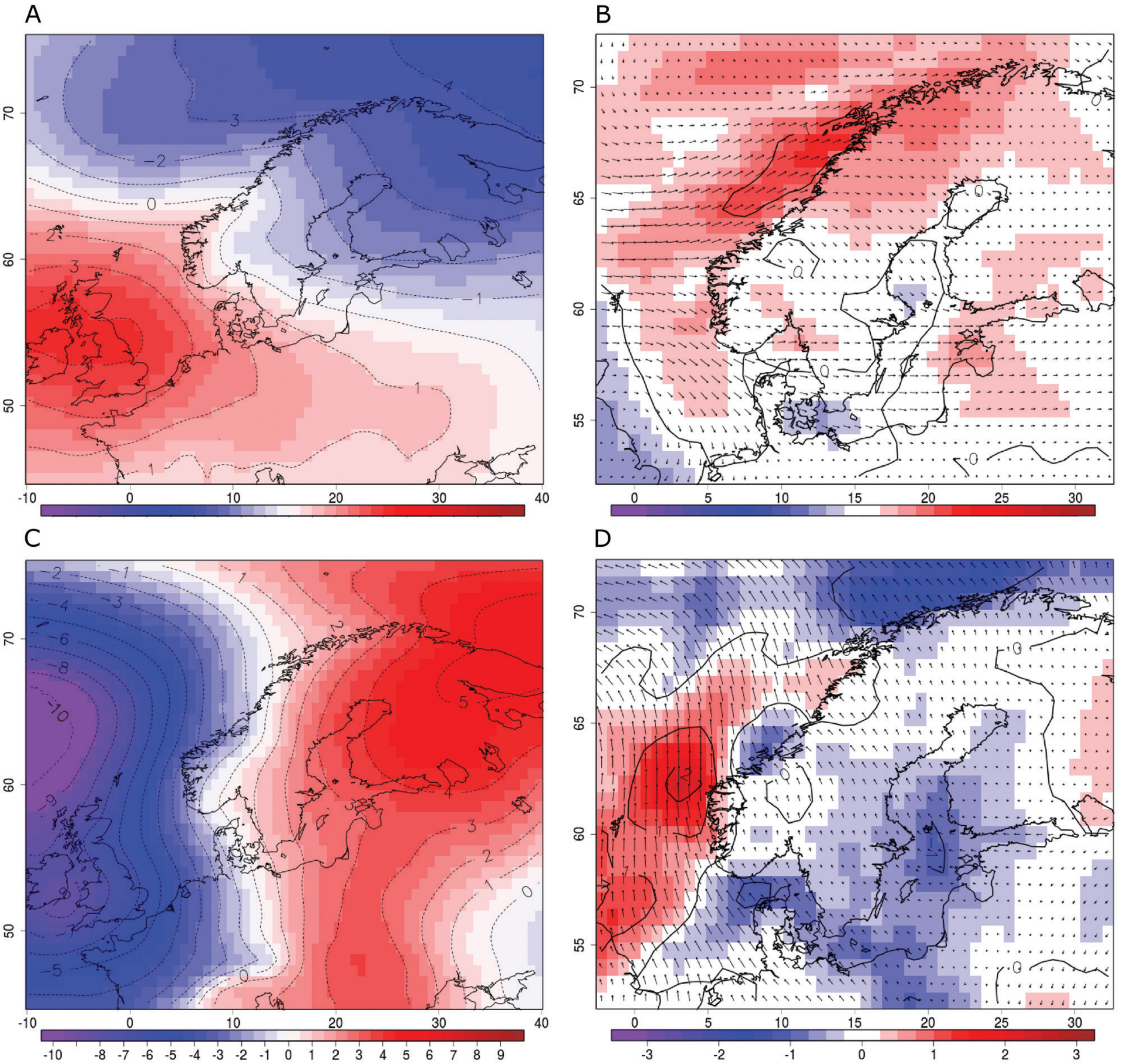

Fig. 10 Types of circulation patterns inhibiting upwelling along the Lithuanian–Latvian coast (A, B for type 1; C, D for type 2). Left (A, C) – anomalies of sea level pressure (hPa); right (B, D) – anomalies of wind direction (arrows) and wind speed (m s^{-1}) (colour shades) (Author Bartosz Czernecki)

Sea, and an anticyclonic centre with positive anomalies > 4 hPa is located over the British Islands (Fig. 10A). A counterclockwise circulation around the cyclonal centre intensifies the western airflow perpendicular to the Lithuanian-Latvian coastline, which suppresses upwelling in that area (Fig. 10B). For type 2, which causes inhibiting of upwelling along the south-eastern Baltic shore, the dipole pattern of SLP anomalies is oriented almost opposite that of type 1. A strong cyclonic centre extends from Iceland to the British Islands and encompasses all the western side of the analysed domain, while a positive centre is located over eastern Scandinavia, and a merged ridge of higher than normal pressure extends southwards (Fig. 10C). A pattern with low pressure in the west and high pressure in the east results in stronger than usual southern airflow (Fig. 10D), and such wind direction constricts the process of upwelling at the Lithuanian–Latvian coast.

The above-described type 2 inhibiting upwelling resembles the synoptic situation IX distinguished by Bychkova *et al.* (1988), in which the low pressure system is located in the west, and the high pressure is in the east; it also has in common a feature with synoptic situation III, namely, an anticyclonic centre over Scandinavia. This proves that in Bychkova's study there are mixed conditions shown as synoptic situations related to upwelling, namely, conditions inducing and inhibiting the process. Subdividing these two allows the sea-atmosphere coupling and the atmospheric forcing of sea waters circulation to be better understood.

DISCUSSION

Coastal upwelling in the southern part of the Baltic Sea is less frequent than along the northern shorelines (Lehmann *et al*. 2012; Myrberg, Andrejev 2003). Several studies have been performed for the Polish coast (e.g. Jankowski 2002; Krężel *et al*. 2005; Myrberg *et al*. 2010), and they proved that this phenomenon appears on approximately 10–15% of days during the warm period of the year (Myrberg, Andrejev 2003; Kowalewski, Ostrowski 2005; Lehmann *et al*. 2012; Bednorz *et al*. 2013). According to this study, the frequency of upwelling along the Lithuanian–Latvian coast differs during the warm season; it is the highest in June (15% approximately), July and August (11–13%) and the lowest in September (7%). The analysis of spatial variability shows that the central and northern part of the Lithuanian–Latvian coast is most favourable for upwelling occurrence (frequencies up to 20% in summer months). Similar characteristics were provided by Lehman *et al*. (2012), although based on different data records. The analysed phenomenon is essentially more frequent along the northern coasts, in particular those that are meridionally oriented. The highest frequencies, which are up to 25–40%, appear on the south and west coasts of Sweden, and frequencies up to 20–25% appear on the northern coast of the Gulf of Finland (Myrberg, Andrejev 2003; Lehman 2012). This attends the prevailing wind conditions with the dominating western sector.

The surface wind direction has been emphasized in numerous studies as being relevant to the appearance of coastal upwelling (i.e. Urbański 1995; Myrberg, Andrejev 2003; Zurbas *et al*. 2004; Lehmann, Myrberg 2008). Fewer studies have considered the macro-scale or local pressure patterns that determine wind conditions. Lehmann *et al*. (2002) proved that the three-dimensional transport of seawaters in the Baltic basin is influenced by the North Atlantic Oscillation (NAO), which is commonly recognized as a large-scale circulation pattern dominant over the Euro-Atlantic region. A positive NAO phase accompanied by intensified westerly airflow induces the upwelling or downwelling process in different coastal regions. The Baltic Sea Index, computed as a difference of normalized SLP anomalies between Szczecin (Poland) and Oslo (Norway), was used to better recognize and define the intensity of the western flow, which induces upwelling along the northern coast of the Baltic Sea (Lehmann *et al*. 2002).

Zhurbas *et al*. (2008) postulated dividing the upwelling process into two phases. The 'active phase' is when the alongshore wind is strong, the upwell current is intensive and the cold water reaches the surface. The 'relaxation phase' then follows when the wind weakens but a strong temperature gradient persists. In this study the final 'inhibiting phase' is proposed, during which the wind conditions suppress upwelling. Our research was inspired mainly by the ideas of Bychkova *et al*. (1988), who described 11 different synoptic situations favourable for upwelling at various Baltic coastal areas. In the context of the present study, the four synoptic situations recognized by Bychkova *et al*. (1988) as being favourable for upwelling along the Lithuanian–Latvian coast can be clarified and divided according to the conditions inducing and inhibiting upwelling. Two circulation types recognized in this study as inducing the occurrence of upwelling along the Lithuanian–Latvian coast are similar to two synoptic patterns indicated by the previous authors. Both of them are characterized by the anticyclonic centres that are located west or northwest of the study area, which intensify the northerly or north-easterly airflow over the research area. The circulation types recognized in this study as inhibiting coastal upwelling in the south-eastern Baltic Sea reveal dipole patterns of SLP anomalies, but they differ substantially in the intensities and locations of the pressure centres and wind conditions. Only one of these pressure patterns resembled the synoptic situation distinguished by Bychkova *et al*. (1988); with the low pressure system located in the west and high pressure in the east, it also has one feature in common with synoptic situation III, namely, an anticyclonic centre over Scandinavia. A comparison of the present findings with the study of Bychkova *et al*. (1988) proves that subdividing synoptic patterns into conditions inducing and inhibiting upwelling allows better understanding of the sea-atmosphere coupling and the atmospheric forcing of sea water circulation.

CONCLUSIONS

Coastal upwelling appears during the warm season (May–September) in the south-eastern Baltic Sea with an average frequency exceeding 10%. Its occurrence is strongly determined by the atmospheric forcing, namely, the dynamics of the wind conditions that are a consequence of the regional pressure patterns; and therefore the main aim of the study was to recognize circulation patterns governing the occurrence of this phenomenon along the Lithuanian–Latvian shore. Within upwelling episodes, two phases should be distinguished, namely, an 'inducing phase' before and at the beginning of the phenomenon and an 'inhibiting phase' at the end of it. They are accompanied by different atmospheric conditions. Two types of pressure patterns were recognized as inducing upwelling, both of which reveal a strong anticyclonic centre located over the northern British Islands (type 1) and over the Norwegian Sea (type 2). Anticyclonic centres located west or northwest of the Lithuanian–Latvian shore, which are disclosed by positive anomalies of sea level pressure, are favourable to the 'inducing phase', as they intensify the northerly (type 1) or north-easterly (type 2) airflow over south-eastern Baltic.

On the other hand, negative anomalies of sea level pressure, namely, cyclonic centres located to the west/north of the study area, intensify the southern/western airflow and are favourable to the 'inhibiting phase'. A cyclonic centre spreading over the Barents Sea intensifies the western airflow perpendicular to the Lithuanian–Latvian coastline (type 1), which suppresses upwelling in that area. Alternatively, a strong cyclonic centre extending from Iceland to the British Islands results in stronger than usual southern airflow, and such wind direction constricts the process of upwelling on the Lithuanian–Latvian coast.

Defining pressure patterns favourable to inducing/inhibiting upwelling along the Lithuanian–Latvian coast proves strong relationships between atmospheric factors and sea water circulation. Obtained results serve as a contribution to the general knowledge of sea-atmosphere coupling, and they could be helpful in predicting the process of the formation and disappearance of upwelling.

ACKNOWLEDGEMENTS

We would like to thank the anonymous reviewers for their efforts to read and valuate our manuscript.

This work was supported by the National Science Foundation, Poland (grant number 2016/21/B/ST10/01440).

The authors would like to thank Hanna Forycka Ławniczak for providing technical support in constructing some of the figures.

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