Papers

Synoptic conditions governing upwelling along the Polish Baltic coast

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Abstract

The study analyses atmospheric feedback to the occurrence of upwelling along the Polish Baltic coast. Upwelling events were identified on the basis of daily mean sea surface temperature (SST) maps from the period 1982–2010 derived from the NOAA OI SST V2 High Resolution Dataset. Synoptic conditions favourable to the occurrence of upwelling were determined on the basis of the NCEP/NCAR reanalysis data. On average, there are approximately 23 days with upwelling each year along the Polish Baltic coast, which account for approximately 13%

of the warm period (April–September). The pressure pattern with an anticyclone centred over Scandinavia and extending over northern Europe induces a north-easterly flow of air along the Polish Baltic coast, which causes upwelling. Such a circulation pattern is accompanied by positive air temperature anomalies. The opposite pressure conditions, during which a trough of low pressure encompasses Scandinavia, cause a westerly flow over the southern part of the Baltic basin, which effectively inhibits upwelling along the Polish Baltic coast.

1. Introduction

Upwelling is a marine ecosystem phenomenon driven mainly by atmospheric conditions. According to the Glossary of Meteorology of the American Meteorological Society (2000), coastal upwelling is the rising of water along coastlines where the wind, blowing alongshore, has the coast on its left in the Northern Hemisphere. In these situations, surface water is drawn away from the coast by surface currents deflecting it offshore (Urbański 1995). The direction of sea surface currents is explained by Ekman's theory, taking into consideration the effect of the Earth's rotation and frictional forces (Lehman & Myrberg 2008). The direction of the air and water current within the Ekman spiral is rotatory and integral with the downward current. In summer, when seawaters are thermally stratified, warm surface water pushed away from the shore is replaced by colder water welling up from deeper layers, usually from below the thermocline (Choiński 2011). In the Baltic Sea, a relatively small semi-enclosed basin, upwelling is a frequent phenomenon observed along different sections of the coast, depending on the wind direction at a given time (Myrberg & Andrejev 2003, Lehmann & Myrberg 2008, Lehmann et al. 2012).

The replacement of warm surface water by colder water from below the thermocline due to upwelling in the warmer half-year appears to have an important environmental impact. The decrease in sea surface temperature (SST), which affects the concentration of nutrients and influences phytoplankton growth, is not yet fully understood. It is nevertheless assumed that upwelling has a strong impact on biogeochemical processes and phytoplankton development (Vahtera et al. 2005, Zalewski et al. 2005, Lehmann & Myrberg 2008).

During an upwelling event during the warmer half of the year, the decrease in SST modifies the local energy balance by increasing the atmospheric heat loss, which may influence the local boundary climate, mainly by changing the stability of the marine boundary layer. The relationship between upwelling and climate is well recognized in the tropical zone (e.g. the El Niño Southern Oscillation) (Tomczak & Godfrey 1995). A few papers have examined the role of atmospheric forcing and weather conditions favourable to upwelling in small temperate zone basins like the

Baltic Sea. Synoptic situations associated with upwelling on different parts of the Baltic Sea coast were studied by Bychkova et al. (1988). Favourable wind conditions forcing upwelling along the Baltic Sea coast were analysed by Lehmann et al. (2012), who demonstrated positive trends of upwelling events in some regions, which are in accordance with the positive trends in the wind conditions giving rise to them.

This study confirms the atmospheric forcing of the sea water circulation and the change in sea water temperature. This is a complex issue, however, not yet fully understood. The main aim of the study was therefore to determine the synoptic conditions that cause upwelling occurring along the Polish Baltic coast. The atmospheric circulation forced by the air pressure pattern will be analysed as the main factor conducive to upwelling. Anomalies of the air temperature accompanying instances of upwelling will also be taken into consideration. Additionally, some quantitative characteristics of upwelling occurrences along the Polish Baltic coast will be given.

2. Area, data and methods

The area of investigation concerning the occurrence of upwelling covered the southern part of the Baltic Sea along the Polish shore, delimited by latitude 54–56°N and longitude 14–19°E. The orientation of the Polish coastline is SW–NE in the western and central part and W–E or NW–SE in the eastern part (Figure 1). The easternmost part of the Polish Baltic coast (along the Vistula Spit (Mierzeja Wiślana)) was excluded from the analysis. This part of the Polish coast is geographically homogeneous with the Russian and Lithuanian shores and should be considered together with the south-eastern part of the Baltic Sea coast.

Maps of daily mean sea surface temperatures (SST) for this area, 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) were analysed. The dataset is a new product, which uses 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 performed on both infrared and microwave data and in situ data from ships and buoys to improve data series resolution. The final dataset has a spatial grid resolution of 0.25° and a temporal resolution of 1 day (Reynolds et al. 2007). Such resolutions and quality of SST data appear to be sufficient for identifying the occurrence of upwelling events. Nevertheless, it must be remembered that a smaller upwelling event close to the coast may

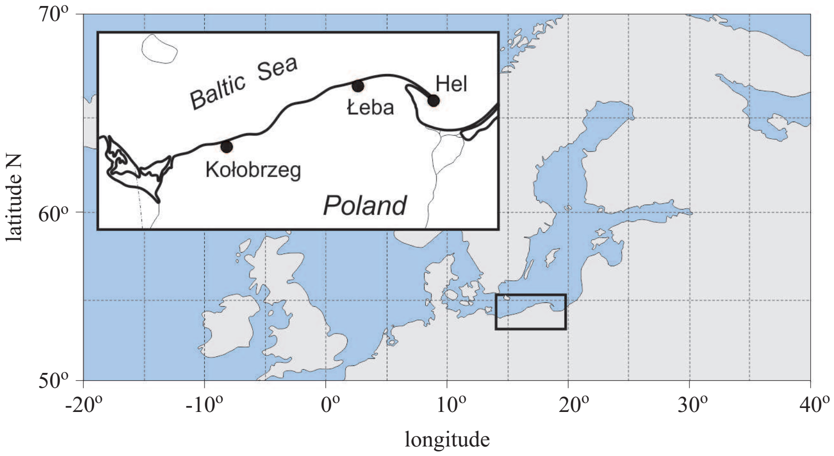

Figure 1. Study area and locations of the upwelling regions

be impossible to detect, especially due to the internal Rossby radius, which is about 2–10 km in the Baltic Sea (Lehman & Myrberg 2008).

The analysis was performed for the period 1982–2010 for the warm part of the year (April–September only) when the sea waters become thermally stratified and the upwelling process is detectable. Spatial and temporal changes of SST, being directly related to the exchanges of heat, momentum and gases between the atmosphere and the ocean, enable a better understanding of the interactions between the two environments (Reynolds & Smith 1994, Siegel et al. 2006, Reynolds et al. 2007). SST is an important variable very often used to detect upwelling (Bychkova & Viktorov 1987, Myrberg & Andrejev 2003, Krężel et al. 2005, Lehmann et al. 2012, etc.).

In this study, a visual detection method was used to identify and quantify the instances of upwelling on each of the 5307 available daily mean SST maps. Upwelling was detected by a significant drop in SST along the coast in comparison with the surrounding open waters, with SST isotherms bent towards the sea. The following categories of upwelling, according to the ranges of the daily mean SST decrease towards the open sea, were distinguished: weak (category 0), when the SST decrease was $< 0.5°$C; moderate (category 1) – 0.5–1.0°C; strong (category 2) – 1.25–2.25°C and very strong (category 3) – $> 2.25°$C (two examples shown in Figure 2). Certain quantitative characteristics of the occurrence of upwelling along the Polish Baltic coast, such as frequency and duration of upwelling, its seasonal and multiannual variability, etc., were determined on the basis of a dataset consisting of selected cases.

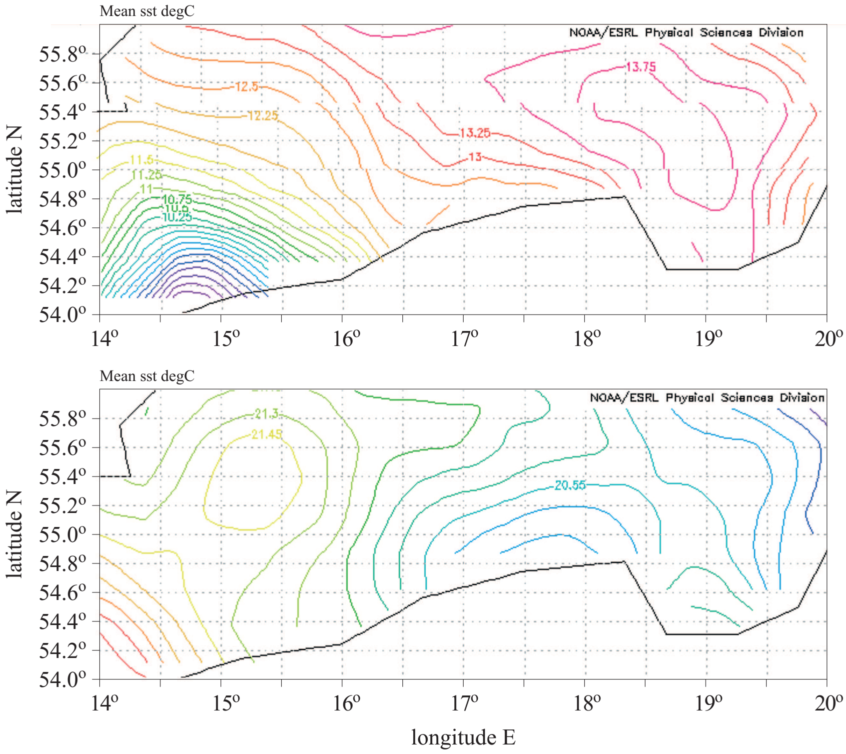

Figure 2. Examples of sea surface temperature (SST) distribution in the southern Baltic during very strong upwelling of the third category (upper) and during weak upwelling of the first category (lower)

Mean daily sea level pressure (SLP) data were used to detect the atmospheric conditions favourable to upwelling. The data were selected from National Centre for Environmental Prediction/National Centre for Atmospheric Research reanalysis data (Kalnay et al. 1996). From the same source, temperature values at an isobaric level of 850 hPa (T850, usually equivalent to that at an altitude of ca 1500 m) and data on wind speed and direction at the 1000 hPa level were obtained and used in the study. All the above reanalysis data are grid-based ($2.5 \times 2.5°$ resolution). Such a spatial grid resolution and quality of data are sufficient for identifying mesoscale SLP patterns (i.e. locations of baric centres) appearing during upwelling events. SLP patterns modify the local wind conditions, which are principally responsible for the occurrence of upwelling. Additionally, the wind direction at three Polish coastal meteorological stations (Kołobrzeg, Łeba, Hel) was taken into consideration.

The 'environment to circulation' approach was applied when relating upwelling events along the Polish Baltic Sea coast to the air circulation and synoptic conditions (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 phenomenon, in this case the occurrence of upwelling along the Polish Baltic Sea coast. Composite maps of SLP means and anomalies were constructed for the days with upwelling selected from the 29-year period. Anomalies were computed as the differences between the composite values and the multiannual averages (1982–2010) of the warm part of the year (April–September). Contour maps of T850 were produced in the same way. Composite analysis was previously used to identify the atmospheric circulation patterns associated with different weather phenomena (Birkeland & Mock 1996).

Furthermore, on the basis of the daily SLP patterns, different circulation types were distinguished for days with upwelling, using Ward's (1963) minimum variance method. This is a hierarchical clustering technique most frequently used for climatic classification (Kalkstein et al. 1987). The method enables the identification of the atmospheric circulation patterns associated with the occurrence of specific weather phenomena (e.g. Esteban et al. 2005, Bednorz 2011). In this study, the clustered objects were the days with upwelling, and the clustering was based on the daily SLP data. The main idea behind clustering data objects (days in this case) is the use of the minimal distance method. Clusters should consist of objects separated by small distances, relative to the distance between clusters. The distance measure commonly used in cluster analysis is the Euclidean distance in the multidimensional space of the data vectors (Wilks 1995).

Finally, composite maps of the synoptic conditions during the first two days of an upwelling event of at least three days' duration were constructed and interpreted as 'inducing conditions'. Complementarily, composite maps for the synoptic conditions of the last days of an upwelling event of at least three days' duration were constructed and interpreted as 'inhibiting conditions'.

3. Results

The 682 events representing upwelling conditions along the Polish Baltic coast were selected from 5307 maps of mean daily sea surface temperature, obtained in 1982–2010. It needs to be emphasized that a wind-driven sea water circulation, i.e. upwelling, may occur at any time of the year, although the thermal and environmental effect may not be noticeable when the sea waters are not thermally stratified. On most SST maps, the core of cold waters adjacent to the coastal line was distinct, and was surrounded by a frontal area of rapidly increasing SST (Urbański 1995). The upwelling area was usually located in one of the main three sectors: central (Łeba region), western (Kołobrzeg region) and eastern (Hel region) (see Krężel et al. 2005, Kowalewski & Ostrowski 2005 and also Bychkova & Viktorov 1987) (Figure 1). Upwelling was most frequently observed along the central (451 days during the 29-year period) and western (434 days) parts of the Polish coast – about 15 days per annum on average. The phenomenon was least frequent along the eastern part of the coast, i.e. in the Hel region (179 days – about 6 days annually). Upwelling events lasted longer in the western and central part of the study area, some of them for more than three weeks. In the eastern part, the duration of upwelling rarely exceeded 10 days. The different frequency and duration may be related to the different orientation of the coastline, which, as we recall, is SW–NE in the western and central part of the Polish coast and W–E or NW–SE in the eastern part. As a result, different wind conditions would be favourable for the occurrence of upwelling.

The mean frequency of days with upwelling was computed on the basis of the 682 events. Every year there are on average 23 days with upwelling along the Polish Baltic coast, which accounts for 13% of the warm period (April–September). A similar frequency of upwelling on the Polish coast was found by Lehmann et al. (2012). However, the number of days varies considerably from year to year: in some years, the number of days with upwelling may exceed 50 (1992, 1996, 1997, 2002, 2006) while in others the phenomenon may not occur at all (e.g. 1983). The maximum number of upwelling days (69) was recorded in 2002. The multiannual course of the number of days with upwelling does not reveal any significant trend of changes (Figure 3).

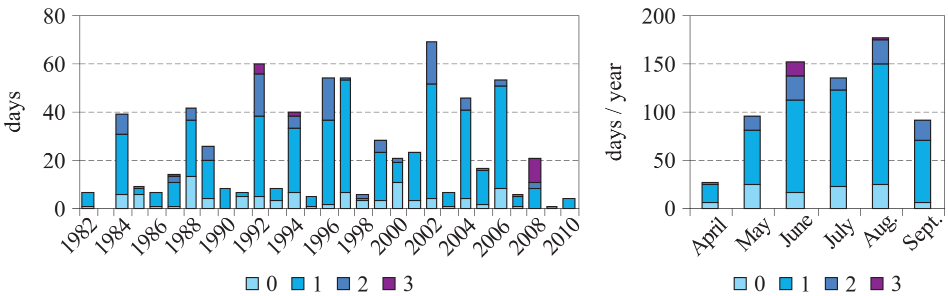

Figure 3. Mean monthly number of days (left) and multiannual course of days (right) with upwelling of different intensity (for explanations, see the section 'Area, data and methods')

Seasonally, upwelling occurs most often in June, July (ca av. 5 days) and August (ca av. 6 days); it is rare in September (av. 3 days) and very rare in April (1 day) (Figure 3). The duration of upwelling events varies from one day to several dozen. Most of the recorded upwelling events were very short and lasted 1–2 days (35 cases out of 96); in 28 instances they lasted 3–5 days and in 15, 6–8 days. 15 upwelling events persisted for more than 10 days.

During the warm half of the year (April–September), the mean SLP is the highest (> 1020 hPa) south-east of the Azores, gradually decreasing towards the north (Figure 4).

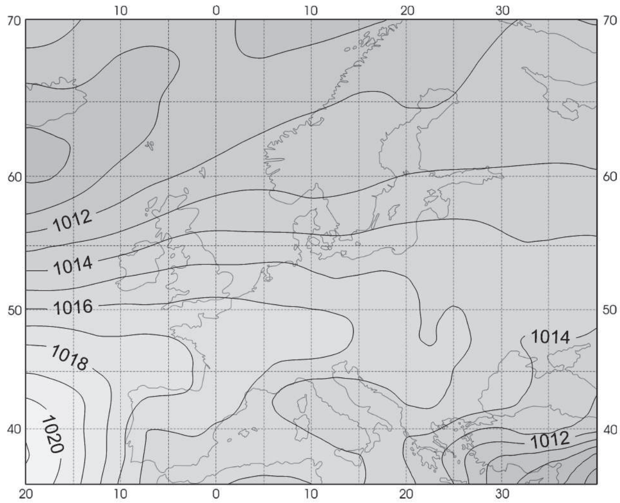

Figure 4. Mean sea level pressure between April and September in 1982–2010

A wedge of high pressure extends to the north-east, encompassing western and central Europe. The low pressure centre (< 1010 hPa) is located over the North Atlantic, south-west of Iceland. A smaller pressure gradient is observed over the European continent than over the Atlantic. Such a pattern gives rise to westerly airflows in the low troposphere, prevailing over the study area in the warm half of the year.

In order to determine the synoptic conditions that cause upwelling along the Polish Baltic coast, composite maps and anomaly maps of the pressure and thermal conditions over the Euro-Atlantic sector of the Northern Hemisphere were constructed separately for all upwelling days (categories 0–3 – 682 days) and for the days with intensive upwelling (categories 2–3 – 118 days) (Figure 5).

A composite anomaly map shows the SLP differences between selected weather situations (days with upwelling) and climatic means for the months from April to September (Figure 5). The most typical characteristics of

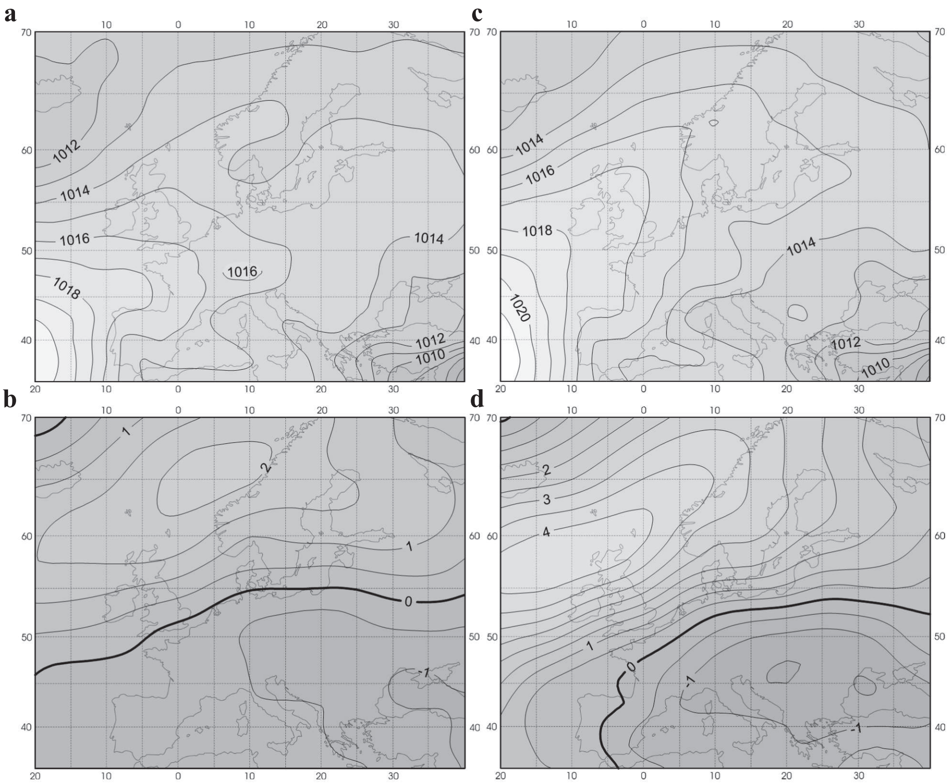

Figure 5. Composite SLP maps (top) and SLP anomaly maps (bottom) for all days with upwelling (left) and for the days with intensive upwelling (right)

the baric conditions favourable to upwelling include positive SLP anomalies over the North Atlantic and northern Europe. They imply the presence of a higher-than-normal pressure there, which is confirmed on the composite SLP maps, where the wedge of the Azores High is shifted to the north-east in comparison to its average position and encompasses the Baltic Sea and southern Scandinavia. Negative low-value anomalies cover central and southern Europe. The interpretation of the contoured composite anomalies is similar to the traditional weather anomaly maps, with clockwise (anti-cyclonic) flow around the positive centres and counterclockwise (cyclonic) flow around the negative centres (Birkeland & Mock 1996). Consequently, circulation on days with upwelling is characterized by a strong easterly and north-easterly flow component over Poland and the Baltic Sea, in contrast to the average circulation in central Europe (Figure 5).

The easterly anticyclonic pattern of circulation discernible in Figure 5 causes positive anomalies of the air temperature in summer (Paszyński & Niedźwiedź 1999), which are confirmed on the T850 anomaly maps

(Figure 6). On the Polish Baltic coast, T850 anomalies amount to 2–2.5°C: this means warm and usually sunny weather with a weak easterly wind accompanied by cold coastal sea waters.

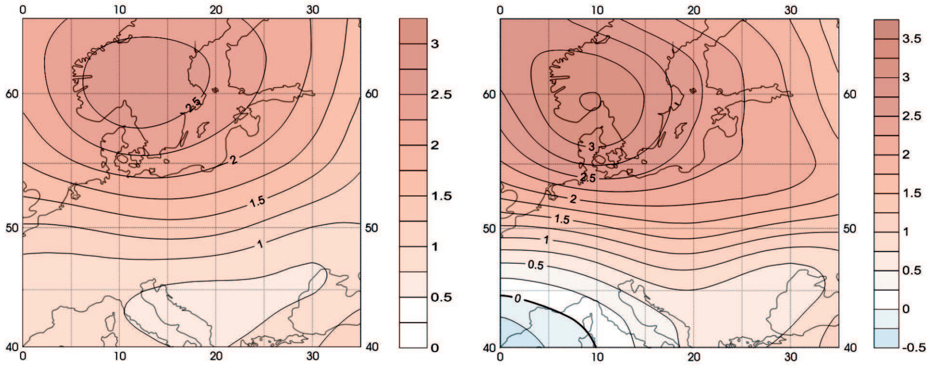

Figure 6. T850 anomaly maps for all days with upwelling (left) and for the days with intensive upwelling (right)

The composite maps shown in Figures 5 and 6 were prepared on the basis of data from 682 upwelling days. However, the synoptic conditions and circulation patterns on those days could not be the same and a number of different types are distinguishable. Therefore, an attempt was made to classify the circulation types causing upwelling along the Polish Baltic coast. The classification is based on the idea of Bychkova et al. (1988), who described 11 different synoptic situations favourable to upwelling in various Baltic coastal areas (Figure 7), but using different statistical methods. Ward's hierarchical minimum variance method was used to cluster the 682 days into groups (types of circulation patterns). Clustering was based on SLP data. Subsequently, composite maps of the three most relevant groups (types) were constructed for both SLP and T850 data (Figures 8a, 9a, 10a). The three types obtained differ greatly from each other.

In Type 1, which consists of 315 days, an anticyclone centred over the North Sea spreads over north-western Europe (Figure 8a). A ridge of high pressure connects it with the Azores High. Type 1 corresponds to weather condition II in Bychkova et al. (1988) (Figure 7). Such a pressure pattern induces a north-easterly flow along the Polish Baltic coast. However, the wind speed is slightly lower than average in the coastal area and is much lower than average over the Baltic Sea basin (Figure 8b). Such an inflow brings warm air to the coastal area; the T850 anomalies over the Polish coast exceed 2°C and increase towards the anticyclone centre (Figure 8c). During upwelling periods lasting for at least 3 days, Type 1 usually occurs

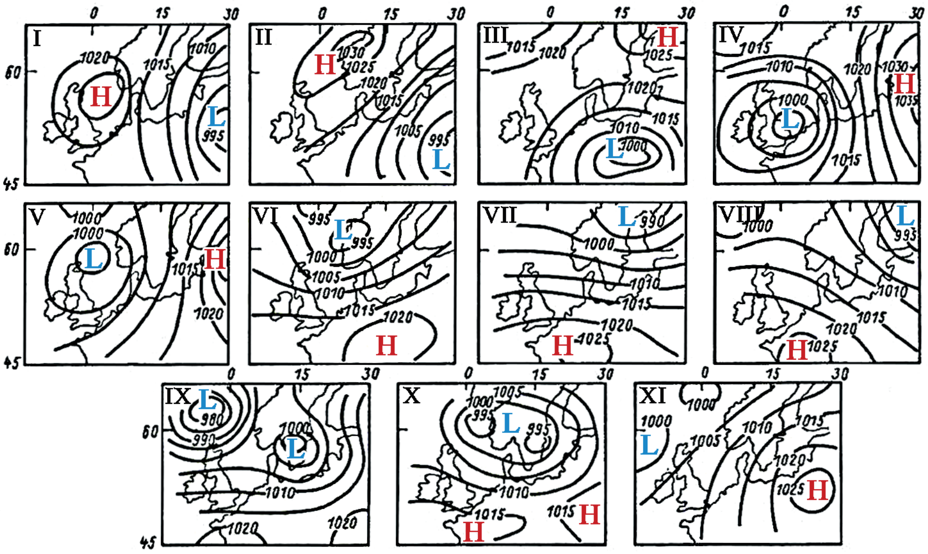

Figure 7. Types of synoptic situations related to upwelling in the Baltic Sea (redrawn from Bychkova et al. 1988)

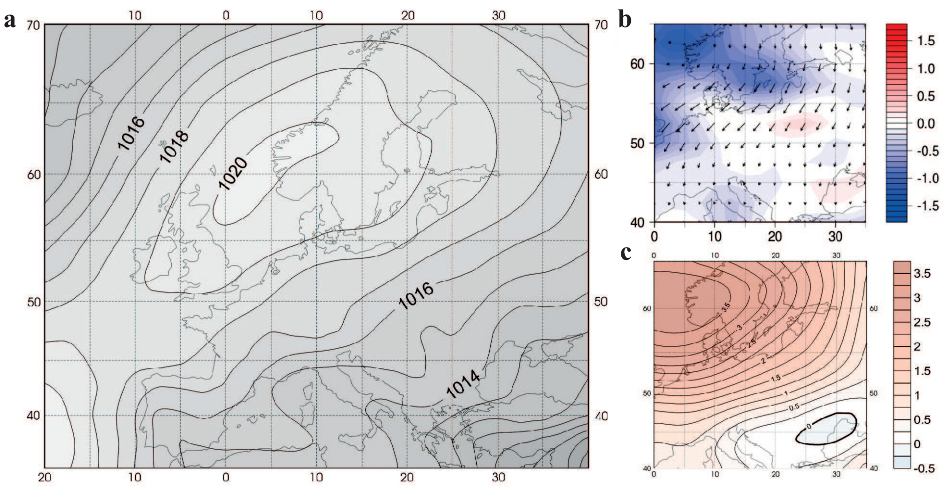

Figure 8. a) composite SLP map; b) mean wind direction (arrows) and wind speed anomaly (colour shades); c) T850 anomalies for Type 1

at the beginning or in the middle of the upwelling event; it is less frequent at the end of it.

In Type 2 (219 days), a low pressure system extends over the North Atlantic. However, the southern Baltic is under the influence of an anticyclone centred to the east of Poland. A similar pressure pattern was

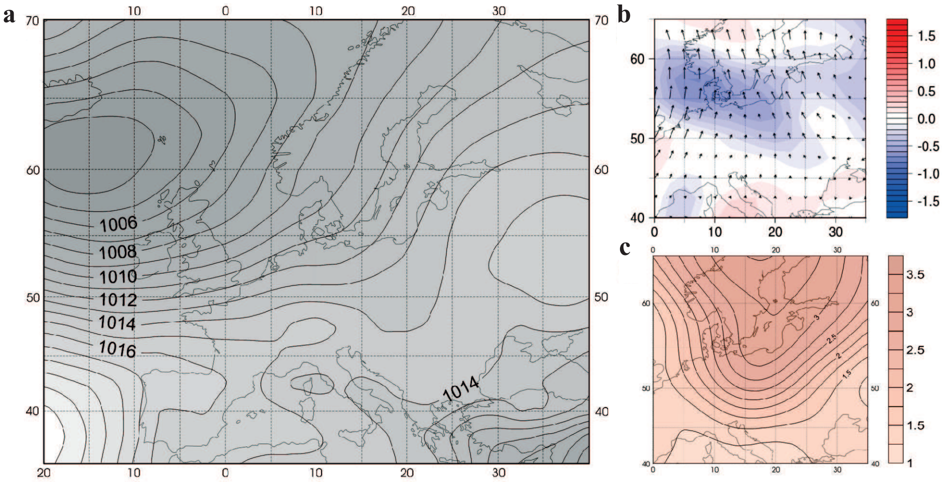

Figure 9. a) composite SLP map; b) mean wind direction (arrows) and wind speed anomaly (colour shades); c) T850 anomalies for Type 2

classified by Bychkova et al. (1988) as weather condition XI. It induces a weak south-easterly flow, accompanied by distinct temperature anomalies, which exceed 3°C in northern Poland (Figure 9).

Type 3 is the least numerous (148 days). It differs from the other two by a deep depression spreading over Scandinavia and resembles Bychkova's weather condition VIII (Figure 7). A counterclockwise circulation around the cyclonic centre induces a westerly flow along the Polish Baltic coast. Westerly air masses are colder and the T850 anomalies are close to 0°C. Types 2 and 3 appear most often towards the end of an upwelling event (Figure 10).

The occurrence of these synoptic situations coincides with the occurrence of upwelling along the Polish Baltic coast. However, this does not mean that all of these circulation types trigger upwelling. In the last stage of the study, the synoptic conditions conducive to upwelling along the Polish Baltic coast were determined. To this end, composite and anomaly maps were constructed for the first two days of an upwelling event of at least three days' duration (Figure 11a,b). The SLP composite map depicts a pressure pattern similar to that of Type 1. An anticyclone centred over Scandinavia, a region of strong positive SLP anomalies (up to 6 hPa), spreads over northern Europe. Such a pressure pattern induces a north-easterly flow along the Polish coast; as in Type 1, the wind speed is lower than average in the coastal area (see Figures 8a and 11a).

The map in Figure 11a is similar to weather conditions II and III distinguished by Bychkova et al. (1988) and bears a close resemblance to

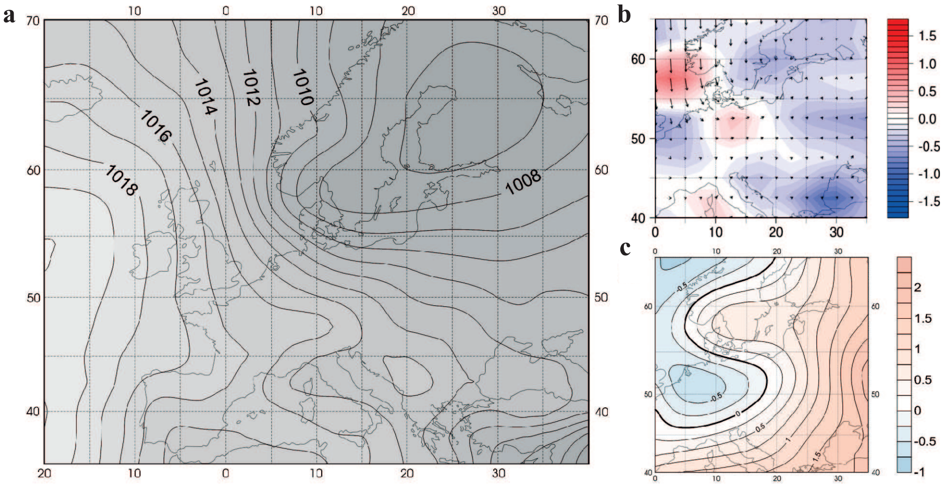

Figure 10. a) composite SLP map; b) mean wind direction (arrows) and wind speed anomaly (colour shades); c) T850 anomalies for Type 3

the Scandinavia circulation pattern (SCAND), identified by the Climate Prediction Centre as one of the most relevant teleconnection patterns in the northern hemisphere. It consists of a primary circulation centre over Scandinavia, with weaker centres of opposite sign over western Europe and eastern Russia. The Scandinavia pattern was previously referred to as the Eurasia-1 pattern by Barnston & Livezey (1987). The positive phase of SCAND is associated with positive pressure anomalies over Scandinavia, sometimes reflecting major blocking anticyclones, while the negative phase of the pattern is associated with negative pressure anomalies in this region. The tau-Kendall correlation computed between the monthly SCAND indices and the number of days with upwelling amounted to 0.16 and was statistically significant at $p = 0.05$.

Complementarily, composite and anomaly maps for the synoptic conditions of the last days of an upwelling event of at least three days' duration were constructed (Figure 11c,d). The anomaly map shows the opposite pressure pattern compared with the map in Figure 11b. This time, the negative anomalies of SLP have spread over the entire northern part of Europe, and a trough of low pressure encompasses Scandinavia. Such a pressure pattern causes a westerly flow over the southern part of the Baltic basin. Owing to the large pressure gradient in this region, the wind speed over the southern Baltic is stronger than normal (Figure 12a,b). Maps of the wind direction and wind speed anomalies were constructed separately for the first two days and for the last days of upwelling events of at least three days' duration. The north-easterly airflow direction triggers upwelling in the

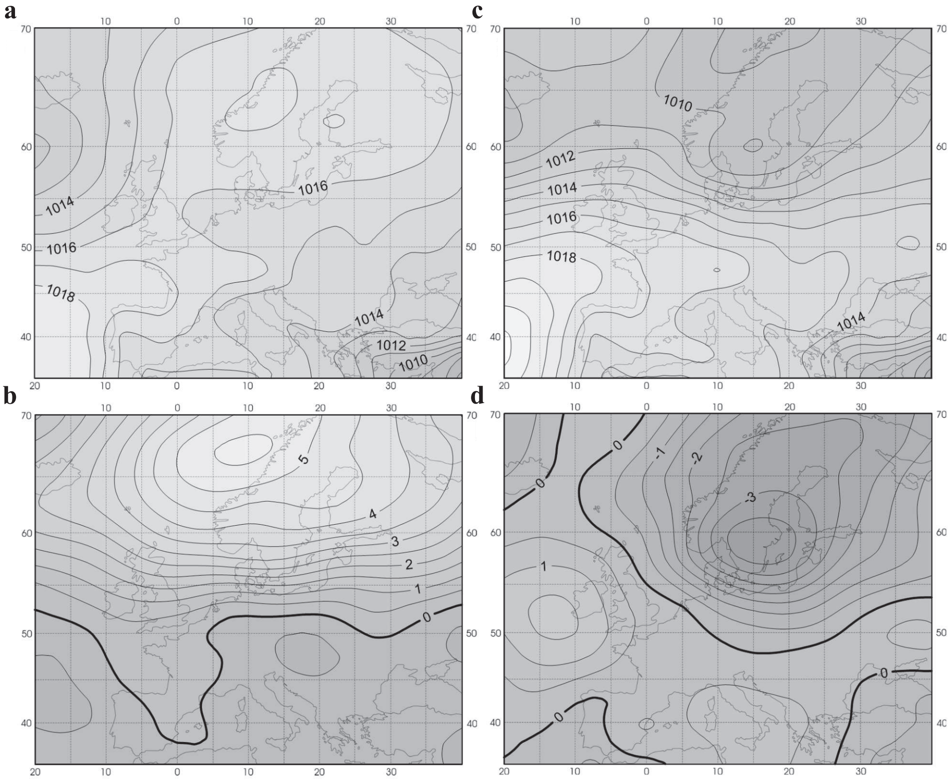

Figure 11. Composite SLP map (top) and SLP anomaly map (bottom) for the first two days (left) and for the last days (right) of upwelling events of at least three days' duration

western and central part of the Polish coast (Figure 12a), while an easterly inflow causes upwelling in the Hel region (Figure 12b). Stronger-than-usual

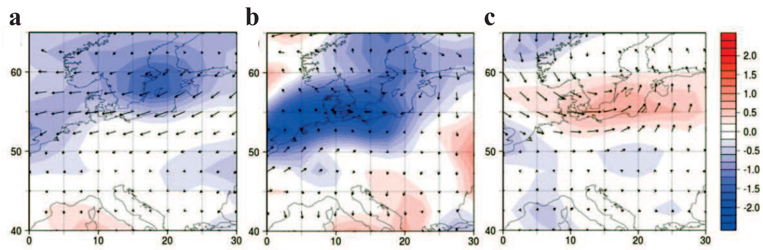

Figure 12. Mean wind directions (arrows) and wind speed anomalies (colour shades) for the first two days (a – western and central regions of the Polish coast, b – eastern region) and for the last days (c) of upwelling events of at least three days' duration

westerly winds, occurring at the end of the upwelling events (Figure 12b) arrest the upwelling process and change the SST.

Similar results were obtained by analysing the wind direction on the first two days and the last days of upwelling events of at least three days' duration computed for three Polish coastal meteorological stations, showing opposite sectors of wind direction (Figure 13). Easterly or north-easterly winds give rise to upwelling-inducing conditions, while westerly or south-westerly winds during the last days of an upwelling event create conditions inhibiting the phenomenon.

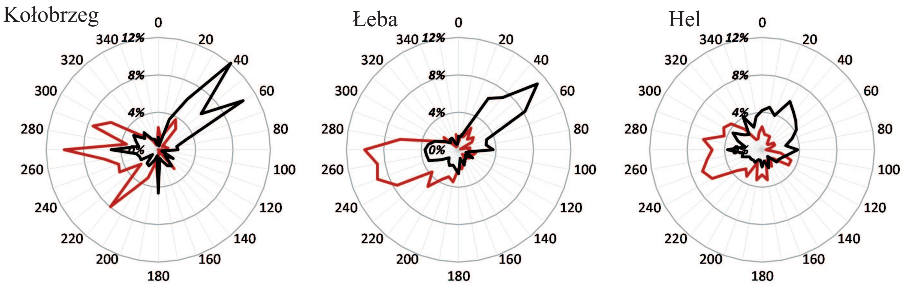

Figure 13. Frequency of the wind direction for the first two days (black) and for the last days (red) of upwelling events of at least three days' duration at three Polish coastal stations

4. Discussion and conclusions

Coastal upwelling on the southern coast of the Baltic is less frequent than in the northern part of this sea (Lehmann et al. 2012). According to that study, it takes place along the Polish Baltic coast on about 13% of days of the warm period (April–September). A similar frequency (10–15%) of upwelling on the Polish coast was found by Lehmann et al. (2012). In summer months the mean frequency of upwelling may reach 20%. Urbański (1995) recorded 26% of upwelling days during the warm halves of the years 1989–1992, with summer upwelling events occurring the most frequently in 1992. Kowalewski & Ostrowski (2005) estimated the frequency of strong upwelling along the western Polish coast at 11.8%, emphasizing that downwelling was more frequent here owing to the prevailing westerly winds (see also Myrberg & Andrejev 2003). The annual number of days with upwelling along the Polish Baltic coast changes significantly from year to year and may exceed 50. On the other hand, upwelling may not occur at all in some years. Also the duration of the upwelling period may vary from one day to several dozen.

With regard to the weather conditions conducive to coastal upwelling in the Baltic Sea, the relevance of the surface wind direction has been emphasized in numerous studies (i.e. Urbański 1995, Myrberg & Andrejev 2003, Lehmann & Myrberg 2008). Far fewer analyses have taken into consideration the general macro-scale or local synoptic conditions, including the pressure field, which determines the wind direction. While studying the atmospheric factors contributing to the water circulation in the Baltic Sea, Lehmann et al. (2002) found that the North Atlantic Oscillation (NAO) influences the three-dimensional transport of sea waters in the Baltic basin in winter. A positive NAO index, which indicates a very strong westerly air circulation, intensifies up- and downwelling in different coastal regions. Those authors used a local circulation index called the Baltic Sea Index (BSI – the difference between normalized SLP anomalies between Szczecin in Poland and Oslo in Norway, computed for the winter months), strongly correlated with the NAO, as a measure of the intensity of the westerly flow, which induces upwelling along northern coasts of the Baltic Sea. NAO is not the only winter circulation pattern; it explains only about 50% of the SLP variability in winter, other patterns such as Blocking and Atlantic Ridge explain the remaining SLP variability (Hurrell & Deser 2009).

The present study confirmed that in summer, when NAO/BSI takes mostly low values, a teleconnection pattern other than NAO, i.e. SCAND (whose main characteristic in the positive phase is an anticyclone over Scandinavia), may influence the occurrence of upwelling along the Polish Baltic coast. A weak but statistically significant correlation was found between the SCAND index and the frequency of upwelling along the Polish Baltic coast.

The pressure pattern with an anticyclone spreading over northern Europe and centred over Scandinavia induces a north-easterly air flow along the Polish Baltic coast, which causes the Ekman effect and triggers the offshore movement of coastal surface sea waters. Favourable winds are necessary to force upwelling and to perpetuate it. There is an inherent inertia in the upwelling process, so when the drop in SST is apparent, some time must elapse before the upwelling signal diminishes, either because the wind calms down or because it changes to an unfavourable direction. Therefore, the conditions that induce upwelling should be analysed separately from the inhibiting conditions. A westerly air flow effectively inhibits upwelling along the Polish Baltic coast. Such a direction of the air circulation is related to SLP conditions with a trough of low pressure over Scandinavia. The same sequence of anemobaric situations, accompanying a strong upwelling event along the Polish Baltic coast in September 1989, was described by Jankowski (2002).

The circulation patterns observed during upwelling events change from day to day, as do the synoptic conditions in the temperate climate zone.

They were classified into three very different types. Bychkova et al. (1988) described 11 different synoptic situations favourable to upwelling in various Baltic coastal areas; five situations were identified as being conducive to upwelling along the Polish Baltic coast. The most numerous Type 1 referred to in this study, characterized by a north-easterly flow along the Polish coast, is related to Bychkova's weather conditions II and III. Bychkova et al. (1988), however, do not consider these conditions as being favourable to upwelling on the Polish coast. Our Type 2 corresponds to Bychkova's situations V and XI, while our Type 3 fits situation VIII (also not regarded by those authors as favourable to upwelling in the Polish coast). Furthermore, Bychkova & Viktorov (1987) suggest that easterly and south-easterly winds induce upwelling along the Polish coast. Such contradictory results concerning the relationship between air circulation and the occurrence of upwelling may arise from ignoring the difference between the conditions at the beginning of the upwelling period and at its end or by analysing single upwelling events. In the present study, easterly and north-easterly winds were found to trigger the offshore current, which confirms the findings of Lehmann et al. (2012) that the local wind component parallel to the coastal segment is the most effective in this respect.

The different results regarding the synoptic conditions giving rise to upwelling along the Polish coast indicate that the problem of the impact of weather conditions on sea water circulation is complex and requires further study.

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