A statistical approach to coastal upwelling in the Baltic Sea based on the analysis of satellite data for 1990–2009

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Abstract

A statistical analysis of Baltic Sea upwelling has been carried out to cover, for the first time, the entire sea area for the period 1990–2009. Weekly composite SST maps based on NOAA/AVHRR satellite data were used to evaluate the location and frequency of upwelling. The results obtained were analysed and compared with earlier studies with excellent agreement. Our study enables the most intense upwelling areas in the entire Baltic Sea to be evaluated. According to the analysis of 443 SST maps, the most common upwelling regions are found off the Swedish south and east coasts (frequency 10–25%), the Swedish coast of the Bothnian Bay (16%), the southern tip of Gotland (up to 15%), and the Finnish coast of the Gulf of Finland (up to 15%). Pronounced upwelling also occurs off the Estonian coast and the Baltic east coast (up to 15%), the Polish coast and the west coast of Rügen (10–15%); otherwise the upwelling frequency was between 5

and 10%. Additionally, simulated SST distributions derived from a Baltic Sea numerical model were analysed for the same period. Furthermore, at specific positions close to the coastline, surface winds based on the SMHI meteorological data base were analysed for the same 20-year period. Wind components parallel to the coast were discriminated into favourable and unfavourable winds forcing upwelling. The obtained frequencies of upwelling-favourable winds fit very well the observed upwelling frequencies derived from satellite SST maps. A positive trend of upwelling frequencies along the Swedish east coast and the Finnish coast of the Gulf of Finland was calculated for the period 1990–2009.

1. Introduction

Upwelling is an important process in the World Ocean as well as in the Baltic Sea. The Baltic Sea is a semi-enclosed, relatively small basin (Figure 1), winds from virtually any direction blow parallel to some section of the coast and cause coastal upwelling, leading to vertical displacement of the water body and pronounced vertical mixing (e.g. Vahtera et al. 2005). During the thermally stratified period, upwelling can lead to a distinct drop in sea surface temperature of more than 10°C during one or two days, abruptly changing the thermal balance and stability conditions at the sea surface (e.g. Lehmann & Myrberg 2008). Upwelling can also play a key role in replenishing the euphotic zone with nutritional components necessary for biological productivity when the surface layer is depleted of nutrients. Summer upwelling often transports nutrients with excess phosphorus in

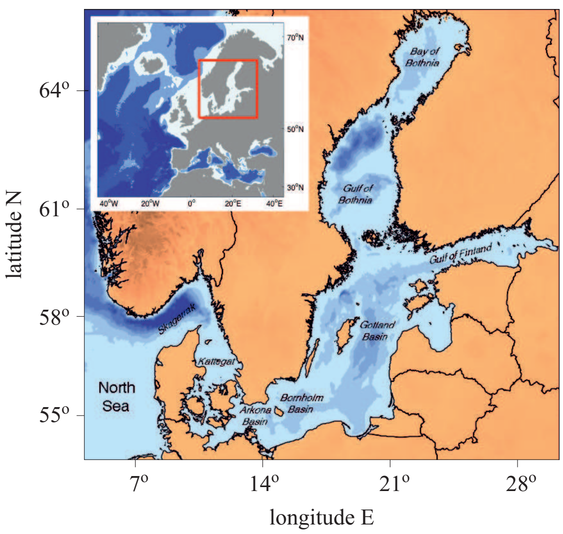

Figure 1. Map of the Baltic Sea showing the areas of investigation

relation to the Redfield ratio (see e.g. Vahtera et al. 2005, Lips et al. 2009). Upwelling as a meso-scale feature is scaled by the baroclinic Rossby-radius. As the thermal stratification varies seasonally in response to solar heating and wind-induced mixing in the Baltic Sea, the baroclinic Rossby-radius has a relatively large range between 2–10 km (Fennel et al. 1991, Alenius et al. 2003, Osiński et al. 2010).

The typical scales of upwelling in the Baltic Sea are:

- vertical motion: 10^{-5}–10^{-4} m s^{-1}, $\sim$1–10 m day^{-1} (Hela 1976),
- horizontal scales: 10–20 km offshore, 100 km longshore (Gidhagen 1987, Bychkova et al. 1988),
- temperature change: 1–5°C day^{-1} (Hela 1976),
- temperature gradient: 1–5°C km^{-1} (Krężel et al. 2005),
- lifetime: from a few days to one month.

Until now, studies of upwelling statistics have been based mostly on the use of in situ and satellite data. The utilization of satellite measurements started in the early 1980s and since then space-borne measurements of various kinds (NOAA/AVHRR etc.) have been applied by numerous authors (see e.g. Siegel et al. 1994, Kahru et al. 1995, Lass et al. 2003, Kowalewski & Ostrowski 2005, Uiboupin & Laanemets 2009). Among the most comprehensive studies is the one by Horstmann (1983), where the author studied upwelling on the southern coast of the Baltic Sea, concluding that it was coupled with easterly winds. Gidhagen (1987) performed an analysis based on AVHRR data and concluded that upwelling on the Swedish coast takes place up to 10–20 km offshore and has a length of the order of 100 km alongshore. According to Gidhagen (1987) water is raised to the surface from depths of 20–40 metres, which is somewhat deeper than previously-estimated values. He also found that in some areas upwelling takes place even one-quarter to one-third of the time. Bychkova et al. (1988) identified 22 typical areas in different parts of the Baltic Sea that were favourable to upwelling during some specific wind events (see Lehmann & Myrberg, 2008, for details). Satellite observations of upwelling in the south-western Baltic Sea off the German and Polish coasts were analysed by Siegel et al. (1994). Moreover, some studies based on modelling have been carried out to statistically describe upwelling events in order to determine their locations and their corresponding frequency of occurrence (Myrberg & Andrejev 2003, Kowalewski & Ostrowski 2005).

In certain areas of the Baltic Sea, upwelling is a very common feature, thus playing an important role in the overall mixing dynamics. Uiboupin & Laanemets (2009) showed that as much as 40% of the area of the Gulf of Finland can be under the influence of upwelling during extreme conditions.

For example, in 2006 the cross-shore extent of upwelling in the Gulf of Finland was 25 km (1/3 of the width of the Gulf of Finland) and the alongshore extension was 360 km (Suursaar & Aps 2007). On the Polish coast upwelling has most often been found to take place off the Hel Peninsula in the Gulf of Gdańsk (see e.g. Matciak et al. 2001, Myrberg et al. 2010). The potential maximum area of all upwelling on the Polish coast is 10 000 km^2, which is ca 30% of the Polish economic zone (Krężel et al. 2005).

Statistical studies of upwelling have been carried out before. Myrberg & Andrejev (2003) determined an upwelling index based on the numerical calculation of vertical velocity for a 10-year period (1979–1988). A similar study was carried out by Kowalewski & Ostrowski (2005) based on a 7-year experiment of calculated vertical velocities in the southern Baltic.

The present paper extends the statistical investigation of Baltic Sea upwelling events based on the integrated use of observations and modelling to cover – for the first time – the entire sea area. For the years 1990–2009, weekly sea surface temperature (SST) maps based on NOAA/AVHRR satellite data were used to evaluate the properties of upwelling during the thermally stratified period from May to September, that is to say, when upwelling is strong enough to raise the thermocline to the surface, thus producing an SST signal. To obtain an independent estimate, numerically simulated daily averaged SST maps were analysed for the same period. Furthermore, favourable and unfavourable wind conditions for upwelling were determined from the wind forcing used as model input.

The structure of the paper is as follows: after this introduction, data and methods are briefly described. Then the results of the statistical analysis are discussed for the period 1990–2009; they are also compared with previous studies. A trend analysis over the total period and for individual months is carried out for identified upwelling areas. Furthermore, for specific upwelling locations, 10-m winds are discriminated into upwelling-favourable and -unfavourable wind conditions, and the relation between upwelling and wind forcing is studied. The paper concludes with a discussion on potential changes in upwelling regions as a consequence of changing climate (wind) conditions.

2. Data and methods

2.1. SST and wind data

The analysis of upwelling regions and their occurrence is based on SST data with a horizontal resolution of about 1 km calculated from NOAA/AVHRR satellite data for the period 1990–2009. The accuracy of the satellite measurement (cloud detection has been carried out) in comparison with in situ data is about 0.5°C (Siegel et al. 1994). From the satellite data, weekly composites are available for the 20-year study period, provided by the Bundesamt für Seeschifffahrt und Hydrographie (BSH in Hamburg, Germany). For each year, upwelling was determined between May and September to cover the part of the year when SST differences due to upwelling are strong enough to be visible, i.e. during the thermally stratified period of the year. A satellite data set of 443 SST maps has been compiled for the 20-year period.

An additional source of SST data has also been provided from model simulations for the period 1990–2009. The numerical model used in this study is a general three-dimensional coupled sea ice-ocean model of the Baltic Sea (BSIOM, Lehmann & Hinrichsen 2000, 2002). The horizontal resolution of the coupled sea-ice ocean model is at present 2.5 km, and in the vertical 60 levels are specified, which enables the top 100 m to be resolved with levels of 3 m thickness. The model domain comprises the Baltic Sea, including the Kattegat and Skagerrak. At the western boundary, a simplified North Sea basin is connected to the Skagerrak to take up sea level elevations and to provide characteristic North Sea water masses resulting from different forcing conditions (Lehmann 1995, Novotny et al. 2005). The coupled sea ice-ocean model is forced by realistic atmospheric conditions taken from the Swedish Meteorological and Hydrological Institute's (SMHI Norrköping, Sweden) meteorological database (Lars Mueller, personal communication), which covers the whole Baltic drainage basin on a regular grid of $1 \times 1°$ with a temporal increment of 3 hours. The database consists of synoptic measurements interpolated on the regular grid using a two-dimensional univariate optimum interpolation scheme. This database, which for modelling purposes is further interpolated onto the model grid, includes surface pressure, precipitation, cloudiness, air temperature and water vapour mixing ratio at 2 m height and geostrophic wind. Wind speed and direction at 10 m height are calculated from geostrophic winds with respect to different degrees of roughness on the open sea and near coastal areas (Bumke et al. 1998). The BSIOM forcing functions, such as wind stress, radiation and heat fluxes, were calculated according to Rudolph & Lehmann (2006). From the model run for 1990–2009 daily mean SST maps (temperature in the uppermost level in the model with a thickness of 3 m) were extracted for the months of May to September, resulting in a database of 3060 SST maps.

For the analysis of upwelling, detailed knowledge about the prevailing wind conditions is of vital importance. In accordance with the upwelling areas presented in Bychkova et al. (1988), daily mean 10-m wind data were extracted from the model forcing database for 21 stations close to the Baltic Sea coastline. The stations chosen represent the wind conditions for the specific upwelling areas along the Baltic Sea coastline.

2.2. Analytical methodology

Upwelling is characterized here by a certain temperature drop (1–10°C) compared to the surrounding water temperature close to the coast (see e.g. Hela 1976, Lehmann & Myrberg 2008); i.e. that the thermocline reaches the surface in the upwelling area, bringing cold water from deep layers to the sea surface. This means in practice that our method is only applicable to strong upwelling events taking place in coastal waters. Such common, strong upwelling events, where a clear drop of SST will take place, could contribute for example, to replenishing the euphotic zone with the nutritional components necessary for biological productivity.

Two methods were utilized here to detect and quantify upwelling events. For the visual detection method a horizontal grid with longitudinal resolution of 0.5° and latitudinal resolution of 0.25° resulting in a grid box about 28 km^2 was overlain on each SST map. As an example Figure 2a shows the SST map for the week 18–25 September 1996 and the overlain grid. It shows that upwelling is occurring along the Polish coast, the Baltic east coast, the west coast of the islands of Saaremaa and Hiiumaa, the Estonian coast of the Gulf of Finland and the Finnish coast of the Bothnian Sea (Figure 2b). For every weekly SST map, upwelling was individually identified and marked in the corresponding box. By doing so, locations within the defined grid and the frequencies of upwelling along the coast of the Baltic Sea could be registered in 443 matrices.

For the automatic detection method, the full resolution of the satellite SST maps was utilized. A simple temperature threshold value was specified. For most parts of the year there exists a latitudinal SST gradient from south to north. Thus, upwelling was detected by calculating the temperature difference for each individual pixel from the zonal mean temperature, for every pixel line. To test the sensitivity of this method with respect to the temperature threshold, two different values (2°C and 3.5°C) were specified. For both thresholds erroneous upwelling areas were detected far offshore. Thus, upwelling was only registered if it occurred within a 28 km zone off the coast. Again, 443 SST maps were scanned and 443 matrices were created but now with a much greater horizontal resolution compared with the visual method. The automatic detection method was also applied to the modelled SST maps, resulting in 3060 matrices showing the location and frequencies of upwelling on the model grid. This method has its limitations if the zonal mean

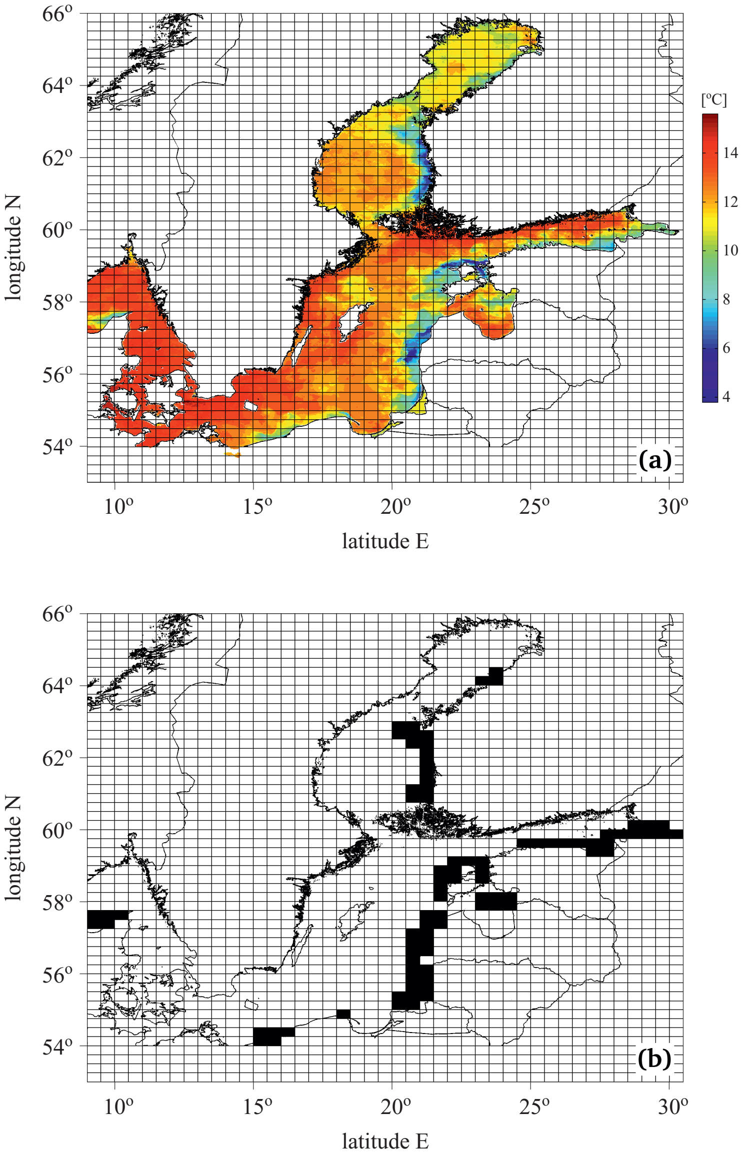

Figure 2. a) SST map for the week 18–25 September 1996 with overlain analysis grid of the visual detection method for upwelling; b) upwelling areas identified using the visual detection method for the same period

temperature is calculated mainly parallel to the coast such as for the Gulf of Finland, and in spring or autumn when the SST is higher/lower in the coastal area than in the open sea. So we cross-checked upwelling frequencies derived by the automatic method with the results of the visual method.

For the wind analysis, the average direction of the different coastal sections was determined from high-resolution bathymetric maps of the Baltic Sea. According to the Ekman theory, winds parallel to the coast are the most effective for causing upwelling. Thus, only the wind components projected parallel to the coast were processed. The wind components were further divided into favourable winds triggering upwelling and unfavourable wind conditions. Upwelling will occur if favourable winds blow with a certain wind speed and for a certain time to raise cold water from within and below the thermocline to the surface. Of course, the depth of the upper mixed layer varies over the thermally stratified season, being shallow in May and June (1–5 m) and deepening over the summer (10–20 m) (see e.g. Haapala & Alenius 1994). According to Hela (1976) a water particle at 5 m depth will be raised to the surface when the wind blows parallel to the coast at 10 m s^{-1} for one day. We chose the threshold value for the favourable wind component inducing upwelling to be ≥ 3.5 m s^{-1} lasting for at least 2 days. We also tested 5 m s^{-1} and 4 m s^{-1} thresholds, but the frequencies derived were too low compared with the upwelling frequencies.

Generally, upwelling frequencies were calculated individually for each month as a 20-year mean, which means that 86/89 weeks (600/620 days) were considered for the calculation. Additionally, the upwelling frequency was calculated for the whole 20-year period (May–September in each year). The upwelling frequency has values between 0 and 100%, which means that if there is an upwelling event on every date the frequency is 100%, and if no upwelling occurs the frequency is equal to 0%.

3. Results of the analysis of SST maps derived from satellite images

3.1. Results of the visual detection method

A somewhat similar study to ours was carried out by Bychkova et al. (1988, Figure 3). Based on the analysis of satellite data for 1980–1984, they found 22 typical upwelling areas for the Baltic Sea. Figure 4 shows our results of the visual detection method based on 443 SST maps for the months of May to September for the period 1990–2009. The scaling is from 1 to 30%, which corresponds to about 4 to 133 weeks of upwelling during the study period. If we compare areas of $> 5\%$ with the upwelling areas presented in Bychkova et al. (1988), we find a very good agreement. Different upwelling areas can be linked to corresponding frequencies of upwelling. High frequencies up to 25% were reached for areas 17 and 18, 18% for area 19. Off the Swedish coast of the Bay of Bothnia (area 14), frequencies of

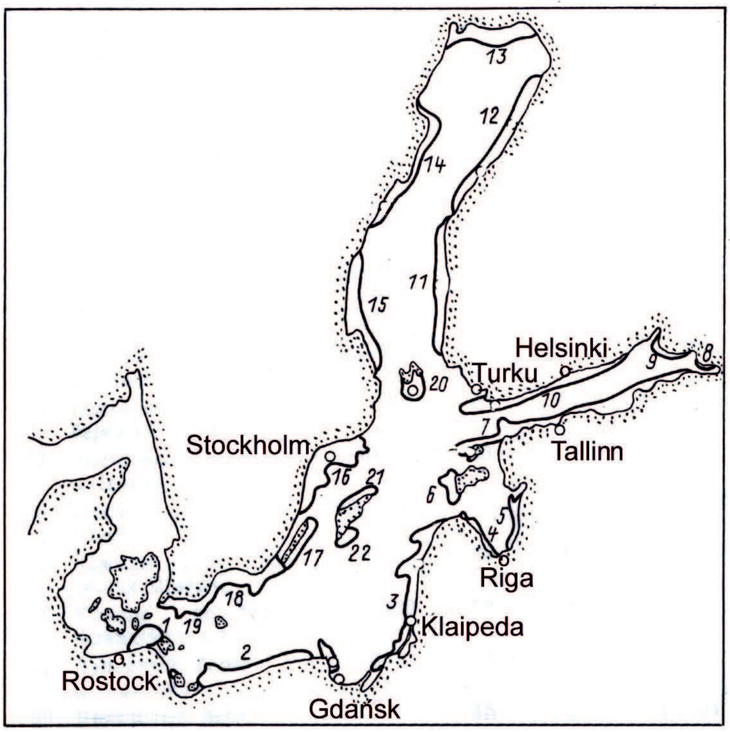

Figure 3. Main upwelling regions in the Baltic Sea related to associated weather conditions (redrawn from Bychkova et al. 1988)

17% can be observed. There were frequencies of 10 to 15% along the Finnish coast (10, 11, and 12), the Swedish coast (15 and 16), the Estonian west coast (7), the Latvian coast, at the southern tip of Gotland (22), on the west coast of Rügen (1) and along the Polish coast (2). Upwelling was less frequent (1–5%) in areas 4, 5, 6, 8 and 21, and no upwelling was found in areas 9, 13 and 20. There is an additional upwelling area off the southern coast of Saaremaa with an upwelling frequency of about 12%.

3.2. Results of the automatic detection method

The visual detection method is time-consuming and the detection grid is rather coarse, so that distinguishing between different upwelling areas is difficult. An automatic detection method for upwelling could work at a much higher resolution, and would additionally lead to an objective method if suitable criteria for the detection could be specified. Figure 5 (a,b) shows the results of the automatic detection method for two different thresholds (2 and 3.5°C) based on 443 SST maps for the months of May to September in the period 1990–2009. For both thresholds the location of the main upwelling

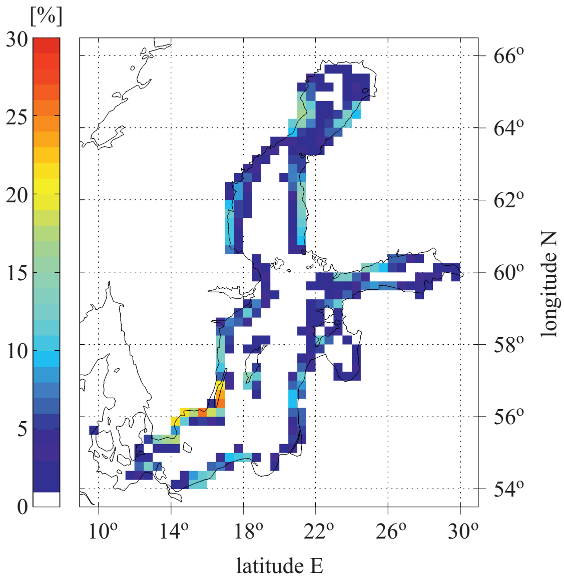

Figure 4. Annual upwelling frequencies [%] obtained using the visual detection method for upwelling based on 443 SST maps for the period 1990–2009 (May–September)

areas (see also Figures 3 and 4) agrees very well. However, higher frequencies result for the lower threshold, although the higher threshold reproduces the borders of the different upwelling areas much better. It should be noted that the correspondence of the upwelling frequencies obtained is very high between the visual and the automatic detection method with a 2°C temperature threshold (compare Figure 4 with Figure 5a). Thus, in the further discussion of our results, we will focus on the automatic detection method with the 2°C threshold, which is in accordance with the criteria specified by Gidhagen (1987). A better distinction between the different upwelling areas can be obtained only if upwelling frequencies $> 5\%$ are considered.

Upwelling frequency in Baltic Sea in 1990–2009 – from May to September

Gidhagen (1987) calculated upwelling frequencies for the Swedish coastal area in the Baltic Sea for 1973–1982 from AVHRR satellite data and in situ measurements. Even if the period of investigations in our case and that in Gidhagen's study are not the same, it makes sense to compare the gross features of the results. In Gidhagen's statistics, for coastal regions, an upwelling event was recorded if the SST measurement showed an abnormal drop of at least 2°C compared with earlier or surrounding

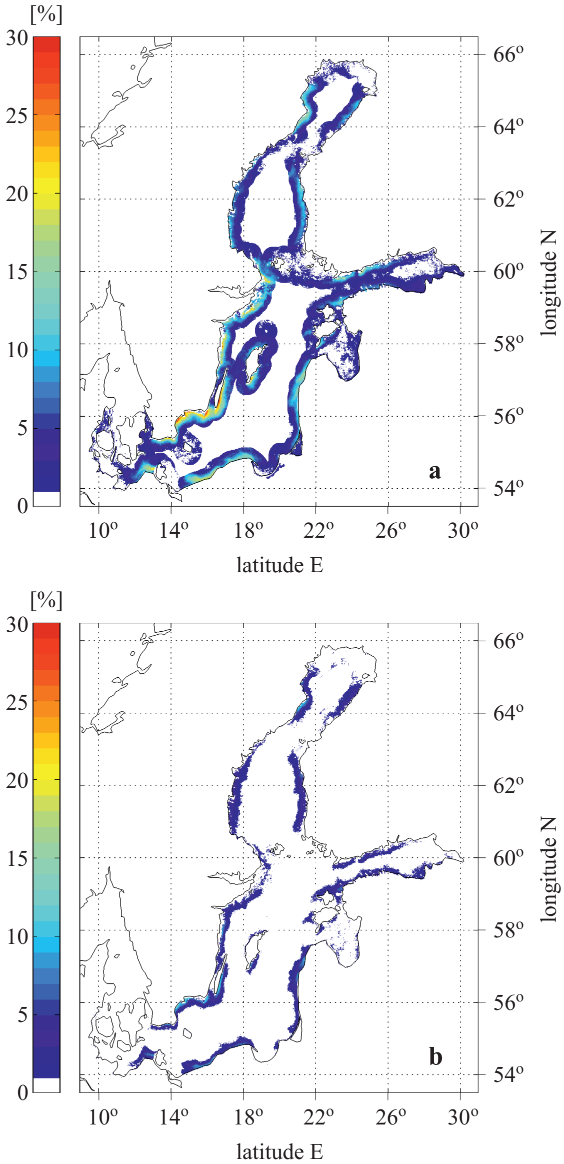

Figure 5. Upwelling frequencies [%] obtained from the automatic detection method for upwelling based on 443 SST maps for the period 1990–2009 (May–September): a) 2°C temperature threshold and b) 3.5°C temperature threshold

measurements. Hence, the methodology used by Gidhagen (1987) is similar to ours. Both approaches lead to a number of similar results. The most favourable upwelling regions are located off the southernmost coast of Sweden (Trelleborg and Ystad (area 19, Figure 3), Karlshamn and Kalmarsund (area 18); Table 1). In most of these regions upwelling takes place in 30% of cases according to both approaches, at some locations even in 40% of cases. However, both approaches confirm that the upwelling frequency there drops abruptly during late summer. By way of explanation Gidhagen stated that the deepening of the mixed layer in late summer makes it difficult even for stronger winds to cause such an upwelling where a drop in SST can be measured, i.e. where the thermocline would be raised to the surface (see section 5 for further discussions).

Table 1. Upwelling frequency [%] at some Swedish coastal stations according to Gidhagen (1987) and the present study (LMH). For the location of upwelling areas, see Figure 3

Coastal station/area	July Gidhagen/LMH	August Gidhagen/LMH	September Gidhagen/LMH
Trelleborg/19	28/26	22/26	10/6
Ystad/19	28/33	22/28	11/7
Karlshamn/18	18/33	23/38	20/24
Kalmarsund/18	15/28	13/31	37/16
Klintehamn	2/2	5/0	10/0
Fårö S/21	0/0	0/0	0/1
Landsort NE/16	5/3	15/12	27/16
Almagrundet	2/6	6/8	24/10
Svenska Högarna	0/5	0/8	0/9
Kuggören/15	16/14	16/12	27/17
Sundsvallsbukten/15	7/14	6/3	28/16
Husum/14	2/1	2/2	14/9
Ratan/14	27/19	25/18	30/23
Bjuröklubb NW/14	22/21	11/21	20/24
Furögrund/13	4/22	19/21	25/26

Both studies show that at Kuggören and Sundsvallsbukten (area 15), Ratan and Bjuröklubb NW (area 14) and Furögrund (area 13) the upwelling frequency increases towards autumn due to the fact that off the west coast of the Gulf of Bothnia upwelling is favoured by south-westerly winds, which increase in speed and frequency towards the end of summer. According to both studies, upwelling hardly ever takes place at Svenska Högarna (north of area 16) and Fårö N (area 21). This is because these areas are located on the open sea and there are no surrounding land areas off which Ekman upwelling could occur. The low numbers in Husum (southern part of area 14), reproduced in both analyses, are due to its being sheltered too strongly by land areas for a proper wind impulse to affect the water masses there.

Upwelling frequencies for May

During May (Figure 6a), the main upwelling regions are located in the southern and eastern Baltic. Off the German and Polish coasts upwelling can have a frequency of 0–25%; these events are due to easterly winds, whereas upwelling along the Baltic east coast (values between 0 and 20%) is generated by northerly winds. This reflects the quite common wind situations in spring: there are winds blowing from the east bringing relatively warm air to the Baltic area or else there is a northerly air flow with cold air masses advecting from the north. In the northern Baltic there is still no pronounced temperature stratification in May and so there are no horizontal temperature gradients along the coast reflecting upwelling. Normally, sea ice disappears from the Gulf of Bothnia during May or early June. However, the automatic detection methods register erroneous upwelling south of Bornholm, in the Gulf of Riga and in the Bay of Bothnia. These horizontal temperature gradients are due to differential coastal heating over sloping bottoms (e.g. Demchenko et al. 2011). The areas marked red have been excluded from the further analysis (Figure 6a).

Upwelling frequencies for June

In June, upwelling in the northern Baltic Sea and the Gulf of Bothnia is still quite infrequent, whereas in other parts of the sea upwelling is already commonly observed because the water masses are now well-stratified (Figure 6b). Off the German-Polish coast upwelling is rather modest (0–15%). Along the southern part of the Swedish coast in the Baltic Proper and close to the southern tip of Gotland frequencies between 10 and 33% are typical. These values are due to south to south-westerly winds which favour upwelling there. In the Gulf of Finland, a well-known upwelling area becomes apparent off the Hanko Peninsula (0–9%, area 10; see e.g. Haapala 1994, Lehmann & Myrberg 2008). This upwelling is related to south-westerly winds, and the corresponding upwelling off the Estonian coast (0–12%) is forced by easterly winds (see e.g. Lips & Lips 2008, Suursaar 2010). However, it should be noticed that along both the Finnish and Estonian coasts of the Gulf of Finland the upwelling frequency is no more than about 10%. This can be explained by the relatively weak temperature stratification in the area during some years and bearing in mind that the minimum of wind forcing is typically in May–June. Again, the areas marked red show erroneous upwelling frequencies which have been excluded from the further analysis (Figure 6b).

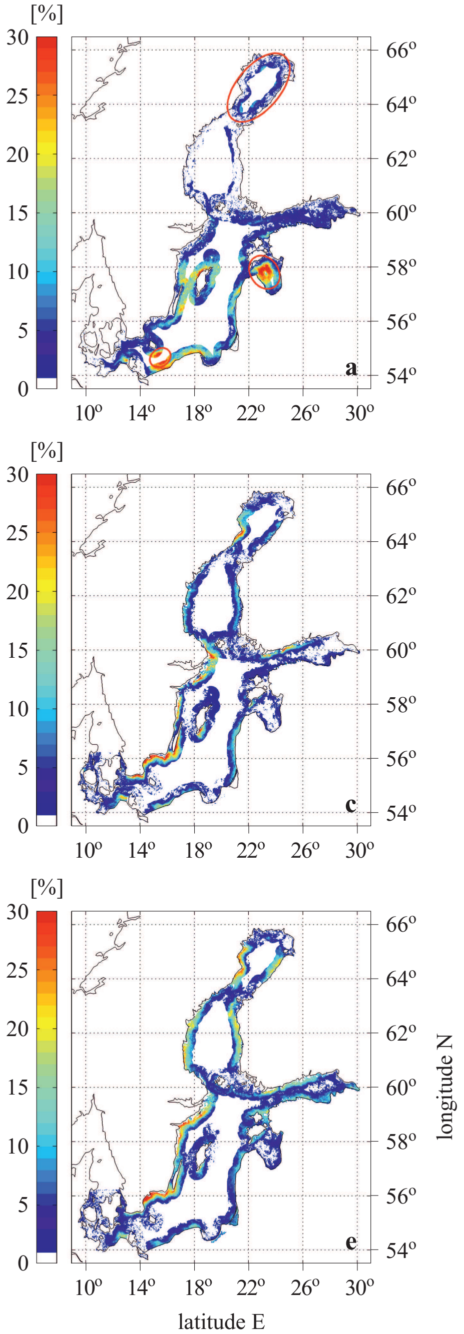

Figure 6. a) Upwelling frequencies [%] for May obtained using the automatic detection method, 2°C temperature threshold, based on 89 SST maps for the period 1990–2009; b) upwelling frequencies [%] for June obtained using the automatic detection method, 2°C temperature threshold, (*continued on next page*)

(Figure 6, *continued***)** based on 86 SST maps for the period 1990–2009; c) upwelling frequencies [%] for July obtained using the automatic detection method, 2°C temperature threshold, based on 88 SST maps for the period 1990–2009; d) upwelling frequencies [%] for August obtained using the automatic detection method, 2°C temperature threshold, based on 90 SST maps for the period 1990–2009; e) upwelling frequencies [%] for September obtained using the automatic detection method, 2°C temperature threshold, based on 90 SST maps for the period 1990–2009

Upwelling frequencies for July

In July (Figure 6c) upwelling is pronounced in all parts of the Baltic Sea; this is characteristic of the strong initial temperature stratification, and no doubt the favourable wind conditions, so that upwelling becomes visible in satellite-derived SST. Also the traditional idea that upwelling can take place in any coastal area of the Baltic Sea becomes true. Off the Swedish south and west coasts in the Baltic Proper upwelling is very well pronounced. So, even in our 20-year average, upwelling in some places can reach a frequency of 40% (e.g. off Karlskrona, Figure 3, area 18), being typically 20–30% in large coastal areas. This was already observed by Walin (1972) in the case of Hanö Bight. Also the southern tip of Gotland is a pronounced upwelling area, whereas the Swedish coast more to the north, as far as the Bothnian Sea, is less favourable to upwelling (frequency 10–20%) mostly due to the shallow, well-mixed archipelago areas.

An interesting detail is the high frequency of upwelling off the southern tip of Saaremaa at the mouth of the Irbe Strait. This upwelling is most probably due to westerly winds or is induced by the adjoining elongated coasts. Along the German and Polish coasts the upwelling frequency is typically between 5 and 15%, which means that the necessary east-north-easterly winds are not so common. This is also true along the coasts of the Baltic States where, due to the low number of northerly wind events, the upwelling frequency is usually no more than 15%, typical values being around 10%. The existence of south-westerly winds in July is further confirmed by the intense upwelling along the Finnish coast of the Gulf of Finland, near the Hanko Peninsula, where the upwelling frequency may reach 20–25%. In July upwelling is also common in the Gulf of Bothnia: along the northern Swedish coast (Ratan and Bjuröklubb, area 14) the upwelling frequency is about 25%. The presence of upwelling along both coasts of the Gulf of Bothnia (frequency 5–15%) reflects the existence of south, south-westerly as well as north-easterly and northerly winds.

Upwelling frequencies for August

In August (Figure 6d) the overall picture of upwelling is to a large extent the same as that in July. The Swedish south and west coasts are still affected by pronounced upwelling with frequencies of about 20–30%. On the coasts of the Baltic states the upwelling frequency is 5–15%, even off the southern tip of Saaremaa. The upwelling frequency is somewhat higher along the German-Polish coast (frequency typically 10–20%), where the famous upwelling region off the Hel Peninsula (see e.g. Matciak et al. 2001) is in evidence with values close to 15%, which means that the frequency of easterly winds is increasing in the southern Baltic. This is also confirmed by the increasing frequency of upwelling along the Estonian coast of the Gulf of Finland (10–15%) and by the somewhat decreasing frequency along the Finnish coast (10–20%). The increasing upwelling frequency (up to 20%) off the Finnish coast of the Gulf of Bothnia indicates that northerly winds seem to be on the increase. At the same time upwelling off the Swedish coast of the Bothnian Sea has weakened slightly, whereas in the Bothnian Bay there is still a high frequency of upwelling on both coasts (up to 22%).

Upwelling frequencies for September

The most remarkable change in September (Figure 6e), compared with previous months, is the sudden weakening of the upwelling frequency off the Swedish south coast (area 19, frequency only about 5–15%). Also along the Swedish coast of the Baltic Proper the upwelling frequency is now only 10–27%. The reasons for this behaviour requires more detailed analysis (see section 5). The upwelling frequency is high off the Estonian coast of the Gulf of Finland (values up to 20%): this reflects the existence of easterly winds, whereas upwelling along the Finnish coast is still quite intense with values $> 20\%$. An interesting feature is that now upwelling sometimes occurs nearly all around the Gulf of Finland, even exceeding the limit of 28 km (see section 2.2). This could be due to the formation of filaments and squirts (see e.g. Zhurbas et al. 2008). A clear signal is visible in the Gulf of Bothnia, where upwelling is intense along both coasts: on the Finnish coast and on the Swedish side the upwelling frequency is typically between 15 and 25%. As in the Gulf of Finland, the area of the Gulf of Bothnia occasionally affected by upwelling is larger (Figure 6e).

4. Results of the analysis of SST maps derived from BSIOM

In addition to the SST maps derived from satellite images, 3060 daily mean SST maps extracted from the model data base were analysed for upwelling areas by utilizing the automatic detections method with a temperature threshold of 2°C. There were two reasons for doing this analysis. Firstly, we wanted to verify BSIOM's ability to simulate upwelling against our statistical analysis based on maps of recorded SST. Secondly, if the model can satisfactorily simulate upwelling, the wind forcing must then be sufficient to cause upwelling. Hence, we can analyse the wind field with respect to wind conditions favourable and unfavourable to upwelling.

Figure 7 displays the results of the automatic detections method based on 3060 SST maps for the months of May to September for the period 1990–2009. The scaling is from 1 to 30%, which corresponds to about 31–918 days with upwelling. In accordance with the satellite derived data, the highest upwelling frequencies (20–25%) can be found in area 10 along the Finnish coast of the Gulf of Finland, 16, 17 and 18 on the Swedish coast of the Baltic Proper and 22 at the southern tip of Gotland. For the west coast of Rügen (1), the Polish coast (2), the Swedish south coast (19), the Swedish coast of the Gulf of Bothnia (14 and 15) the frequency is 10–16%. Areas 3, 4, 5, 7, 11 and 21 have somewhat lower values – 5–10%. No upwelling was recorded in areas 9, 13 and 20.

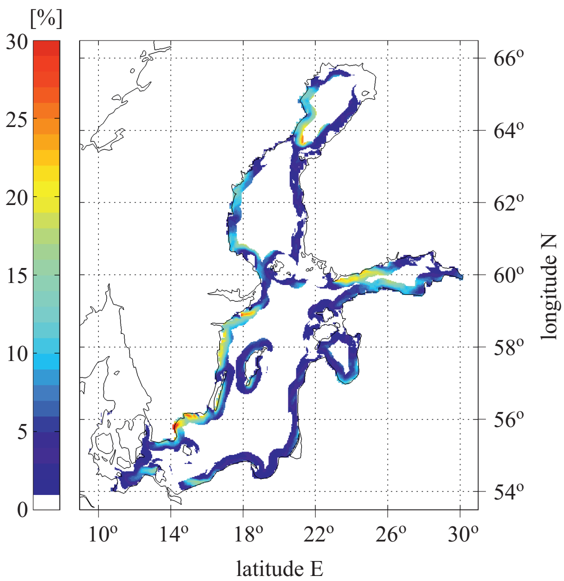

Figure 7. Upwelling frequencies [%] for the months May to September obtained using the automatic detection method, 2°C temperature threshold, based on 3060 BSIOM SST maps for the period 1990–2009

Generally, upwelling frequencies derived from satellite data and from BSIOM are highly correlated. To estimate the quality of the agreement we calculated the total number of pixels/boxes, and the number of pixel/boxes for specific upwelling frequency ranges for which upwelling could be detected. Corresponding areas can be determined from the different resolutions of the data used (Table 2). If we compare the total areas derived from the different methods and data, there is good correspondence between model and satellite data when using a 2°C threshold. The visual methods cause an approximate doubling of the upwelling areas, which is obviously due to the coarse resolution. Comparison of the results for the different frequency ranges shows that the correspondence is best for the visual and automatic method for the 2°C threshold. The 2°C threshold therefore seems to be the appropriate choice.

Table 2. Upwelling areas derived from different data types and methods (compare the colour coding of frequency ranges in Figures 4–7)

Method	Satellite data			Model data	
	visual	2.0°C	3.5°C	2.0°C	3.5°C
total number of pixels	290	129181	43504	23909	11419
1–5 %	56.2	64.5	90.1	54.2	81.7
5–10%	24.5	25.2	9.4	25.9	16.0
10–15%	15.2	7.3	0.5	12.1	2.1
>15	4.1	3.0	0.0	7.8	0.2
area in km^2	**227360**	**156309**	**52640**	**149431**	**71369**

5. Results of the analysis of wind station data

Figure 8 illustrates the result of the analysis of the surface wind data used to force BSIOM. Only the percentages of favourable winds to potentially force upwelling are shown. The analysis is based on 3060 daily mean wind fields for the months of May to September in the period 1990–2009. A frequency of 10% corresponds to 306 days of upwelling-favourable winds. The highest frequencies – up to 30% of favourable wind conditions – appear along the Swedish south and east coasts, off the southern tip of the island of Gotland (about 15%) and on the Finnish coast of the Gulf of Finland (14%). The overall agreement of upwelling frequencies with favourable wind conditions is very high (see Figures 4 and 5a). It should be noted that 10-m wind data were calculated from geostrophic winds and that the choice of thresholds strongly biased the results of our statistical analysis.

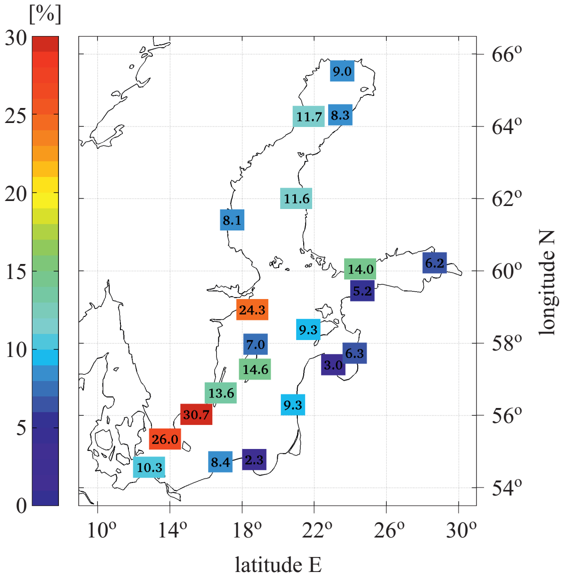

Figure 8. Frequencies of favourable wind conditions forcing upwelling [%] for the months of May–September for the period 1990–2009

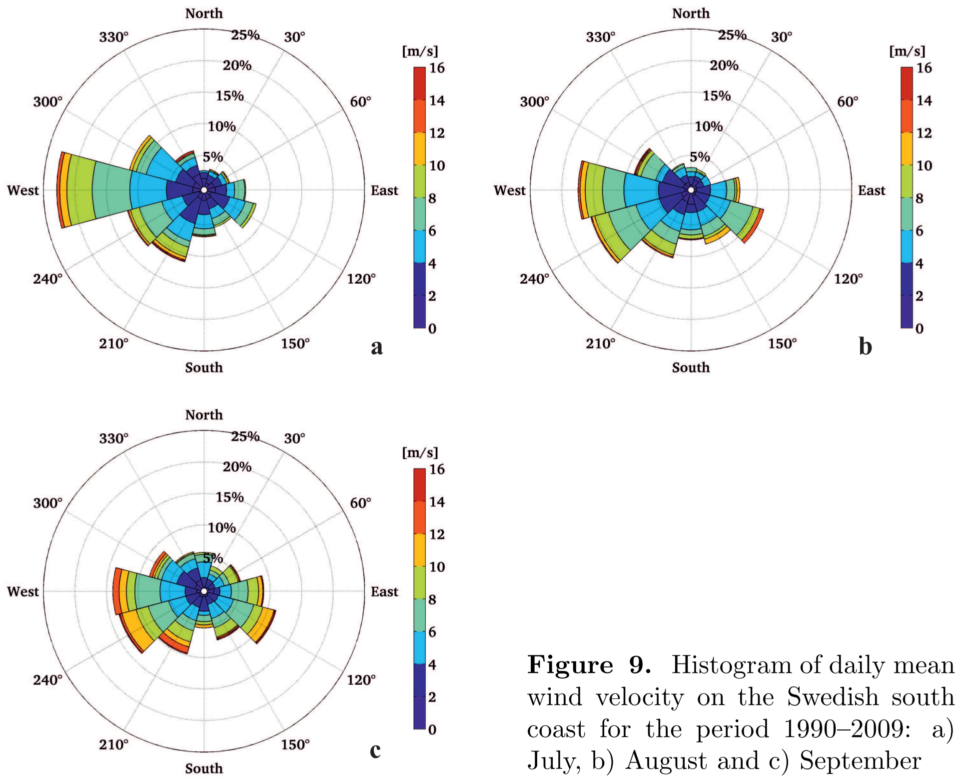

Figure 9. Histogram of daily mean wind velocity on the Swedish south coast for the period 1990–2009: a) July, b) August and c) September

Thus, perfect agreement between upwelling frequencies and favourable wind conditions cannot be expected.

It was stated previously that the upwelling frequency along the Swedish south coast was very high – 25–40% in July and August, followed by an abrupt drop in September (15–20%). Although the wind conditions on the Swedish south coast changed from July to September (Figure 9), the favourable wind conditions changed only slightly from 30 to 25% (not shown). In July westerly winds prevail (about 23%), but then in August westerly winds decrease in frequency (about 17%) and south-westerlies increase to 15%. In September westerly and south-westerly winds both account for about 14% but with increasing frequencies of stronger winds > 10 m s^{-1}. Thus, the decreasing upwelling frequency on the Swedish south coast is due to increasing mixed layer depths, as suggested earlier by Gidhagen (1987).

6. Trend analysis

The temporal development of upwelling events along the Baltic Sea coast can be calculated from the time series of upwelling frequencies (443 weeks). Figure 10 depicts the temporal trend of upwelling frequencies in

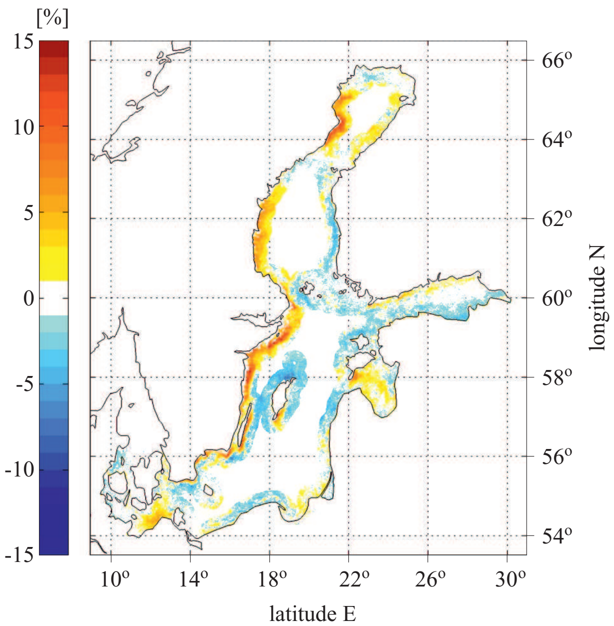

Figure 10. Trend for upwelling frequencies [% decade^{-1}] May–September (1990 –2009) based on the analysis of 443 weeks

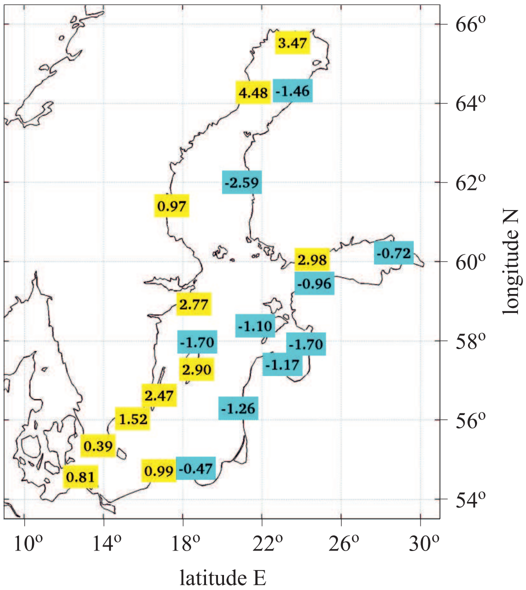

Figure 11. Trend of upwelling-favourable wind conditions [% decade^{-1}] May –September (1990–2009) based on wind station data

% per decade for May–September in 1990–2009. Only those areas where the trend is stronger than $\pm 5\%$ per decade are statistically significant (p-value < 0.05). Generally, there is a positive trend of upwelling frequencies along the Swedish coast of the Baltic Sea and the Finnish coast of the Gulf of Finland and a negative trend along the Polish, Latvian and Estonian coasts. This is in line with the warming trend of annual mean air temperatures and mean SST derived from infrared satellite images (1990–2008) presented in Lehmann et al. (2011). The smallest trends occurred along the east coast of Sweden 0.3 to 0.5°C decade^{-1} compared to 0.5 to 0.9°C decade^{-1} in the central part of the Baltic Proper. Those authors postulated that the decrease in the warming trend along the coast was due to increased upwelling connected with a shift in the dominant wind directions. Our trend analysis of favourable wind conditions derived from the wind station data May–September for the period 1990–2009 support this hypothesis (Figure 11). There is a positive trend of south-westerly and westerly wind conditions along the Swedish coast and the Finnish coast of the Gulf of Finland and a corresponding negative trend along the east coast of the Baltic Proper, the Estonian coast of the Gulf of Finland and the Finnish coast of the Gulf of Bothnia. September contributes most to this trend, whereas in June and August the trend undergoes a partial reversal.

7. Summary and discussion

The present paper extends the statistical investigation of Baltic Sea upwelling to cover the entire area of the sea for the first time. For the period 1990–2009, weekly maps based on NOAA/AVHRR satellite data were used to analyse the locations and frequencies of upwelling along the Baltic Sea coast. These characteristics compare very well with earlier studies, also based on satellite observations (Gidhagen 1987, Bychkova et al. 1988). Additionally, daily SST fields derived from a coupled sea ice-ocean model run were analysed for the same period. The statistical analysis was carried out over the thermally stratified period from May to September but also for each individual month. Different methods and various thresholds were applied to different data sets (satellite observations and numerical model results). The overall agreement of the derived statistics was very high, which confirms the robustness of the results.

Upwelling events occurred most frequently along the Swedish east coast and the Finnish coast of the Gulf of Finland. Upwelling frequencies were related to prevailing wind conditions during particular months and the orientation of the coastline with respect to the wind direction. For the period 1990–2009 a positive trend of upwelling frequencies along the Swedish east coast and the Finnish coast of the Gulf of Finland was calculated, which is in accordance with the positive trend in the wind conditions forcing upwelling, i.e. an increase in south-westerly winds over the Baltic Proper and more westerly directions over the Gulf of Finland. A negative trend occurs along the east coast of the Baltic Proper, the south coast of the Gulf of Finland and the Finnish coasts of the Gulf of Bothnia.

For our analysis we assumed a fixed mixed layer depth, which of course varies during the summer and from year to year. For a deep mixed layer the necessary wind impulse to force upwelling is larger than for a shallow mixed layer in order to produce a signal in SST (Haapala 1994). Additionally, during successive upwelling events, mixed layer depths will not be as deep as during the initial event (Myrberg et al. 2010). Thus a consideration of the mixed layer depth would lead to a better correspondence between upwelling frequencies and favourable wind conditions, but this is somewhat beyond the scope of the present paper. Mixed layer depths can be determined from the numerical modelling results, but our focus was on the statistical analysis of SST observations derived from infrared satellite data for which no information on mixed layer depths was available.

Our results show that upwelling frequencies can be up to 40% in some coastal areas of the Baltic Sea; in certain cases upwelling can cover even one third of the surface area of the sea. Upwelling strongly affects the environmental conditions of the sea by increasing vertical mixing, replenishing nutrient-depleted mixed layers and cooling vast areas of the sea surface. This not only impacts biological processes, but can strongly affect the coastal weather, causing unexpected fogs in late summer and an abrupt cooling of coastal areas. The accurate numerical prediction of SST should thus be coupled even better than now as a part of routine numerical weather prediction modelling.

For tourist areas, increasing upwelling frequencies during summer will have a negative impact because of the lower sea surface temperatures. Moreover, the nutrient supply to the nutrient-depleted summer mixed layer can trigger phytoplankton blooms. Values of pH could drop by 0.1 pH-units in upwelled water, so with increasing upwelling frequencies in certain areas, there is greater stress on marine organisms resulting from these rapid changes in environmental conditions. Hence, even if the process of upwelling is fairly well understood, climatological changes may affect the frequencies and locations of coastal upwelling; further investigation of upwelling conditions are therefore of vital importance.

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