Reports

Upwelling events, coastal offshore exchange, links to biogeochemical processes – Highlights from the Baltic Sea Science Congress at Rostock University, Germany, 19–22 March 2007

OCEANOLOGIA, 50 (1), 2008.
pp. 95–113.

KEYWORDS
Baltic Sea
Upwelling
Coastal-open sea
Biogeochemistry

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Received 31 October 2007, revised 1 February 2008, accepted 4 February 2008.

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

Abstract

The Baltic Sea Science Congress was held at Rostock University, Germany, from 19 to 22 March 2007. In the session entitled 'Upwelling events, coastal offshore exchange, links to biogeochemical processes' 20 presentations were given, including 7 talks and 13 posters related to the theme of the session. This paper summarises new findings of the upwelling-related studies reported in the session. It deals with investigations based on the use of in situ and remote sensing measurements as well as numerical modelling tools. The biogeochemical implications of upwelling are also discussed. Our knowledge of the fine structure and dynamic considerations of upwelling has increased in recent decades with the advent of high-resolution modern measurement techniques and modelling studies. The forcing and the overall structure, duration and intensity of upwelling events are understood quite well. However, the quantification of related transports and the contribution to the overall mixing of upwelling requires further research. Furthermore, our knowledge of the links between upwelling and biogeochemical processes is still incomplete. Numerical modelling has advanced to the extent that horizontal resolutions of c. 0.5 nautical miles can now be applied, which allows the complete spectrum of meso-scale features to be described. Even the development of filaments can be described realistically in comparison with high-resolution satellite data. But the effect of upwelling at a basin scale and possible changes under changing climatic conditions remain open questions.

1. Introduction

Up- and downwelling events are typical phenomena in the World Ocean and also in the Baltic Sea. Because of the complex coastline and the many islands, winds from any direction can cause up- and downwelling near coasts. The extent of upwelling in an offshore direction can be scaled from the dynamic point of view by the internal Rossby radius, which in the Baltic Sea is about 2–10 km. During summer and autumn, when the sea surface is warm, upwelling is seen on infrared satellite images as a local drop in temperature of several degrees. Cold water from below the thermocline rises, eventually reaching the surface, where it mixes with the considerably warmer upper layer waters. Upwelling is produced by sudden storms or strong winds most effectively when the wind blows parallel to the coast with the coastline on the left (right) in the northern (southern) hemisphere. Satellite data indicate that horizontal scales of coastal upwelling are of the order of 100 km alongshore and some 10–20 km off the coast. Typical time scales range from a few days to as long as one month. Sometimes, upwelled water may spread several tens of kilometres out into the basin, forming filaments of cold water. Upwelling is strongly coupled to biological processes: during thermal stratification, when the surface layer is depleted of nutrients, upwelling plays an important role in replenishing the euphotic zone with the nutritional components necessary for biological productivity.

The present paper is a collection of contributions of the most recent results, presented at the Baltic Sea Science Congress at Rostock University, Germany, in March 2007. It is therefore not a general review of upwelling but describes the most recent findings of upwelling studies in the Baltic Sea. Lehmann & Myrberg's (2007) Congress presentation, reviewing our common knowledge of upwelling, will be published elsewhere (Lehmann & Myrberg 2008, accepted), and will thus be discussed only briefly here. The structure of the paper is as follows. The second section summarises the main findings based on observations and the third discusses the results of numerical modelling. Section 4 analyses recent findings with respect to the links between upwelling and biogeochemical processes. The paper closes with a summary and outlines suggestions for future work.

2. Advances in observations of upwelling events

2.1. Characteristics of upwelling

The general lifetime of upwelling in the Baltic Sea ranges from several days to one month. The horizontal dimensions are rather large in comparison of the size of the sea. Typically, the scale of upwelling is 10–20 km offshore and about 100 km alongshore. The temperature gradient is some 1–5°C km^{-1} in the upwelling area, while the temperature change is at least a few degrees per day, at most up to 10°C day^{-1} (Lehmann & Myrberg 2007).

Satellite remote sensing provides a good opportunity to study particular upwelling events and to obtain statistical characteristics of upwelling. An upwelling study based on satellite measurements was carried out for the entire Baltic (Lehmann et al. 2007; Figure 1). To identify extreme upwelling events in the Baltic Sea for the period 1990–2006, monthly mean surface temperature anomalies were calculated from infrared satellite data. Strong upwelling occurred along the eastern coast of the Baltic Proper in September 1996, along the Finnish coast of the Bothnian Bay and the Bothnian Sea in September 2003, along the Swedish coast of the Bothnian Bay and the Bothnian Sea in September/October 2005, and along the southern coast of the Gulf of Finland and the eastern coast of the Baltic Proper in August 2006; the last-named event did not extend as far offshore as the other events. These upwelling events could be attributed to specific atmospheric conditions (see Bychkova & Viktorov (1987)). Offshore transports were of the order of 1000 m^3 s^{-1} km^{-1} coastline, and about 25% of the surface area (Bothnian Sea and Bay) was affected by upwelling. Upwelling events in 2003 and 2005 were identified as extreme events during the period 1990–2006.

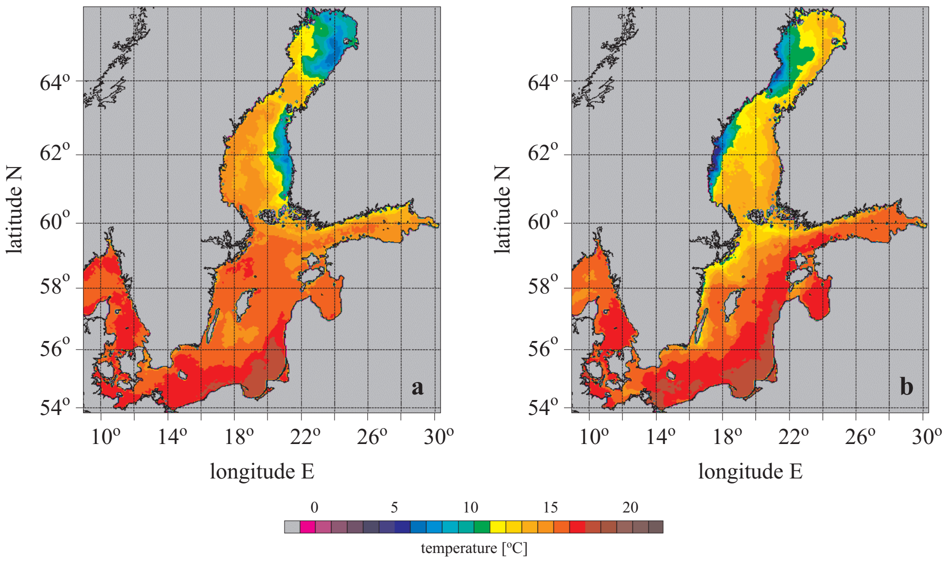

Figure 1. Monthly mean composites of sea surface temperature (SST) in °C for September 2003 (a) and September 2005 (b). SST composites were constructed by combining (averaging) available NOAA-satellite overpasses for one month. The scale for SST is from −1.0 to 22.0°C, increment 1°C

In the Gulf of Finland MODIS (Moderate Resolution Imaging Spectroradiometer) sea surface temperature (SST) data from 2000–06 were examined to determine the area covered by upwelled water, the temperature difference between upwelled and surrounding water, and the location of filaments (Uiboupin & Laanemets 2007). It would be pertinent to mention here that some of the figures cited differ from those in the BSSC 2007 abstract owing to the inclusion of new SST data. Examination of SST data showed that the average area covered by upwelled water during an event was 4820 km^2, which is about 15% of the Gulf's area. In the case of the most intensive upwelling, some 40% (12 140 km^2) of the Gulf's area was covered with upwelled water. Upwelling events along the Finnish coast were more extensive than those along the Estonian coast, the average areas covered with upwelled water being 6120 and 4070 km^2 respectively. The average area of upwelled water in the western part of the Gulf (3100 km^2 – 22%) was larger than in the eastern part (2420 km^2 – 13%). Temperature differences between the upwelled and surrounding waters were 3–7°C off the northern coast and 8–15°C off the southern coast. Filaments were related mainly to upwelling events along the Finnish coast; those associated with upwelling along the Estonian coast were very much weaker and occurred more rarely. Upwelling filaments were most frequently observed off the

Hanko and Porkkala peninsulas. The area of filaments of an upwelling event was as large as 1420 km^2, i.e. some 12% of the total area of upwelled water in the Gulf, and the filaments emerging from an upwelling front were up to 35 km in length. Almost all the upwelling filaments were rotated cyclonically regardless of their occurrence along either the northern or southern coast.

Talpsepp (2007) and Kauppinen et al. (2007) also analysed upwelling events in the Gulf of Finland. In summer 1995 an intermittent upwelling in the Gulf of Finland was observed. A diurnal wind of speed >8 m s^{-1} blowing from appropriate directions caused upwelling along the Estonian coast. Up- and downwelling took place on both the Estonian and Finnish coasts of the Gulf of Finland. This led to higher salinity along the coasts with a strip of less saline water in the central part of the Gulf (Talpsepp 2007). The wind impulse necessary to produce upwelling off the coast of Estonia was found to be more than 6900 kg m^{-1} s^{-1} lasting for a period of three days, as happened in September 1996 (Kauppinen et al. 2007). This is in accordance with an earlier study by Haapala (1994).

Golenko et al. (2007) studied a strong upwelling event recorded in October 2005 off the Curonian Spit following strong N–NE winds (15 –18 m s^{-1}). As a result of this storm, cold water appeared at a distance of about 10 km offshore. The cold water extended for 5 km in the sea surface layer and more than 12 km in the bottom layer. The temperature of the water dropped to 4.5°C. This upwelling event produced considerable changes in the thermohaline structure in nearshore waters down to depths of 25–30 m, but also caused the intermediate layer to decrease in deeper areas.

The application of remote sensing methods is often dependent on cloudiness, whereas unattended Ferrybox measurements serve as a suitable tool for assessing upwelling-related meso-scale physical forcing on the pelagic ecosystem (Lips U. et al. 2007). Ferrybox measurements (unattended measurements of temperature, salinity, chlorophyll *a* and fluorescence, and automatic water sampling from pre-defined locations at 4–5 m depth) along the ferry route between Tallinn and Helsinki started in 1997 within the framework of the Alg@line project (Rantajärvi (ed.) 2003). An upwelling intensity index was developed and applied on the basis of a statistical analysis of cross-gulf temperature recordings. The intensity estimates of upwelling events were analysed in relation to the coastal-offshore Ekman transport calculated from Kalbådagrund (59°59.1′N, 25°36.1′E) wind data. Characteristic wind patterns led to intensive upwelling events off the southern or the northern coast of the Gulf, and the peculiarities of the observed upwelling events on opposite coasts could be described. The estimated upwelling index and the off-coast 10-day average Ekman transport correlated very well.

Additionally, links between the (seasonally) integrated upwelling intensity index and the intensity of cyanobacterial blooms characterised by integrated biomass values of *Nodularia spumigena*, *Aphanizomenon* sp. and *Anabaena* spp. over the bloom period were studied (Lips 2005). Total bloom biomass (and especially the *Aphanizomenon* biomass) was found to be well correlated with the estimated intensity of upwelling events in May –June. Thus, the operational estimates of the pre-bloom upwelling intensity index can be used to forecast cyanobacterial blooms in the Gulf of Finland in summer.

In the oceans, upwelling is known to have extensive and long-lasting effects on fog formation. The horizontal scales in the Baltic are much smaller, making the atmosphere-sea interactions sometimes very intense and sudden. Suomi (2007) studied a marine fog situation that took place over an upwelling area in the northern Gulf of Finland on 8 September 2002. The upwelling took place off the Finnish coast near the Helsinki archipelago between the end of August and the beginning of September and caused the sea surface temperature to fall from $>20°C$ to $14°C$ in response to weak SW winds blowing off the warm, open sea.

2.2. Upwelling in the Gulf of Finland in summer 2006

A strong upwelling event took place off the Estonian coast in August 2006. This case was studied by a number of scientists and several papers were presented at the Congress.

E winds in August 2006 generated a strong upwelling event along the Estonian coast of the Gulf of Finland, which lasted almost an entire month (Raudsepp et al. 2007, Lips I. et al. 2007; Figure 2). Water at a temperature of $5°C$ rose to the surface from below the thermocline, while the surrounding water temperature was $20°C$. Simultaneous downwelling was observed along the Finnish coast. During the upwelling period the sky was mostly cloudless, so that several satellite images could be obtained from the MODIS instruments installed on the Terra and Aqua satellites. Sea-surface temperature, chlorophyll *a* and turbidity distributions were analysed simultaneously. The sea-surface temperature was low on the Estonian coast and rather homogeneous outside the upwelling area. In contrast to the sea-surface temperature distribution, a strip of high chlorophyll *a* concentration was detected along the Finnish coast. There was no significant difference in turbidity values between the up- and downwelling regions, and the open Gulf.

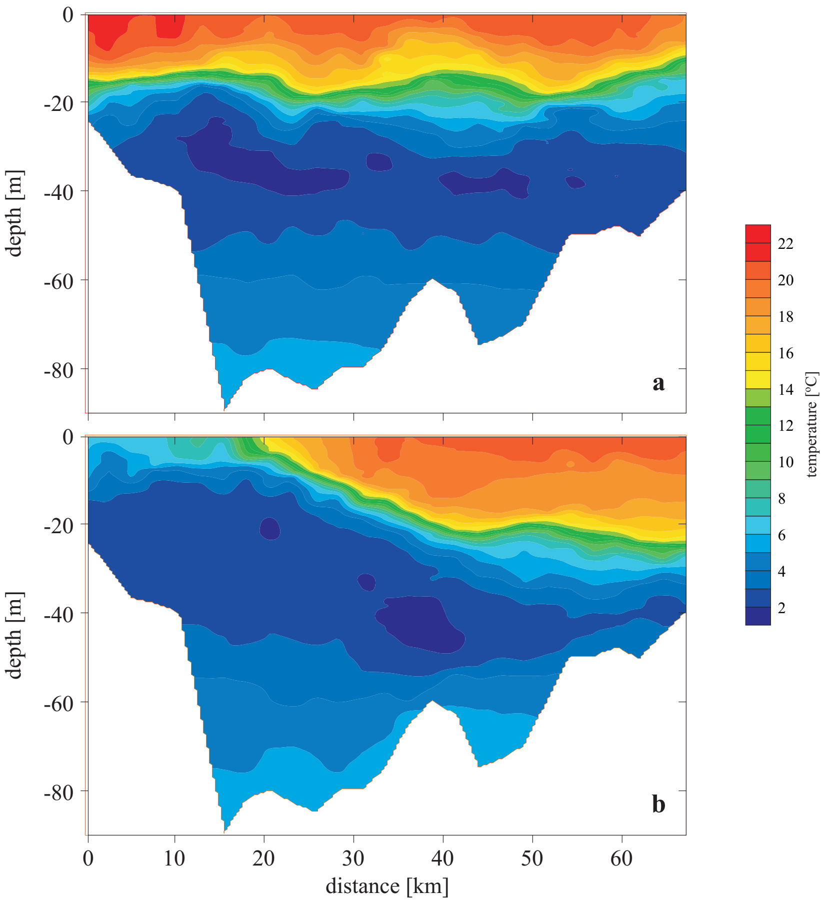

Figure 2. Measured temperature [°C] cross-section in the Gulf of Finland in summer 2006; stratification (a) is normal off the Estonian coast on 11 July, pronounced upwelling (b) in this region on 8 August (Lips I. et al. 2007)

Lips I. et al. (2007) studied the August 2006 upwelling event by conducting an intensive measurement campaign in this sea area (Figure 2). The aim of those measurements was to demonstrate the links between the variability of the upper layer nutrient and chlorophyll *a* content and meso-scale hydrophysical processes. Weekly mapping of hydrographic, hydrochemical and -biological fields were carried out across the Gulf between Tallinn and Helsinki in July–August 2006. Vertical profiles of temperature, salinity and fluorescence were recorded at 27 stations (distance between stations 2.6 km); water samples for chemical analyses (PO_4^-, NO_2^-+NO_3^-, SiO_3^-) and phytoplankton chlorophyll *a* content, biomass and species composition were collected at 14 stations (distance between stations 5.2 km).

A typical summer situation of hydrophysical, hydrochemical and -biological variables with the seasonal thermocline at depths of 10–20 m was observed at the start of measurements in July. Nutrient concentrations in the upper layer were below the detection limit and the nutriclines lay just beneath the thermocline. The chlorophyll *a* content was the highest in the top 10 m layer, but some patches of subsurface maxima were observed in the southern part of the cross-section.

Very low temperatures (down to 5°C) were recorded in the whole of Tallinn Bay, and the cold water covered more than 1/3 of the cross-section during the August upwelling event. High nutrient concentrations were measured in upwelled water (e.g. > 0.4 μmol dm^{-3} of phosphate P). Successive cross-section temperature, salinity and nutrient content data enabled the vertical movements of water masses and nutrient fluxes related to the upwelling event to be estimated. The response of phytoplankton to the observed meso-scale processes was described on the basis on chlorophyll *a* data (Lips I. et al. 2007).

3. Advances in the modelling of upwelling dynamics

Numerical modelling tools have been actively used in upwelling studies during recent years. An important reason is that state-of-the-art computers allow us to carry out simulations with a very high resolution, so that the fine structure of upwelling can now be studied. High-resolution satellite and in situ measurements provide excellent verification data for models.

The Princeton Ocean Model (POM) has been used by Zhurbas et al. (2007); it is a sigma-coordinate, hydrostatic, free-surface version with embedded turbulence closure. Two equations describing passive tracer balance have been added to the model to simulate nutrient transport. Nutrients can be regarded as a conservative passive tracer when only the transport of nutrients from deep layers to the surface is examined; the later behaviour of nutrients is non-conservative (e.g. because of consumption by phytoplankton). The model domain is the whole Baltic Sea closed off at the Sounds. The bottom topography is taken from Seifert & Kayser (1995). The horizontal resolution is 0.5 nautical miles and in the vertical direction there are 20 sigma layers. Atmospheric forcing (wind stress and heat flux components) for a 20-day period starting from 20 July 1999 was constructed by means of the space/time interpolation of a meteorological data set established and maintained by SMHI (Swedish Meteorological and Hydrographical Institute; the respective space and time resolutions are 1° and 6 h). Initial thermohaline fields were constructed with the help of the Data Assimilation System (DAS) coupled with the Baltic Environmental

Database (BED) established and maintained by Stockholm University (see http://data.ecology.su.se/models).

The results of the model (Zhurbas et al. 2007) can be summarised as follows. It reproduced reasonably well the coherent meso-scale structures (filaments or squirts) and also the relaxation of the temperature field after the Gulf of Finland upwelling (Figure 3). The model estimate of phosphate concentration in the surface layer on the cold side of the upwelling front, about 0.3 mmol m^{-3}, was consistent with observations. The total phosphorus and nitrogen contents in the upper 10 m layer of the Gulf of Finland introduced by the upwelling event were estimated at 377 and 37 tonnes respectively. The upwelling event transported nutrients into the upper layer with a clear excess of phosphorus (N:P=37:377=0.1) as compared to the optimum Redfield ratio of 7.2. Thus, phosphorus inputs caused by summer upwelling events are most likely to promote blooms of nitrogen-fixing cyanobacteria. Relaxation of longshore baroclinic jets and related thermohaline fronts, caused by coupled up- and downwelling in the Gulf, took place in the form of warm and cold water squirts running back and forth across the Gulf, thereby contributing to lateral mixing. Apparent lateral heat diffusivity due to squirts was directly estimated to be 500 $m^2\ s^{-1}$.

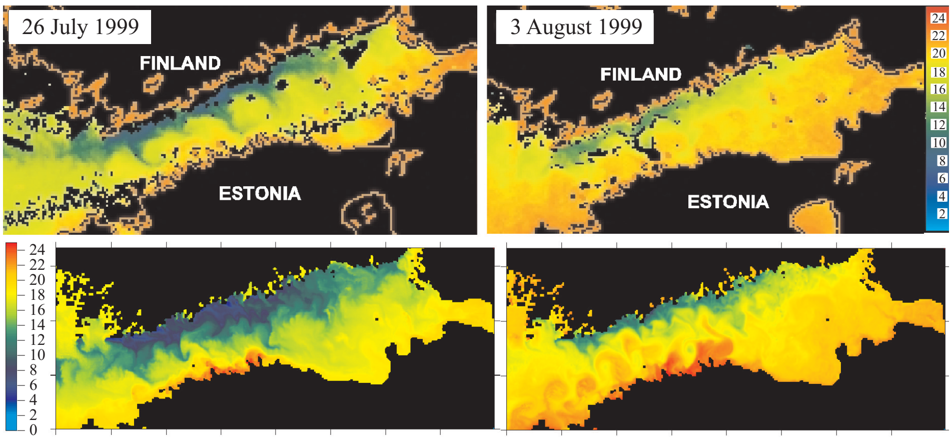

Figure 3. Comparison of SST maps of the Gulf of Finland (top) obtained from satellite imagery (Remote Sensing Laboratory, Stockholm University) and (bottom) simulated by Zhurbas et al. (2007). The numbers on/by the colour scales refer to the temperatures [°C]

A series of other numerical upwelling studies were also presented at the Congress (Andrejev & Myrberg 2007, Gałkowska 2007, Golenko et al. 2007, Raudsepp et al. 2007, Soosaar & Raudsepp 2007). The main results are summarised here. The Regional Ocean Modelling System (ROMS) was used to simulate the upwelling event in summer 2006 already discussed in the previous section from the observational point of view (see e.g. Lips I. et al. (2007), Raudsepp et al. (2007)). ROMS solves primitive equations in a rotating frame based on the Boussinesq approximation and the hydrostatic vertical momentum balance (Shchepetkin & McWilliams 2003, Shchepetkin & McWilliams 2005). ROMS is a split explicit, free-surface ocean model using discretised coastline- and terrain-following curvilinear coordinates. Short time steps are applied to calculate surface elevations and barotropic momentum equations, whereas much larger time steps are used for temperature, salinity and baroclinic momentum. The model area consisted of the Gulf of Finland only; the bottom topography was prepared from Seifert & Kayser (1995). Radiation boundary conditions were used for the western boundary of the Gulf of Finland. The horizontal resolution was 1/20 degree (5 km), and in the vertical direction there were 20 sigma layers. The simulation was done for the period 26 July–1 September 2006. The model was forced by wind stress calculated using measurements from the Kalbådagrund weather station; the other atmospheric fluxes were set to zero. Initial water temperature and salinity were treated as horizontally constant and there was in general a two-layer vertical stratification.

Preliminary results show the development of upwelling in the same area where the event was observed from satellite images. The upwelling zone, broadened in time due to favourable winds and weak upwelling filaments, started to form. Soosaar & Raudsepp (2007) used the same ROMS model to assess the influence of a horizontal salinity gradient on the formation and dynamics of upwelling filaments in the Gulf of Finland. Two model setups with constant E and W winds were made. Runs were made with and without a horizontal salinity gradient. The water temperature was treated as horizontally constant and there was a two-layer vertical stratification. With the E wind, the upwelling formed more quickly and exhibited a steeper salinity gradient. In this case the upwelling filaments were not stable. With the W wind, filaments were clearer than with the E wind. In the absence of a salinity gradient, the upwelling event was stronger and also formed more filaments. In the presence of a salinity gradient, filaments were longer and clearer, and their location was different. The upwelling event took longer to form than when the wind was from the east.

The three-dimensional baroclinic model (OAAS) is a z-coordinate, hydrostatic, free-surface one. The model domain is the whole Baltic Sea with an open boundary in the northern Kattegat. The bottom topography is taken from Seifert & Kayser (1995). The horizontal resolution is 1 nautical mile and in the vertical direction there consists of 44 layers. Atmospheric forcing (wind stress and heat flux components) for a two-month period starting from 1 July 1996 was constructed by means of the space/time interpolation of a meteorological data set established and maintained by SMHI (space/time resolutions of 1° and 6 h respectively). Initial thermohaline fields were constructed with the help of the Data Assimilation System (DAS) coupled with the Baltic Environmental Database (BED). During August 1996 a series of Ekman-type upwelling events off the Hel Peninsula were reproduced by a three-dimensional numerical model (Andrejev & Myrberg 2007; Figure 4). Upwelling became visible as a sharp drop in sea surface temperature. This was driven mainly by E winds and confirmed by measurements made on r/v 'Baltica'. For the first upwelling a wind impulse of c. 36 000 kg m^{-1} s^{-1} over 220 hours was needed; for the second event a wind impulse of only c. 1800 kg m^{-1} s^{-1} over 66 hours was recorded. Between the events, sea surface temperatures increased again, then dropped to the values recorded during the first event. Hence, the first upwelling event pre-conditioned the subsequent ones.

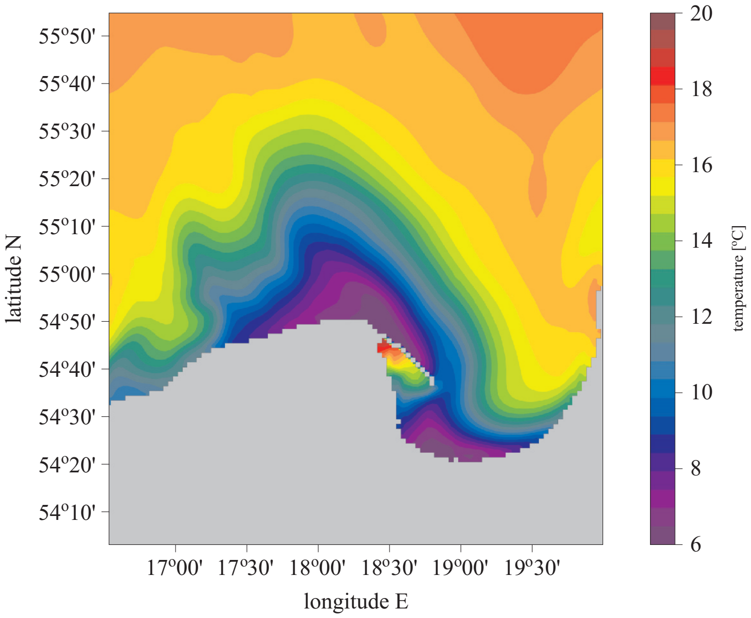

Figure 4. Sea-surface temperature [°C] simulation of a mature upwelling event off the Hel Peninsula on 13 August 2006 (Andrejev & Myrberg 2007)

Gałkowska (2007) used a different kind of methodology to study upwelling – Principal Component Analysis (PCA). PCA offers an objective method of reducing large data sets to a few representative, uncorrelated (orthogonal) principal components, which explain most of the variability

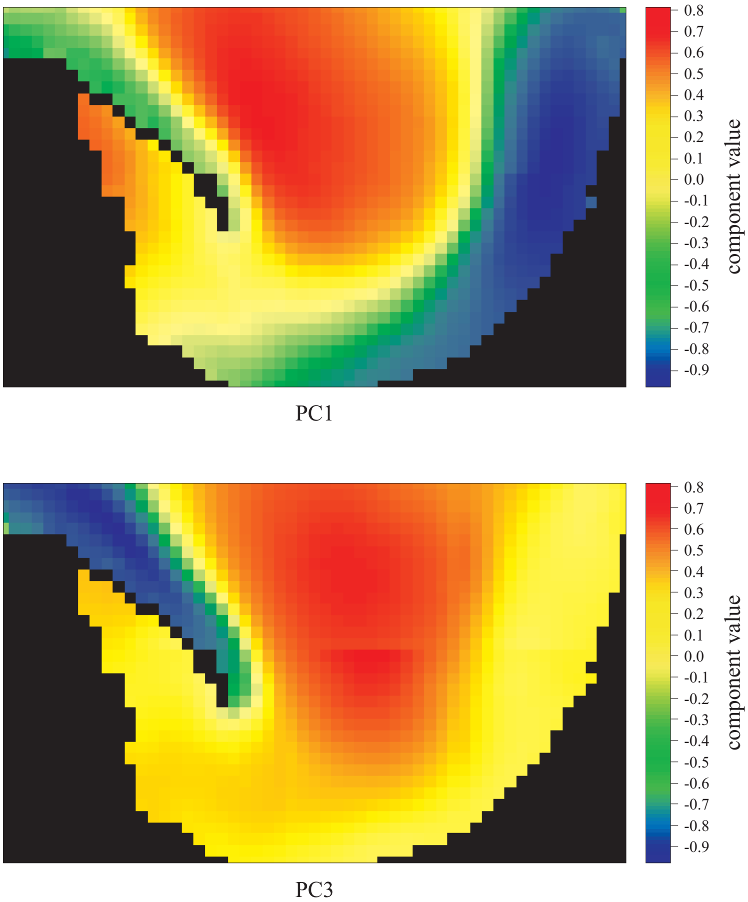

Figure 5. Maps of selected principal components (PC1 and PC3) for the Gulf of Gdańsk sea level for the best correlated upwelling/downwelling events. Low values of PC1 and PC3 correspond to the Vistula and Hel upwelling regions respectively (Gałkowska 2007)

of the original data. PCA was applied to three-dimensional model data from 1994 to 2005 (4283 days) relating to the sea surface temperature, salinity and sea level in order to identify upwelling and downwelling in the Gulf of Gdańsk and off the Hel Peninsula and Vistula Spit. Principal Component Analysis of the data revealed differences between the areas affected by upwelling and other areas (Figure 5). The spatial pattern of the PC1 and PC3 accounted for 57.6% of the total spatial sea level variance in the data set. The first and third eigenvector (PC1 and PC3) had the highest negative loadings along the Hel Peninsula and the Vistula Spit, but were positive in other areas. This can be interpreted as a measure of the spatial variation of the upwelling intensity. PCA enabled the temporal and spatial identification of upwelling/downwelling events on the basis of model data. The area off the Vistula Spit was characterised by the dominance of strong downwelling (7.4%) over strong upwelling (4.9%). The downwelling/upwelling frequency along the Hel Peninsula was 25.6%, that along the Vistula Spit was 28.5%. The strong upwelling frequencies along the Vistula Spit and the Hel Peninsula calculated on the basis of sea surface temperatures were 5.4% and 27.2% respectively.

Golenko et al. (2007) applied a local version of the POM to the SE Baltic to simulate upwelling events. Radiation conditions were used at lateral boundaries. Initial values of vertical momentum exchange were about 10^{-5} m^2 s^{-1}. The simulations gave a good fit between the simulated fields and corresponding data from an upwelling event on 12 October 2005, based on a high-resolution transect running along the Russian-Lithuanian border. It was found that, during just a single upwelling event in autumn, the heat store of the cold intermediate layer stretching from the shelf break to the open sea over a distance of 80 km increased by 38%. As a result, considerable erosion of the cold intermediate layer took place. In the open sea the temperature dropped slightly (by 0.4°C), whereas the lower boundary of the thermocline deepened by c. 4 m. As a consequence of upwelling, the layer with a temperature suitable for phyto- and zooplankton growth may be extended in early autumn.

Modelling calculations showed that after an upwelling period lasting approximately one week, part of the upwelled waters spread out in an upper quasi-homogeneous layer, this process taking place most intensively close to the coastal area. Another part of the upwelled water sank slowly, with a considerable portion of the sinking water eroding the thermocline.

4. Links to biogeochemical processes

Nowadays, the relation between upwelling events and biogeochemical processes is an extensively studied topic. A Polish research group (Szymelfenig et al. 2007) has studied upwelling off the Polish coast, drawing conclusions based on physical, chemical and biological measurements, and on satellite observations (Krężel et al. 2007). Studies have also been carried out using an ecohydrodynamic model (Kowalewski 2007).

Thermal satellite sea surface images and numerical simulations based on a three-dimensional hydrodynamic model were used to find upwelling zones off the Polish coast. Four sites were identified where intense upwelling occurs: off Kołobrzeg, Łeba, the Hel Peninsula and the Vistula Spit. The frequency of strong vertical currents was highest in the area north of the Hel Peninsula. High percentages of strong upward (27.1%) and downward (37.1%) currents were recorded there, so this was the region chosen for carrying out extensive in situ measurements (Szymelfenig 2005). During the upwelling events investigated, the maximum drop in sea surface temperature was almost 14°C. Like the observations made in other Baltic areas and reported in this paper, the upwelling waters could be very cold, with temperatures of c. 4°C.

The centre of cold, transparent waters was characterised by a decrease in mass concentration (total SPM, POC, PON) and a decrease in particle abundance as compared to the reference area (Bradtke et al. 2007). It was accompanied by low chlorophyll *a* concentrations, low primary production values, high assimilation numbers (Zalewski et al. 2007) and the intensive emergence of nutrients, mainly phosphates. These changes were reflected in the lower abundance and biomass, and in differences in the taxonomic composition of plankton in the upwelling centre as compared to the surrounding waters. Primary production induced by nutrient-rich upwelling waters develops when the water gradually warms up. Within the upwelling plume the amount of chlorophyll *a* increased together with the sea water temperature, albeit at a different rate: in autumn this was almost three times faster than in the spring-summer months (Szymanek et al. 2007).

Comparison of vertical profiles of sea water chlorophyll *a* concentrations obtained on the basis of fluorescence measurements revealed significant differences in phytoplankton distributions in the autumn and spring-summer months. In spring and summer the chlorophyll *a* concentration reached a maximum (except in the coldest water) in the first few metres of the water column. This was probably caused by phytoplankton sinking, since the chlorophyll *a* maxima lay along the density gradient; nonetheless, photo-acclimation may also have played some part here. In the autumn, chlorophyll *a* was homogeneously distributed in the sea surface layer.

Numerical simulations were carried out using an ecohydrodynamic model for two upwelling events, each one month long, which took place in spring and autumn 2000. The results showed that the upward nutrient load raised by the Hel upwelling event was almost equal to the load carried to the sea in the same period by the Vistula, one of the largest rivers in the Baltic Sea catchment area. However, the modelled upwelling resulted in an increase in primary production in spring and a decrease in early autumn. Analysis of satellite data (AVHRR, SeaWiFS) showed that the chlorophyll *a* concentration increased in the upwelling plume off Łeba and Kołobrzeg (Figure 6). Along the Hel Peninsula, the chlorophyll *a* concentration fell in spring but rose in autumn, which contradicts the

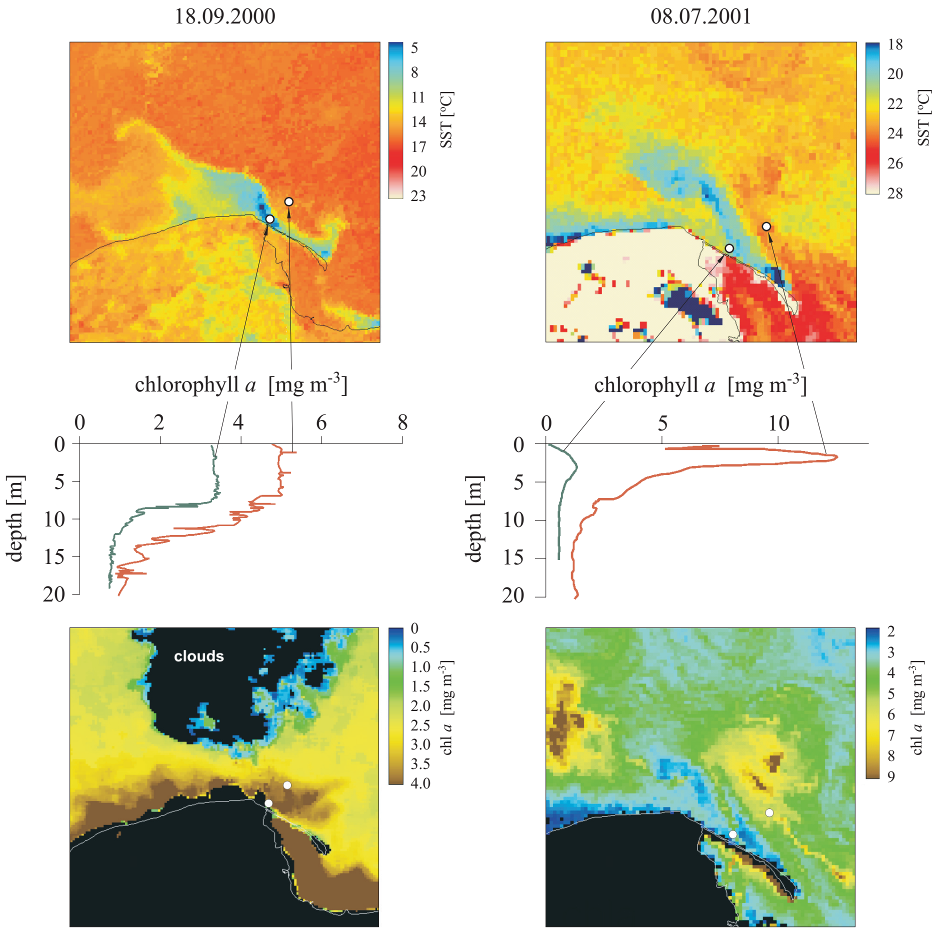

Figure 6. Satellite-derived thermal images of the upwelling events along the Hel Peninsula in early autumn 2000 and summer 2001 (upper row), in situ vertical distribution of the chlorophyll *a* concentration (locations marked with white circles), and the corresponding surface chlorophyll distributions obtained with the use of SeaWiFS radiometer data (lower row, Szymelfenig et al. 2007)

results of the numerical model. The satellite underestimation of chlorophyll concentrations may have partially resulted from the fact that the largest amounts of phytoplankton lay too far below the surface to be accurately detected by remote sensing. The difference between satellite observations and numerical modelling results as regards upwelling events deserves further study, including the development of a biological module of the ecohydrodynamic model. At present, the model takes into account only early spring diatoms, which thrive in cold water, and does not yet include autumn diatoms, which are usually recorded in warmer water.

5. Summary and future work

The CBO Session 'Upwelling events, coastal offshore exchange, links to biogeochemical processes' was held during the Baltic Sea Science Congress at Rostock University, Germany, from 19 to 22 March 2007. We can draw the following conclusions and outline suggestions for future work.

Progress has been made by observing and analysing a number of recent upwelling events in different parts of the Baltic Sea. The quantification of the forcing and overall structure, as well as the duration and intensity of individual upwelling events is fairly well known. This is due not only to traditional in situ measurements; the utilisation of satellite observations in registering upwelling events and in observing their development has gained more and more in importance. However, combined observations of physical parameters such as temperature, salinity and nutrients or even chlorophyll *a* are still only few in number. The links between upwelling and biogeochemical processes are still incompletely understood and need further investigation.

Numerical modelling has advanced to the extent that horizontal resolutions of c. 0.5 nautical miles can now be applied, which allows the complete spectrum of meso-scale features scaled by the internal Rossby radius to be described. Even the development of filaments can be described realistically in comparison with high-resolution satellite data (MODIS satellite). However, current modelling efforts concentrate mostly on single events; more general modelling studies with longer simulation periods for the entire Baltic Sea are still lacking. The recently-acquired information about upwelling from advanced observations provides an excellent basis for model validation and the verification of upwelling processes.

As always, the research effort needs to be sustained. One key aspect is to study further single upwelling events with the aid of both measurements and modelling tools. The role of different mechanisms forcing upwelling events are still incompletely understood, especially the quantification of wind strength and duration, changes in stratification conditions during upwelling, and local effects related to topography (depth, specific features). It is also important to study local mixing processes, because the question of how much of the total mixing can be attributed to upwelling is to some extent still open.

On the other hand, there is also a need to proceed from studying single events towards a more general and integrated view of the effects of upwelling on the whole Baltic system. Only by using a combination of measurements and modelling for the studies of the entire Baltic over a long timescale can we obtain statistically relevant results, and advanced mathematical methods should be applied to their analysis. By using such results, transport, the areas affected and other general characteristics of upwelling events can be approximately quantified at a basin-wide scale. The acquisition of a sound overall picture of the physics of upwelling in the Baltic Sea, with statistical relevance, forms an important basis for future studies. One key application is to find out how global climate change will affect upwelling dynamics in the future. Climate change will certainly have some effects on upwelling in the Baltic. Only when we know what they are, will we be able to assess the related changes in biogeochemical processes.

References

Andrejev O., Myrberg K., 2007, *How prehistory can intensify coastal upwelling*, Baltic Sea Science Congress, 19–23 March 2007, Rostock, Germany, Poster abstracts, p. 44.

Bychkova I., Viktorov S., 1987, *Use of satellite data for identification and classification of upwelling in the Baltic Sea*, Oceanology, 27 (2), 158–162.

Bradtke K., Gromisz S., Matciak M., Szymelfenig M., 2007, *Quantity and quality features of suspended matter and phytoplankton in the Hel upwelling region (the Baltic Sea) – influence on optical properties of water*, Baltic Sea Science Congress, 19–23 March 2007, Rostock, Germany, Poster abstracts, p. 40.

Gałkowska A., 2007, *Application of principal component analysis for identification coastal upwelling in the Gulf of Gdańsk on base model data*, Baltic Sea Science Congress, 19–23 March 2007, Rostock, Germany, Poster abstracts, p. 39.

Golenko N., Golenko M., Shchuka S., 2007, *Characteristics of the upwelling events in the South-East Baltic*, Baltic Sea Science Congress, 19–23 March 2007, Rostock, Germany, Poster abstracts, p. 45.

Haapala J., 1994, *Upwelling and its influence on nutrient concentration in the coastal area of the Hanko Peninsula, entrance of the Gulf of Finland*, Estuar. Coast. Mar. Sci., 38 (5), 507–521.

Kauppinen O.-K., Myrberg K., Andrejev O., 2007, *Upwelling at Estonian coast during August 1996*, Baltic Sea Science Congress, 19–23 March 2007, Rostock, Germany, Poster abstracts, p. 38.

Kowalewski M., 2007, *A numerical study of upwelling events along the Hel Peninsula and its influence on nutrient dynamics*, Baltic Sea Science Congress, 19–23 March 2007, Rostock, Germany, Poster abstracts, p. 32.

Krężel A., Kozłowski Ł., Szymanek L., Szymelfenig M., 2007, *Consequences of coastal upwelling on temperature and chlorophyll a concentration distribution at the sea surface along Polish coast of the Baltic Sea*, Baltic Sea Science Congress, 19–23 March 2007, Rostock, Germany, Poster abstracts, p. 33.

Lehmann A., Myrberg K., 2007, *Upwelling in the Baltic Sea – A review –*, Baltic Sea Science Congress, 19–23 March 2007, Rostock, Germany, Abstract volume, lectures – CBO Session, Topic B: Upwelling events, coastal offshore exchange, links to biogeochemical processes, p. 52.

Lehmann A., Myrberg K., 2008, *Upwelling in the Baltic Sea – A review –*, J. Marine Syst., (accepted).

Lehmann A., Myrberg K., Hinrichsen H.-H., 2007, *Strong upwelling in the northern Baltic Sea in summer 2003 & 2005*, Baltic Sea Science Congress, 19–23 March 2007, Rostock, Germany, Poster abstracts, p. 36.

Lips I., 2005, *Abiotic factors controlling the cyanobacterial bloom occurrence in the Gulf of Finland*, Diss. Biol. Univ. Tartuensis, 108, Tartu Univ. Press, 47 pp. + 5 articles.

Lips I., Lips U., Liblik T., Kuvaldina N., Belikova V., 2007, *An upwelling event in the Gulf of Finland in August 2006: observational results*, Baltic Sea Science Congress, 19–23 March 2007, Rostock, Germany, Abstract volume, lectures – CBO Session, Topic B: Upwelling events, coastal offshore exchange, links to biogeochemical processes, p. 60.

Lips U., Lips I., London L., Kikas V., Liblik T., 2007, *Upwelling index based on ferrybox measurements in the Gulf of Finland: a tool to assess meso-scale physical forcing on the pelagic ecosystem*, Baltic Sea Science Congress, 19–23 March 2007, Rostock, Germany, Abstract volume, lectures – CBO Session, Topic B: Upwelling events, coastal offshore exchange, links to biogeochemical processes, p. 53.

Rantajärvi E. (ed.), 2003, *Alg@line in 2003: 10 years of innovative plankton monitoring and research and operational information service in the Baltic Sea*, Rep. Ser. Finn. Inst. Mar. Res., 48, 36 pp.

Raudsepp U., Belikova V., Lips U., Sipelgas L., Soosaar E., Uiboupin R., 2007, *The upwelling event in the southern Gulf of Finland in August 2006 on satellite images and in the numerical model results*, Baltic Sea Science Congress, 19–23 March 2007, Rostock, Germany, Poster abstracts, p. 37.

Shchepetkin A. F., McWilliams J. C., 2003, *A method for computing horizontal pressure-gradient force in an oceanic model with a nonaligned vertical coordinate*, J. Geophys. Res., 108 (C3), doi: 10.1029/2001JC001047.

Shchepetkin A. F., McWilliams J. C., 2005, *The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model*, Ocean Model., 9 (4), 347–404.

Seifert T., Kayser B., 1995, *A high resolution spherical grid topography of the Baltic Sea*, Meereswiss. Ber., 9, 72–88.

Soosaar E., Raudsepp U., 2007, *Numerical modelling of upwelling filaments in the Gulf of Finland*, Baltic Sea Science Congress, 19–23 March 2007, Rostock, Germany, Abstract volume, lectures – CBO Session, Topic B: Upwelling events, coastal offshore exchange, links to biogeochemical processes, p. 61.

Suomi I., 2007, *Marine fog over an upwelling zone on the southern coast of Finland*, Baltic Sea Science Congress, 19–23 March 2007, Rostock, Germany, Abstract volume, lectures – CBO Session, Topic B: Upwelling events, coastal offshore exchange, links to biogeochemical processes, p. 62.

Szymanek L., Matciak M., Szymelfenig M., 2007, *Field and satellite observations of the upwelling events along the Hel Peninsula, the Baltic Sea*, Baltic Sea Science Congress, 19–23 March 2007, Rostock, Germany, Poster abstracts, p. 41.

Szymelfenig M., 2005, *Upwellings along the Hel Peninsula (the Baltic Sea): bio-physico-chemical observations – preface*, Oceanol. Hydrobiol. Stud., 34 (Suppl. 2), 3–10.

Szymelfenig M., Kowalewski M., Krężel A., Matciak M., Ameryk A., Bielecka L., Bradtke K., Burska D., Gromisz S., Jędrasik J., 2007, *Bio-physico-chemical manifestations of upwellings along the Polish coast of the Baltic Sea*, Baltic Sea Science Congress, 19–23 March 2007, Rostock, Germany, Abstract volume, lectures – CBO Session, Topic B: Upwelling events, coastal offshore exchange, links to biogeochemical processes, p. 57.

Talpsepp L., 2007, *The influence of the intermittence of coastal upwellings and downwellings on water distribution*, Baltic Sea Science Congress, 19–23 March 2007, Rostock, Germany, Poster abstracts, p. 43.

Uiboupin R., Laanemets J., 2007, *Upwelling characteristics derived from satellite sea surface temperature data in the Gulf of Finland*, Baltic Sea Science Congress, 19–23 March 2007, Rostock, Germany, Poster abstracts, p. 35.

Zalewski M., Ameryk A., Szymelfenig M., 2007, *The changes of primary production in the Hel upwelling region*, Baltic Sea Science Congress, 19–23 March 2007, Rostock, Germany, Abstract volume, lectures – CBO Session, Topic B: Upwelling events, coastal offshore exchange, links to biogeochemical processes, p. 42.

Zhurbas V., Laanemets J., Vahtera E., 2007, *Integrated study of an upwelling event in the Gulf of Finland, July 1999*, Baltic Sea Science Congress, 19–23 March 2007, Rostock, Germany, Abstract volume, lectures – CBO Session, Topic B: Upwelling events, coastal offshore exchange, links to biogeochemical processes, p. 59.