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Upwelling in the Baltic Sea
-A review -

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Review article

revised version

Abstract

Upwelling is a typical phenomenon of the Baltic Sea. Because the Baltic Sea is a semi-enclosed basin, winds from favorable directions blowing predominately parallel to the coast cause upwelling leading to vertical displacement of the water body and mixing. During the thermal stratified period, upwelling can lead to a strong sea-surface temperature drop of more than 10°C changing drastically the thermal balance and stability conditions at the sea-surface. Upwelling can play a key role in replenishing the euphotic zone with the nutritional components necessary for biological productivity when the surface layer is depleted of nutrients. Consequently, it has been found out that in such areas where upwelling lifts phosphorus-rich deep water to the surface, the N/P ratio becomes low which favors the blooming of nitrogen-fixing blue-green algae. The rapid temperature decrease during such events was recognized and documented a long time ago when temperature measurements became available. Thus, the study of the upwelling process has a long tradition. However, although the importance of upwelling has generally been accepted for the Baltic Sea, no general review of upwelling exists. The objective of this paper is a comprehensive review of the upwelling process, its dynamics and reflections to ecosystem processes in the Baltic Sea using all relevant literature which will help to close the gaps of present knowledge and some recommendations for future work are outlined accordingly.

Keywords: Baltic Sea, coastal upwelling, Ekman transport

1. Introduction

In general, upwelling is the result of horizontal divergence in the surface layer of the ocean. It involves wind-driven motion of dense, cooler and usually nutrient-rich water towards the ocean surface, replacing the warmer, mostly nutrient-depleted surface water. There are at least five types of upwelling: coastal upwelling, large-scale wind-driven upwelling in the ocean, upwelling associated with eddies, topographically induced upwelling, and broad-diffusive upwelling in the ocean interior. Most pronounced regions of upwelling cover the coasts of Peru, Chile, Arabian Sea, south-west, south and eastern Africa, eastern New Zealand and the California Coast (e.g. Defant, 1936, Sverdrup 1938, Defant 1961, Philander and Yoon 1982). Since the importance of upwelling for the ocean is generally known there is a large number of papers dealing with this topic. Detailed descriptions of upwelling are given in textbooks by e.g Tomzcak and Godfrey (1994) and reviews by e.g. Smith (1968).

Upwelling is also an important process in the Baltic Sea. As the Baltic Sea is a semi-enclosed basin with a small size (Fig. 1), upwelling become frequently visible all along the coast depending on prevailing wind conditions. However, in spite of the important role of upwelling to the overall physics of the Baltic, with reflection to ecosystem as well, no general review paper of it exists at present. This is at least partly because upwelling is still poorly understood at detailed level due to methodological difficulties since the events are irregular and by no means spread equally around the Baltic.

The objective of this paper is a to produce a comprehensive review of the upwelling dynamics and its reflections to ecosystem processes in the Baltic Sea using all relevant literature which will help us to close the gaps of our present knowledge and some recommendations for future work are outlined accordingly.

The structure of the paper is the following. In the next section, the historical development of upwelling studies in the Baltic Sea will be summarised and a brief look on corresponding results for the World Ocean will be given. The following chapter deals with observational evidence of upwelling – from traditional methods to remote sensing. In chapter 4 the basic physics of upwelling is introduced, also taking into account the scales of this feature and its description as a three-dimensional process. The next chapter describes the modelling efforts to study upwelling. The resolution needed for modelling and the role of atmospheric forcing are discussed additionally. Then, chapter 6 gives a view how upwelling has effects onto the ecosystem level -distributions of nutrients and phytoplankton dynamics and fish. The paper is concluded by a chapter where the requirements for future work are outlined.

2. Early studies of upwelling

The first documented scientific observation of upwelling in the Baltic Sea was carried out by Alexander von Humboldt (Kortum and Lehmann 1997). During August 1834 von Humboldt was traveling with a Russian steam boat from Szczecin to Kaliningrad and back to Szczecin. While the boat was traveling at about 2-3 nm off the coast, Humboldt measured a strong drop in sea-surface temperature of about 10°C near the 18° longitude off the Polish coast (Fig. 2), while eastward of Hel Peninsula, the temperature again increased to values of about 20°C. Von Humboldt speculated that in deeper layers of the Baltic Sea cold water exists which reach the surface in a similar manner like katabatic winds that blow down a topographic incline but in opposite vertical direction (anabatic winds).

A first comprehensive explanation of the upwelling process could be given by the application of Ekman's theory (1905). It provided a basis for understanding the effect of wind stress on ocean circulation, and showed that due to the effect of Earth's rotation and frictional forces, the net transport of water due to the wind stress is directed 90° to the right of the wind in the Northern Hemisphere (see chapter 4 for details).

Further studies of Baltic Sea upwelling were carried out by Palmén and Laurila (1938), Hela (1946), Sjöblom (1967), Walin (1972a/b) and Svansson (1975). These results were based on analyses of measurements. Their work has been summarized by Hela (1976). Palmén and Laurila (1938) described the change in surface temperature after a strong wind event. Additionally, Hela (1946) and Sjöblom (1967) argued that certain sub-regions of the Baltic Sea coast are more favorable for upwellling and that these regions are also favorable as fishing areas. Svansson (1975) discussed a possible relation between upwelling and the generation of Kelvin waves.

Hela (1976) presented a simple empirical linear equation between wind speed and vertical velocity in the upwelling region in the Gulf of Finland

$$w_z = 5.82 \times 10^{-6}\ U \qquad (1)$$

where U is the wind speed and w_z is the vertical velocity of upwelling, both in the same unit. Additionally, estimations of the Ekman transport normal to the coast were calculated and related to the total volume of the Gulf of Finland. For a period of stormy winds, the transport normal to the coast amounted to about $3 \times 10^3\ m^3s^{-1}$ per km coastline. Assuming that the upwelling occurred for a whole day, along a strip of the southern Finnish coast of about 270 km, 6 % of the volume of the Gulf of Finland were affected by upwelling.

From this calculation, Hela (1976) concluded that upwelling contributes strongly to the vertical turbulent diffusion in the sea, and its biological consequences - to primary production and to spreading of pollution in the sea.

3. Observations (from traditional methods to remote sensing)

Detection

Before satellite data were available upwelling could only be detected on the basis of temperature measurements during the thermal stratified period (Hela 1976). Among those studies an important early founding was the one by Palmén and Laurila (1938). In the transition from September to October, 1936, hydrographic sections across the Gulf of Finland were carried out which documented strong changes in temperature and salinity distributions due to upwelling at the Estonian coast. At the end of September a low pressure system developed over Finland and subsequently moved to the south to the Gulf of Riga, deepening. Over the Gulf of Finland strong winds with maximum wind speeds of 25 m/s from north-easterly directions led to strong upwelling close to the Estonian coast and a temperature drop of about 6°C.

Even if first results were already published before World War II, upwelling as a process itself remained poorly understood for a long while. So, the measurements of upwelling were in some extent random in character and not results of well-prepared measurement campaigns. Only in the 1970's more comprehensive results were obtained. Walin (1972a) detected upwelling at the Swedish east coast and found that temperature fluctuations extended only 5-10 kilometers offshore. He also proposed these fluctuation to have a tendency to propagate along the coast as internal Kelvin waves. Svansson (1975) also found upwelling in the Hanö Bight, as Walin (1972a). Svansson also took up the question of the biological significance of upwelling in the coastal regions where nutrients may be transported to the uppermost, euphotic layer of the sea. This fact has been later found to be an important element of the upwelling phenomenon (see below).

One of the main areas where upwelling has been observed in temperature measurements, is the northern coast of the Gulf of Finland (Hela 1976, Niemi 1979, Kononen and Niemi 1986, Haapala 1994). All these papers confirm that upwelling is especially favoured by south-westerly winds. In such cases, sea-surface temperatures can drop by 10 degrees in 1-2 days during stratified periods. During such conditions, when the surface layer can be depleted of nutrients, upwelling plays a key role in replenishing the euphotic zone with the nutritional components necessary for biological productivity. Consequently, upwelling favors fishing in the area (Sjöblom 1967). Niemi (1979) found out that in such areas where upwelling lifts phosphorus-rich deep water to the surface, the N/P ratio becomes low which favors the blooming of nitrogen-fixing blue-green algae.

<u>Analysis</u>

The utilization of satellite measurements started in the early 1980's and since then space borne measurements of various kinds (AVHRR radiometers in NOAA satellites etc.) have been utilized by numerous authors (e.g Siegel et al. 1994, Kahru et al. 1995, Lass et al. 2003, Kowalewski and Ostrowski 2005). Among the most comprehensive studies is the one by Horstmann (1983) where the author studied upwelling at the southern coast of the Baltic Sea from AVHRR satellite data for the year 1982. Sequences of satellite pictures documented the development of upwelling during south-east and easterly winds at the western coast of Rügen, along the Polish coast between the Pommeranian Bight and Ustka, and from Leba to Hel Peninsula. Gidhagen (1987) did an analysis based on AVHRR data and concluded that upwelling at the Swedish coast take place up to 10-20 kilometers offshore and about 100 kilometers alongshore. According to Gidhagen (1987) water is lifted to the surface from depths of 20-40 meters which is somewhat larger than previously estimated. He also found that in some areas upwelling exists even one-fourth to one-third of the time. Bychkova and Vikorov (1987) found 14 upwelling cases around the Baltic with different scales and life-times. In the southwestern Baltic, at the German and Polish coasts, satellite observations of upwelling were analyzed by Siegel et al. (1994).

Regional features

Upwelling in the various parts of the Baltic has some specific features based on topography and shape of the coastline. Consequently, the wind pattern favorable for the birth of upwelling depends on the local features. Upwelling has been frequently studied at the Polish coast. Its development is favoured by such meteorological conditions where a high pressure system is located over north-eastern Russia, accompanied by light or moderate easterly to south-easterly winds over the southern Baltic (Malicki and Wielbińska 1992). Most often upwelling has been found to take place offshore Hel Peninsula (e.g. Matciak et al. 2001). According to Krężel et al. (2005), in the Hel area the upwelling region has a spatial range of 14000 km^2 while in Leba area the range is 3500 km^2, that being at most 5000 km^2 in Kolobrzeg area. The temperature difference between upwelled deep water and surface water can reach 14 degrees and the temperature gradient has a maximum value of 5 °C/km according to observations. The potential maximum area of upwelling along the Polish coast equal to 10 000 km^2 which is about 30 % of the Polish economic zone (Krężel et al. 2005).

At the Lithuanian and Latvian coasts upwelling is favored by northerly winds and the length-scale of upwelling is typically about 250 km and the width is between 5 and 20 km. The temperature gradient ranges between 4 and 8 degrees. At the west coast of the Gulf of Riga upwelling is observed when winds are blowing parallel to the coast (south-easterly winds). The length scale is typically 75-100 km and the width scale 10-30 km while the life-time of the feature varies between 0.5 and 10 days and the temperature difference is typically 2-4 degrees. At the east coast upwelling is observed during northerly winds (length 55 km, width 5-30 km, see Bychkova and Viktorov 1987 for details).

In the Gulf of Finland, upwelling takes place at the southern coast while east-southeasterly winds blow. The length scale at the Estonian coast is typically 20-40 km or more, and the width is between 5 and 40 km. The duration is typically some 7-8 days, sometimes even several weeks (Suursaar and Aps 2007). The temperature difference is about 6-8 degrees (Bychkova and Viktorov 1987). At the Finnish coast the length-scale is 100-300 km and width scale 30-40 km. Especially winds blowing from south to south-west cause upwelling, where the coastline trends east-west. Also northerly wind may cause upwellings. Typically upwelling takes place near the Hanko Peninsula (Haapala 1994) or near Porkkala Peninsula (Sjöblom 1967). Haapala (1994) concluded that the wind events should take at least 60 h for upwelling to take place, this depending both on the wind speed and degree of vertical stratification. Temperature changes in the upwelling region can easily reach 10 degrees in a few days. However, salinity changes in the surface are usually small, not more than 0.5 PSU, but below the thermocline more pronounced changes exist (Haapala 1994). The high frequency of upwelling in the north-western Gulf of Finland becomes visible in satellite images. Upwelling plays an important role in the formation of a quasi-permanent temperature front in that area (Kahru et al. 1995)

In the Gulf of Bothnia upwelling basically takes place at the Finnish coast by northerly winds and at the Swedish coast by south to south-westerly winds.
The upwelling zone is rather long at both coasts because of the regular shape of the coastline, being typically 100-200 km, the width is about 5-20 km. A temperature front becomes visible in satellite images at the Finnish side of the Bothnia Sea. In the formation of the front, upwelling plays an important role (Kahru et al. 1995). At the Swedish side of the Gulf of Bothnia upwelling can occur in some places one-fourth to one-third of the time. Such areas are Hornslandet (Bothnian Sea) and the coastal area from Ratan to Bjuröklubb (Bothnian Bay).

At the Swedish coast of the Baltic Proper the most well-known upwelling region is the Hanö Bight where the length of the upwelling area is typically 100 km and the width 5-15 km (Walin 1972a, Svansson 1975, Bychkova and Victorov 1987) as well as the Trelleborg-Ystad region where the length scale is about 60 km and the width 5-10 km (Gidhagen 1987). The steep west coast of Gotland is also a well-known upwelling area with northerly winds (Shaffer 1979).

The most pronounced upwelling area at the German coast is that stretching from the west coast of Hiddensee island in north-northwesterly direction (e.g. Siegel et al. 1994, Lass et al., 2003). However, this observed upwelling is not driven by local Ekman off-shore transport at the west coast of Hiddensee island. It is found that the lowering of the sea-level in the Kattegat caused by easterly winds triggers an adjustment process in the Belt Sea resulting in a pressure step trapped at the Darss Sill. The currents geostrophically adjusted to this step are fed by upwelled water from the west coast of Hiddensee island maintaining the mass balance of the dynamical system. The characteristic scales of the upwelling feature at the west coast of Hiddensee island are: 20 km basis at shore, 60 km offshore length, duration of 5 days and temperature deviations –4 °C (Lass et al. 2003). Observations show as well (Fennel and Seifert 1995) that in the western Baltic during upwelling favorable winds the intensity of the coastal upwelling varies alongshore and even turns into downwelling in the western part. This is due to the generation of Kelvin waves (see below).

4. Basic physical principles of upwelling

Two main classes of upwelling can be distinguished: open ocean and coastal upwelling. The first class is of considerable larger scale and pertains such vertical motions as those caused by the wind, by influences of the main oceanic thermocline and by the equatorial ocean currents. Coastal upwelling is more regionally limited than oceanic upwelling but its stronger vertically motion can lead to sharp horizontal hydrographic gradients mostly in temperature and nutrients which might impact on marine biology and local weather scale. Vertical motions in coastal upwelling are in the order of 10^{-5} ms^{-1}, but in the open ocean of about 10^{-6} ms^{-1}, that means a vertical lift of the layers of about 1 m/day and 0.1 m/day, respectively (Dietrich, 1972). The phenomenon of upwelling is mostly correlated with divergence on the sea-surface produced by prevailing winds. The reverse of upwelling is called downwelling and correlated with surface convergence and divergence at a lower layer where the descending terminates.

Ekman transport

The work of Ekman (1905) provided a basis for understanding the effect of wind stress on an infinite unstratified ocean. Due to the effect of the Earth's rotation and frictional forces the net transport due to the wind stress is directed 90° to the right of the wind in the northern hemisphere. Thorade (1909) first applied Ekman's theory to an upwelling situation. He showed that coastal winds blowing parallel to the coast were sufficient to induce an offshore transport of surface water. A comprehensive description of the dynamics of upwelling is given in Smith (1968) and will not be repeated here. We will focus only on the basic principles of Ekman's theory which are still used to estimate wind induced transports off the coast. It should be remembered that the Ekman spiral is only a theoretical consideration and there are for our knowledge no direct measurements of its existence in the wind-driven surface mixed layer. However, observed transports fairly well correspond with the theoretical Ekman transport. For a continuously stratified ocean, momentum exerted by wind stress is rapidly mixed downward by turbulence to create a well mixed-layer with a certain depth. If a well-mixed surface layer already exists overlying a strong thermocline, momentum generated by a surface stress will be spread through the whole of the mixed layer in a time short compared to the inertial period, but the depth of the mixed layer will increase due to the vertical shear of inertial waves on a time scale longer than inertial. The vertical momentum transport due to wind induced turbulence causes a more or less uniform current direction in the mixed layer (Pollard 1970, Krauss 1981).

The frictional stress exerted on the sea-surface boundary is τ, the wind stress. Actually, the major factor of an upwelling to occur is the divergence/convergence of the wind stress, representing inhomogeneities in the wind fields, coasts and ice edges etc.

The wind stress on the sea-surface is based on the following formula

$$\tau = C_D \rho_a |U_a| U_a, \qquad (2)$$

with C_D the drag coefficient, ρ_a density of air and U_a the wind velocity at 10 m height. Unfortunately, the drag coefficient depends on the wind velocity, the stability of the overlying airmass and the wave field. Thus a great variety of different parameterization to describe the drag coefficient exists (e.g. Csanady 2001, Large and Pond 1981) .

The current field produced directly by the wind stress which acts on the ocean surface is described by the well-known Ekman spiral: At the surface, the direction is deflected 45° to the right of the wind on the northern hemisphere, due to the rotation of the Earth; with increasing depth, direction changes continuously towards right, and current speed decreases exponentially. Thus, the effect of the driving force is limited to a small surface boundary layer, the Ekman boundary layer of depth $D_E = \pi\ (2\mu_V/f)^{1/2}$ within which the current rotates and decreases with depth. μ_v denotes the vertical eddy viscosity and f the Coriolis parameter. This depth, D_E, called the depth of the frictional influence or the depth of the wind current. This depth coincides not necessarily with the depth of the mixed layer. Although the transport of water within the Ekman layer is in different directions at different depths, the total wind-induced mass transport, integrated over this layer, is 90° to the right of the wind. Therefore, a horizontal surface divergence must occur wherever a coastline is found on the left of the wind. The width of the frictional boundary layer at the coast depends on the horizontal viscosity, and is given by $D_H=\pi\ (2\mu_H/f)^{1/2}$ (Tomczak 1972).

The Ekman transport is given by

$$M_x=\tau_y/f \qquad (3)$$

$$M_y=-\tau_x/f. \qquad (4)$$

The relation between Ekman transport and wind stress is independent of ρ_w and the vertical friction coefficient and f is the Coriolis parameter ($f = 2\omega sin\varphi$). Once the wind stress has been determined the corresponding offshore transport can be calculated from Ekman transport relations (Smith 1968). For two similar wind events the same transport will result, but whether upwelling will have a temperature signal in the sea surface depends additionally on the bathymetry and the thermal stratification. Lentz and Chapman (2004) proposed a simple theory for two-dimensional coastal upwelling that relates the structure of wind-driven cross-shelf circulation and associated dynamics in the region of upward sloping isopycnals to the stratification, the bathymetry, and the wind forcing. The new element is an estimate of the nonlinear cross-shelf momentum flux divergence due to the wind-driven cross-shelf circulation acting on the vertically shared geostrophic along-shelf flow. The cross-shelf momentum flux divergence relative to the wind stress depends on the Burger number $S=\alpha N/f$, where α is the bottom slope, N is the buoyancy frequency, and f the Coriolis parameter. For $S \ll 1$ (weak stratification), the cross-shelf momentum flux divergence is small, the bottom stress balances the wind stress, and the on-shore return flow is primarily in the bottom boundary layer. For $S\approx 1$ or larger (strong stratification), the cross-shelf momentum flux divergence balances the wind stress, the bottom stress is small, and the onshore return flow is in the interior. Model results show that the onshore return flow shifts from the bottom boundary layer for small S to just below the surface boundary layer for $S\approx 1.5\text{-}2$ (Lentz and Chapman 2004).

Upwelling as a meso-scale feature is scaled by the internal Rossby radius. It is defined as

$$R_n=c_n/f_n \qquad (5)$$

where $n=1,2,\ldots$, c_n 's are the phase and group speed of Kelvin waves and As the thermal stratification varies seasonally depending on changes in heating and wind induced mixing in the Baltic Sea, the baroclinic Rossby radius varies between 1.5-10 km (Fennel et al. 1991, Alenius et al. 2003). Typical scales of upwelling in the Baltic Sea are:

- vertical motion: 10^{-5}-10^{-4} ms^{-1} ~ 1-10 m/day
- horizontal scales: 10-20 km offshore, 100 km longshore
- temperature change: 1-5 *°C/day*
- temperature gradient: 1-5°C/km
- lifetime: several days up to one month

The principle response of a stratified elongated basin to constant wind in length direction of the basin can be described as follows (Krauss and Brügge, 1991) expecting that the wind direction is parallel to the coasts:

(i) In the surface layers there results an Ekman transport in cross direction.

(ii) This Ekman transport produces (northern hemisphere) a sea level rise on the right hand coast (viewing in wind direction) and a fall on the left-hand-side. Furthermore downwelling occurs on the right-hand-side and upwelling on the left-hand-side resulting in baroclinic effects of the same sign at both coasts.

(iii) Consequently coastal jets are produced along both coasts parallel to the wind direction and a slow return flow compensates this transport in the central area of the basin.

The scheme of this circulation (Fig. 3) can be applied to the different sub-basins of the Baltic Sea. Krauss and Brügge (1991) demonstrated that upwelling in the Baltic Sea should be regarded as a three-dimensional current system effecting not only the local coast but also the opposite coast and the internal of the basin (Fennel and Sturm 1992, Fennel and Seifert 1995). However, the vertical extension of the Ekman compensation below the mixed layer is restricted in a Baltic due to the existence of the halocline normally at a depth of 50-80 m.

Kelvin waves

Abrupt changes in the longshore component of the wind stress generate in stratified waters internal Kelvin wave fronts which limit the amplitude of upwelling and give rise to a countercurrent under the thermocline (e.g. Gill and Clarke 1974). Coastline irregularities generate Kelvin waves in a manner similar to the wind-stress variability (e.g. Crepon et al. 1984). It depends on the shape of the coastline irregularity and the incident angle of the wind whether upwelling will be stabilized or destabilized by propagating Kelvin waves. The generation of Kelvin waves fronts is not only linked to the existence of abrupt discontinuities in the coastline, even continuous variations of the angle of the incident wind on the coasts can initiates Kelvin wave fronts (Crepon et al. 1984, Fennel and Seifert 1995).

Thus, upwelling areas are related to the shape of the coast, and filaments will be generated at the same locations under similar atmospheric conditions. Even remote areas which are not affected by local upwelling directly will be reached by propagating Kelvin wave fronts.

Atmospheric forcing

Coastal upwelling depends on atmospheric forcing: wind speed, direction and duration of the wind events. So, accurate descriptions of the wind, temperature and humidity fields are essential for studying upwelling dynamics. From Ekman's theory, longshore winds are most effective to generate upwelling.

A measure of the characteristics of the wind suitable to produce upwelling is the wind impulse I (Haapala 1994).

$$I=\int_0^t \tau\, dt=\int_0^t C_D \rho_a U_{10}^2 dt \qquad (6)$$

where ρ_a is the air density, C_D is the drag coefficient, U_{10} the wind speed at 10 m height and t the wind duration. The occurrence of upwelling depends on the stratification and the strength of the wind impulse. During thermal stratification a 4000-9000 $kgm^{-1}s^{-1}$ wind impulse of about 60 h duration is needed to generate upwelling, and when the sea is thermally homogeneous the impulse required is 10500-14000 $kgm^{-1}s^{-1}$. This implies that under strongly stratified conditions the wind stress has a direct effect only on the relatively thin water column over the thermocline. Even quite weak winds can lead to upwelling. If the stratification is weak the influence of the wind penetrates distinctly deeper, and more wind energy is needed to produce upwelling (Haapala 1994).

For the Baltic area there exist different general weather conditions which are favorable for upwelling at various coastal areas. Bychkova et al. (1988) identified 22 typical areas in different parts of the Baltic Sea which were favorable for upwelling in relation to 11 different wind conditions (see Figs. 4 & 5). For example the wind event I (north-easterly wind) is coupled with upwelling regions 3, 5, 6, and 9 while for example case VI (west, south-westerly winds) are coupled with cases 2, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 and 22 (see Bychkova et al. 1988 for details).

5. Modeling

Upwelling is a meso-scale process and thus scaled by the baroclinic Rossby radius which depends on the shape of the bottom topography and stratification conditions. It equals to a few kilometers in the Baltic Sea. For upwelling studies the appropriate grid size for numerical models should be in the order of the baroclinic Rossby radius or even finer. However, these requirements can be difficult to fulfill, not only because of the increasing needs of computing power, but because of the reason that the bottom topography is most probably not known accurately enough and that for validation high resolution measurements of upwelling hardly exists. Fennel et al. (1991) carried out the most comprehensive study of Rossby radii in the Baltic Sea. They analyzed both spatial and temporal variations of the Rossby radius. Their study covered the southern parts of the Baltic Sea and the Baltic Proper well and partially the Gulf of Finland. Their result was that the internal Rossby radius varies between 3 and 10 kilometers in the Baltic Proper whereas in the Gulf of Finland (Alenius et al. 2003) it falls into the range 2-4 kilometers. When keeping in mind the small values of the Rossby radius and the limited offshore extension of upwelling area at a steep coastal slope, the area being normally 10-20 kilometers only, we need very high resolution models to describe upwelling dynamics and related processes properly. In spite of these requirements several model studies have been carried out which were not able to fully resolve the upwelling process (e. g. Fennel and Seifert 1995, Jankowski 2002, Lehmann et al. 2002; Myrberg and Andrejev 2003). The reason is that these models have been designed as circulation models and not specifically to study upwelling. Kowalewski and Ostrowski (2005) as well as Zhurbas et al. (2004) used a nested grid to resolve the area under interest (southern Baltic Sea) with 1 nm and 1 km horizontal resolution, respectively. Some of the models have been used to statistically describe upwelling in determining its location and their corresponding frequency of occurrence (Myrberg and Andrejev 2003, Kowalewski and Ostrowski 2005). The annual average frequency of upwelling appeared to be higher than 30 % in some parts of the Baltic Sea coast.

Model results presented so far demonstrate the applicability of numerical models for further deepening our understanding of upwelling and related statistical properties. With increasing computer power and availability numerical models can have a horizontal resolution which allows to study the full range of meso-scale dynamics for long-term runs.

6. Implication on the marine environment

Eutrophication, and its ecological manifestations, e.g. harmful algal blooms, has been a severe problem during the latest decades representing the most acute problem in the Baltic Sea ecosystem. An important aspect is to define the role of water displacements across the thermocline as an agent inside the system supporting high productivity. Even though the episodic pulses of nutrients across the density gradients stimulate the Baltic primary production significantly (e.g. Kononen et al. 1996), so far this source of new production is poorly quantified. Anyhow, the studies of Kononen and Niemi (1986), Raid (1989) as well as Haapala (1994), Fonselius (1996) show that upwelling can play significant role in the vertical water displacements of the surface layers with the nutritional components necessary for biological productivity (Burska and Szymelfenig, 2005; Zalewski et al.,2005, Gromisz and Szymelfenig, 2005; Bielecka et al. 2005). Szymelfenig (2005) has carried out a detailed study of upwelling at the Hel Peninsula with bio-physico-chemical manifestations.

It is still poorly understood how the decreased surface temperatures, increased nutrient concentrations and turbidity of surface waters are reflected in phytoplankton growth and especially what is the effect of *upwelling to* late-summer cyanobacteria blooms. Some earlier paper (e.g Nõmmann, 1991) stated that a persistent, moderate wind is favorable to sustain local phytoplankton bloom while keeping the vertical transport of the deeper nutrient-rich water still going on but being not strong enough to stir away the growing phytoplankton. However, Vahtera et al. (2005) summarize that the total biomass of phytoplankton declined in the area affected by the upwelled waters and only within five days after the start of the upwelling,the primary production showed a slight increase. So, according to latest results its looks like that the first response of upwelling is a decrease in primary production (s. also Zalewski et al., 2005), however supply of nutrients to the euphotic zone and a gradual increase of temperature after the upwelling event lead to potentially favorable conditions for phytoplankton development.

Janssen et al. (2004) investigated inter-annual variability of late summer cyanobacteria blooms in the Baltic Sea using a three-dimensional ecosystem model. There is evidence that the late-winter phosphate concentration in the surface layer has a important influence on late summer cyanobacterial blooms. A large fraction of the inter-annual variability in such blooms can be attributed to the variability in excess of dissolved inorganic phosphorus (eDIP) in the surface layer. The amount of available eDIP in the surface layer depends on the wintertime depth of the mixed layer and on the magnitude and persistency of coastal upwelling. Their results suggest an impact of the large-scale atmospheric conditions in winter, namely the North Atlantic Oscillation (NAO), on the occurrence of cyanobacterial blooms in the Baltic Sea. It is given an explanation that the impact of the NAO is transferred by a cause-and-effect chain starting in winter and developing until late summer: high NAO index → high wind stress, low ice cover → high mixed-layer depth, strong upwelling → high surface-layer eDIP concentration → (potentially) strong cyanobacterial bloom.

The effects of upwelling to late-summer cyanobacteria growth has been studied in detail by further on by Vahtera et al. (2005). The authors remind that usually the phytoplankton growth in the Baltic is nitrogen-limited, an exception being the filamentous cyanobacteria which fix atmospheric nitrogen. The cyanobacteria growth is thus phosphorus-limited and the growth is also limited by temperature. So, the effects of upwelling on cyanobacteria bloom is not straight-forward due to the decrease of temperature in the upwelling regions and due to potential changes in DIN:DIP ratios. According to Laanemets et al. (2004) nutriclines, at least in the Gulf of Finland, lie in the thermocline, the phosphacline being shallower than the nitracline. Thus, upwelling leads to phosphorus enrichment and low DIN:DIP ratios in the euphotic layer. So, it might be so that the filamentous nitrogen-fixing cyanobacteria would benefit from the phosphorus enrichment. This was suggested also already by Niemi (1979). Stipa (2002) studied the effect of upwelling on the preconditions for noxious cyanobacterial blooms in a nitrogen-limited estuary. Since a low N/P ratio is often mentioned as prerequisite for cyanobacterail blooms, the distinct character of the N/P ratio in combination of stratification maximum is indicative of the tendency of such events to favor off-shore *Nodularia* blooms.

However the direct effect of upwelling with related decreasing surface temperature is the decline in the filamentous cyanobacteria biomass. According to Vahtera et al (2005) *Nodularia Spumigena* is more severely affected due to its strong buoyancy and vertical displacement near to surface. It was concluded finally by the authors that the lifetime of a typical upwelling remnant is too long for populations outside the upwelled water to be able to benefit directly from the nutrient input. Owing to the low DIN:DIP ratio of the upwelled water the nitrogen-fixing *A. flos-aquae* populations locating at the top of the thermocline can be approximated to have been in a good position for exploiting the additional phosphorus in good light conditions.

However, the utilization of the lowered DIN:DIP ratio does not lead straight forward to enhanced cyanobacteria blooming. There is a clear lag between the upwelling and the biomass increase. According to Vahtera et al. (2005) this is about 2-3 weeks. So, an upwelling may enhance cyanobacteria blooming by only after a certain “relaxation time”.

7. Requirements on future research

To resolve the full spectrum of meso-scale features numerical models should have a horizontal resolution in the order of the internal Rossby radius or even higher. These high resolution models should be validated with high resolution satellite data and hydrographic measurements which provide information not only on the location of upwelling but also on the temporal development and horizontal extent. Thus high resolution hydrographic measurements campaigns are needed to describe the upwelling process mainly due to changes in stratification and mixing of different properties including nutrients. High resolution modeling can then attribute corresponding transports and quantification of the upwelling process including mixing. The combined advances in observational techniques and modeling can help to understand the upwelling process and related implications. The mostly needed research should aim at:

- quantification of transports and fluxes on-/offshore related to upwelling including coastal jets
- contribution to the total mixing and impact on residence times
- impact and quantification of changes of the interaction between ocean and atmosphere
- documentation of upwelling areas and their probability to occur with respect to specific atmospheric general conditions for the total Baltic Sea
- impact of upwelling on bio-geochemical processes and phytoplankton development

- impact of climate change on wind fields and related changes in upwelling regions

A deeper understanding of the upwelling process and its implication on the marine environment will lead to an improvement of the prognosis of the local weather prediction, algae bloom forecasting, transports and mixing of nutrients and harmful substances.
First activities in that direction have been undertaken and results of this work have been presented at the Baltic Sea Science Conference in March 19-22, 2007 at Rostock University (see Myrberg et al. 2007).

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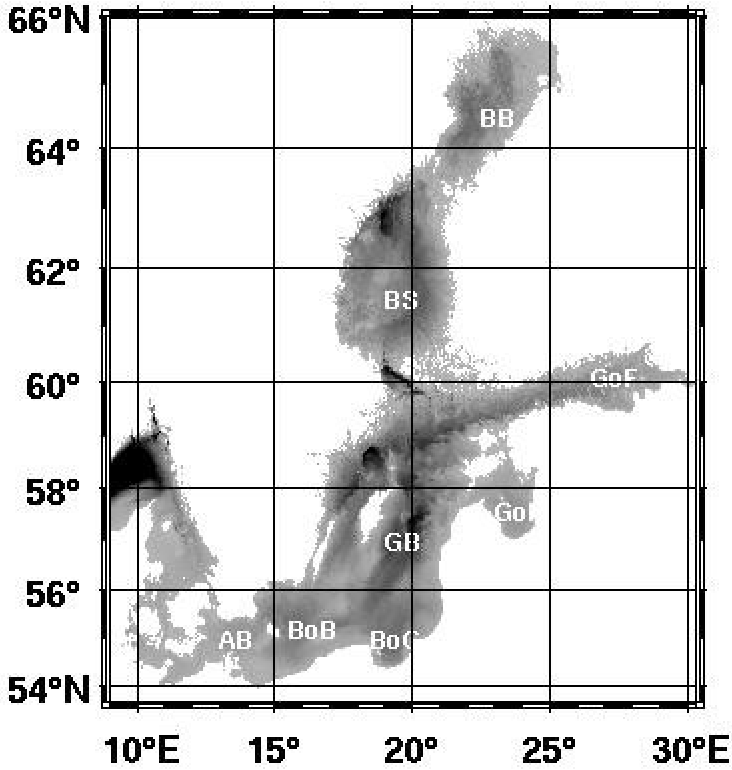

Figure 1. Topographic map of the Baltic Sea and its sub-basins (AB – Arkona Basin, BoB – Bornholm Basin, BoG – Bay of Gdansk, GB – Gotland Basin, GoF – Gulf of Riga, GoF – Gulf of Finland, BS – Bothnian Sea, BB – Bothnian Bay).

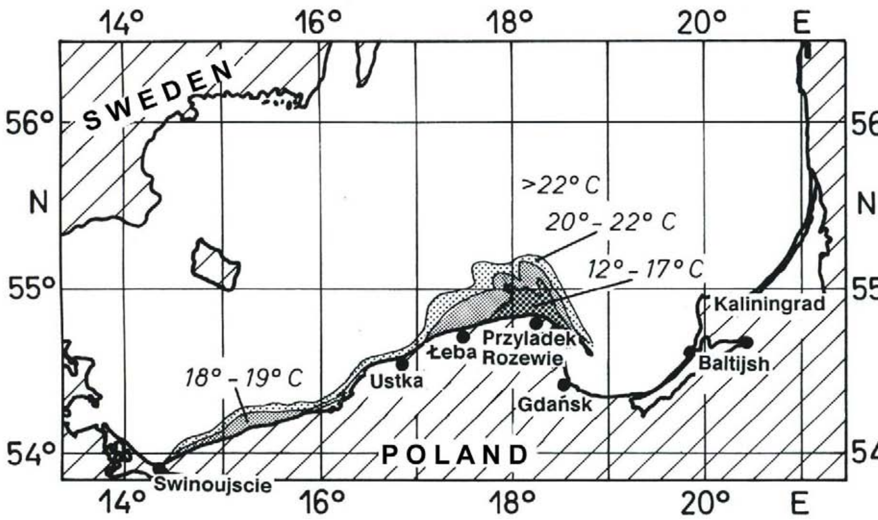

Figure 2. Sea- surface temperature in the beginning of September 1997 redrawn from infrared satellite data. A similar upwelling situation has been observed in August 1834 by A. v. Humboldt when traveling from Szcczecin to Kaliningrad (Kortum and Lehmann 1997).

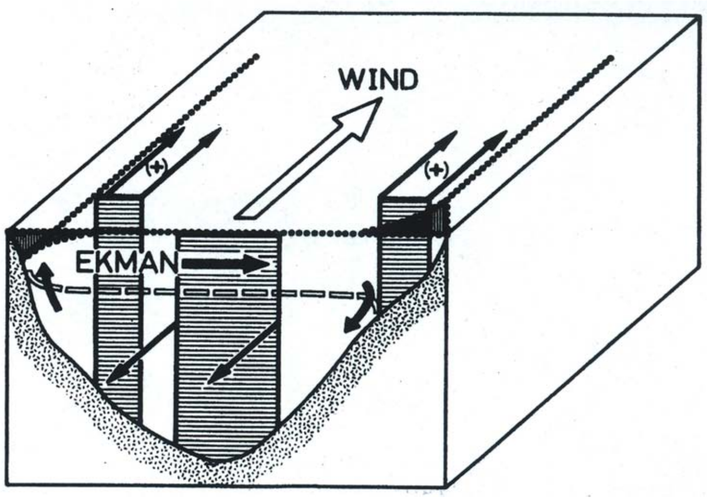

Figure 3. Principle response of an elongated basin to constant wind in length direction of the basin, redrawn from Krauss and Brügge (1991).

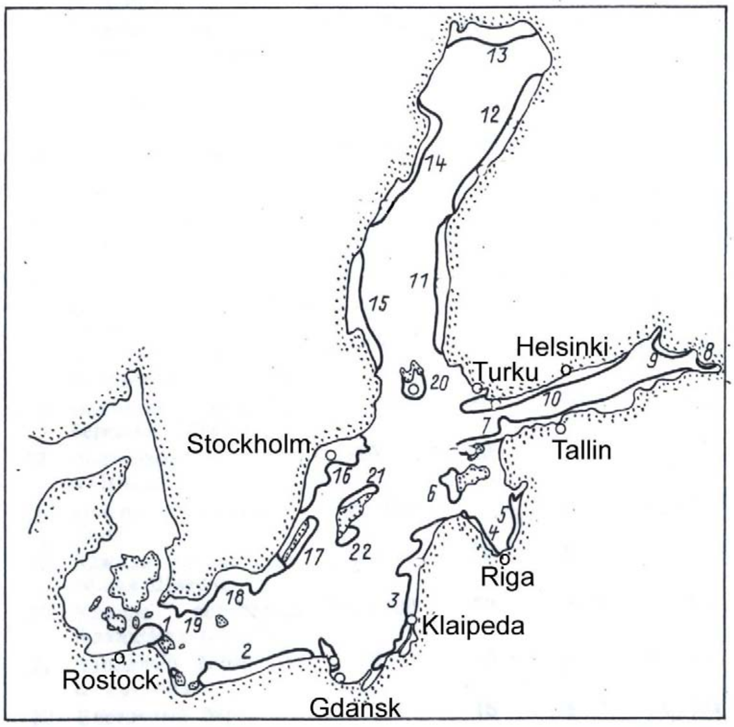

Figure 4. Main upwelling regions in the Baltic Sea due to corresponding general weather conditions, redrawn from Bychkova et al. (1988).

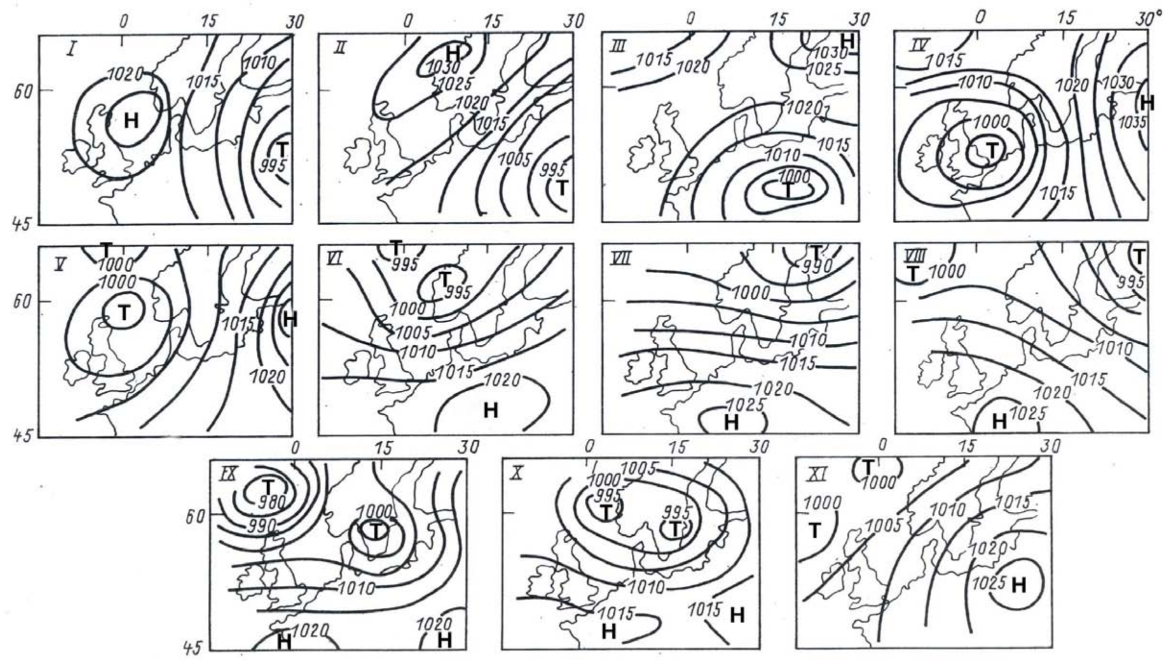

Figure 5. Typical general weather conditions favoring upwelling in the Baltic Sea, redrawn from Bychkova et al. (1988).