Influence of coastal upwelling on chlorophyll a concentration in the surface water along the Polish coast of the Baltic Sea*

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Adam Krężel[1,*]
Lena Szymanek[2]
Łukasz Kozłowski[1]
Maria Szymelfenig[1]

[1] Institute of Oceanography,
University of Gdańsk,
al. Marszałka Piłsudskiego 46, PL–81–378 Gdynia, Poland;

e-mail: oceak@univ.gda.pl

*corresponding author

[2] Sea Fisheries Institute,
ul. Kołłątaja 1, PL–81–332 Gdynia, Poland

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Abstract

Space-time variations in chlorophyll a (Chl a) concentrations in the surface water of upwelling regions along the Polish coast of the Baltic Sea were analysed. Carried out between 1998 and 2002 in the warmer season (from April till October), the measurements were targeted mainly at the Hel upwelling. Satellite-derived sea surface temperature (AVHRR) and Chl a data (SeaWiFS) were used. Generally speaking, the Chl a concentration increased in the upwelling plume, except

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along the Hel Peninsula, where two scenarios took place: a reduction in Chl a concentration in spring and an increase in autumn.

1. Introduction

Polish coastal waters of the southern Baltic are characterised, among other things, by the frequent occurrence of coastal upwelling (Bychkova & Viktorov 1987, Urbański 1995, Krężel 1997, Kowalewski 1998). At the sea surface, the effects of upwelling are recognisable as a patch of water with properties different from those of 'typical' surface waters. These differences are easily revealed by temperature field analysis (Krężel et al. 2005, this volume). It is also evident that water upwelling from deeper waters may be characterised not only by temperature, but also by many other physical and chemical features differing from the typical properties of the surface water at a given site and season. This can influence the course and intensity of biological processes, including such essential ones as primary production.

Integral constituents of phytoplankton cells, pigments such as chlorophylls, carotenoids and phycobilins absorb electromagnetic radiation of specific wavelengths. They can thus be identified by analysis of the scattered radiation spectrum in the surface sea layer as recorded by a satellite-borne radiometer. The methods so far applied to estimate pigment concentrations are not very accurate, especially in coastal regions, for a variety of reasons (Sathyendranath (ed.) 2000, Darecki et al. 2005). However, they share at least one great advantage – the data cover an extensive area and are collected at low cost. Therefore, the absolute chlorophyll a (Chl a) concentrations obtained hitherto should be treated as approximate. Of far greater value, however, are the conclusions to be drawn from the changes in the spatial distribution of Chl a concentrations.

The analysis of satellite images from different marine basins points to a clear relationship between an elevated concentration in the surface water layer and the surface area of cool water raised by upwelling (Solanki et al. 2001, Davenport et al. 2002, Joint et al. 2002, Acha et al. 2004). Such a relation is not obvious in a shallow enclosed sea. This applies in particular to the coastal zone, where organic life, mainly phytoplankton, develops more quickly than in the open sea because of the nutrients supplied by terrigenous runoff.

Generally speaking, the mean Chl a concentration in the surface water layer reaches higher values along the coast and at the fresh-salt water interface than in open sea water bodies. This is manifested, for example, by the multiyear mean surface distribution of chlorophyll concentrations in the Gulf of Gdańsk. The only exceptions to this are the coastal waters spreading eastwards along the Hel Peninsula from its base (Fig. 1). A large part of

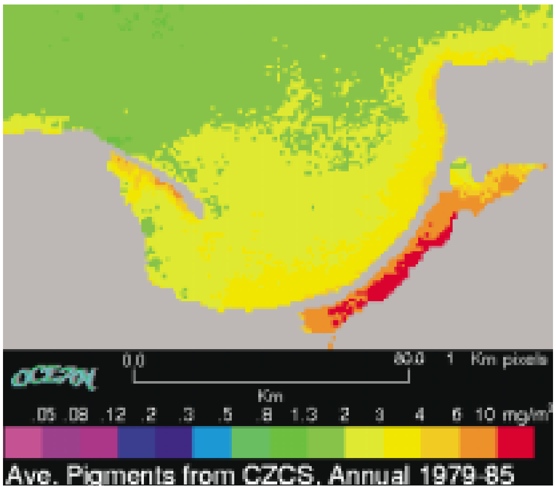

Fig. 1. Mean concentration of phytoplankton pigments in the Gulf of Gdańsk on the basis of CZCS data (Ocean... 1996)

this area overlies a plume of upwelling water. It is here that a relationship between the Chl a concentration in surface water and the occurrence of upwelling could be found.

The aim of the work was to analyse, on the basis of satellite-derived data supported by sea truth measurements, the influence of coastal upwelling on Chl a concentrations along the Polish coast of the Baltic Sea with special reference to the Hel Peninsula.

2. Material

The study area covered the Kołobrzeg, Łeba and Gdańsk upwelling regions (Fig. 2) along the Polish coast of the Baltic Sea. The seven-month spring-early autumn period (April–October) was chosen rather than the whole year because (i) this period includes the main phytoplankton growing season, (ii) the frequency of valid satellite observations during autumn and winter is relatively low, and (iii) it is practically impossible to identify areas covered by upwelled water in winter.

Satellite images of the southern Baltic (c. 500) and the Gulf of Gdańsk (c. 200) were recorded in 1998–2002 by:

- a SeaWiFS radiometer (OrbView 2 satellite; data registered by the receiving station of the University of Dundee),
- an AVHRR radiometer (NOAA 12–17 series satellites; data registered by receiving stations of the University of Dundee, and the Institute of Oceanography, University of Gdańsk).

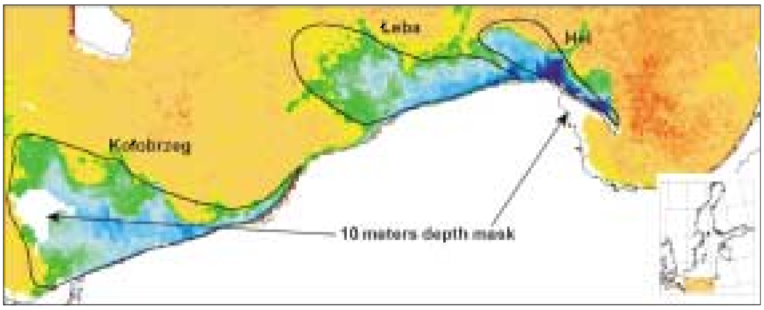

Fig. 2. Approximate maximum ranges of the upwelling plume areas along the Polish coast of the Baltic Sea

The parameters of the OrbView 2 satellite orbit allowed at most two images to be recorded in the southern Baltic during daylight hours, and usually only one of them was of satisfactory quality. Moreover, only cloudless areas could be analysed, a precondition fulfilled during c. 20% of the investigation time (Krężel 1985), mainly in the warmer part of the year.

Sea depth is another factor diminishing the amount of satellite data in the study area. Earlier results (Siegel & Seifert 1985, Matciak & Krężel 1991) had suggested that in the southern Baltic, a VIS signal registered by a satellite radiometer could be significantly disturbed by the sea bottom at depths below 10 m. These particular data were therefore ignored.

The analysis of every scene required data from two independent satellites working in different orbits (OrbView 2 and NOAA). However, because of the rapid changes in the weather conditions (mainly cloudiness), the Chl *a* concentration maps were in many cases compared to temperature maps produced up to twelve hours earlier or later. In the event, more than 50 satellite maps of sea surface temperature and Chl *a* concentration were used. The high quality of the satellite images, i.e. lacking any signs of atmospheric heterogeneity in the study area, was the basic criterion for selecting data from individual measuring times for calculations. Selection was pseudo-random, thereby enabling a preliminary assessment of the effect of upwelling on Chl *a* concentration in the coastal zone in the warmer period of the year.

The sea truth data on surface water temperature and Chl *a* concentration were collected during 7 upwelling events (28.04.2000, 18.09.2000, 18.07.2001, 27.09.2001, 13.05.2002, 02.08.2002 and 28.08.2002) in the vicinity of Hel (Matciak et al., in press, Zalewski et al., in press). Three stations were chosen on every cruise. The central station (U) was situated at the upwelling centre. The reference station (O) was set sufficiently far from station U at a point where the surface waters were not directly affected by upwelling. A transitional station was sited between stations U and O.

Chl a concentrations were measured fluorometrically (Zalewski et al., in press), the samples being extracted in 90% acetone (24 h) in darkness and at a temperature of c. 4°C.

3. Method

The maps of Chl a concentration were produced with the aid of the OC4 algorithm (O'Reilly et al. 1998) implemented in the SEADAS system. The algorithm is based on the following empirical relation:

$$\mathrm{Chl}\,a = 10^{(0.366-3.067\,R+1.93\,R^2+2.649\,R^3-1.532\,R^4)} - 1.0414,$$

where

Chl a – Chl a concentration,

R – $\log_{10} R_G$,

R_G – the highest coefficient from among (ρ_w – remotely sensed reflectance):

– $\rho_w(443)/\rho_w(555)$,

– $\rho_w(490)/\rho_w(555)$,

– $\rho_w(510)/\rho_w(555)$.

In view of the geographical proximity, similar coast and water type (homogeneous and terrigenous material inflow from river estuaries), the procedure of atmospheric correction elaborated for the Belgian coast of the North Sea (Ruddick et al. 2000, 2001) by MUMM (Management Unit of the Mathematical Models) was used for the calculations. The algorithm was modified for case 2 waters, i.e. the relationships between channels 7 and 8 of SeaWiFS[1] were verified for the whole study area. This enabled a *priori* assumption of a constant value for coefficient ϵ (765 nm, 865 nm)[2] in the area (this parameter identifies the type of aerosol content and distribution model

[1] A SeaWiFS radiometer is equipped with 8 spectral channels (wavelength ranges [nm]): 1 – 402–422, 2 – 433–453, 3 – 480–500, 4 – 500–520, 5 – 545–565, 6 – 660–680, 7 – 745–785, 8 – 845–885.

[2] $\epsilon(\lambda_i,\, \lambda_j) = \frac{\rho_{as}(\lambda_i)}{\rho_{as}(\lambda_j)} = \frac{\overline{\omega}_a(\lambda_i)\tau_a(\lambda_i)p_a(\theta,\theta_0,\lambda_i)}{\overline{\omega}_a(\lambda_j)\tau_a(\lambda_j)p_a(\theta,\theta_0,\lambda_j)}$,
where $\overline{\omega}_a$ – aerosol single scattering albedo; ρ_a – aerosol optical thickness; p_a – phase function of attenuation by aerosols; θ and θ_0 – satellite and solar zenith angle, respectively (Gordon & Wang 1994).

in a vertical atmospheric column). Such a model was then used instead of a single pixel for calculating the atmospheric correction for the whole study area. Since the Gulf of Gdańsk is relatively small body of water, such an approximation seems justified.

The procedure for calculating parameter ϵ (765 nm, 865 nm) for case 2 waters involved:

1. Calculating the reflectance, reduced by a value due to Rayleigh molecular scattering, using the standard atmospheric correction algorithm.
2. Calculating the atmospheric correction parameter from the plot of the reflectance dependence between channels 7 and 8 of SeaWiFS. When the relationship between the low reflectance (0.002–0.01) in channel 7 and the reflectance in channel 8 is almost linear (coefficient = c. 1), the pixels of the study area are assumed to be 'clear water' ones. Such pixels are used to estimate the atmospheric correction parameter for case 2 waters.

   Higher reflectance values in channel 7 are also significantly dependent on the reflectance in channel 8. But the coefficient is then subject to relatively large changes. These pixels are assumed to be the pixels for case 2 waters; in this case, Rayleigh scattering and attenuation are lower in value than the signal of water-leaving radiation.

   15 images were randomly chosen from the Gulf of Gdańsk and the relationship between channels 7 and 8 analysed. The calculated coefficients (0.99–1.12) were close to those of Ruddick et al. (2000). The atmospheric correction parameter (1.01) was applied to the whole data series. As a result, positive values of the water-leaving radiation were obtained in the whole area (Fig. 3). This stands in contrast to the

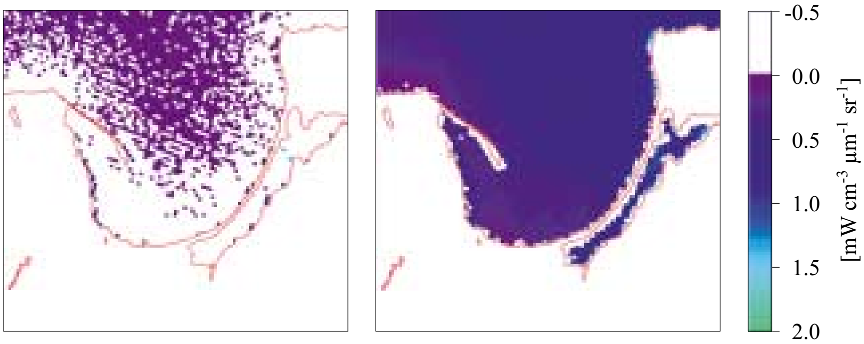

Fig. 3. Water-leaving radiation in the Gulf of Gdańsk determined by two algorithms for atmospheric correction: the standard OC4 (left) and that used in the present work (right)

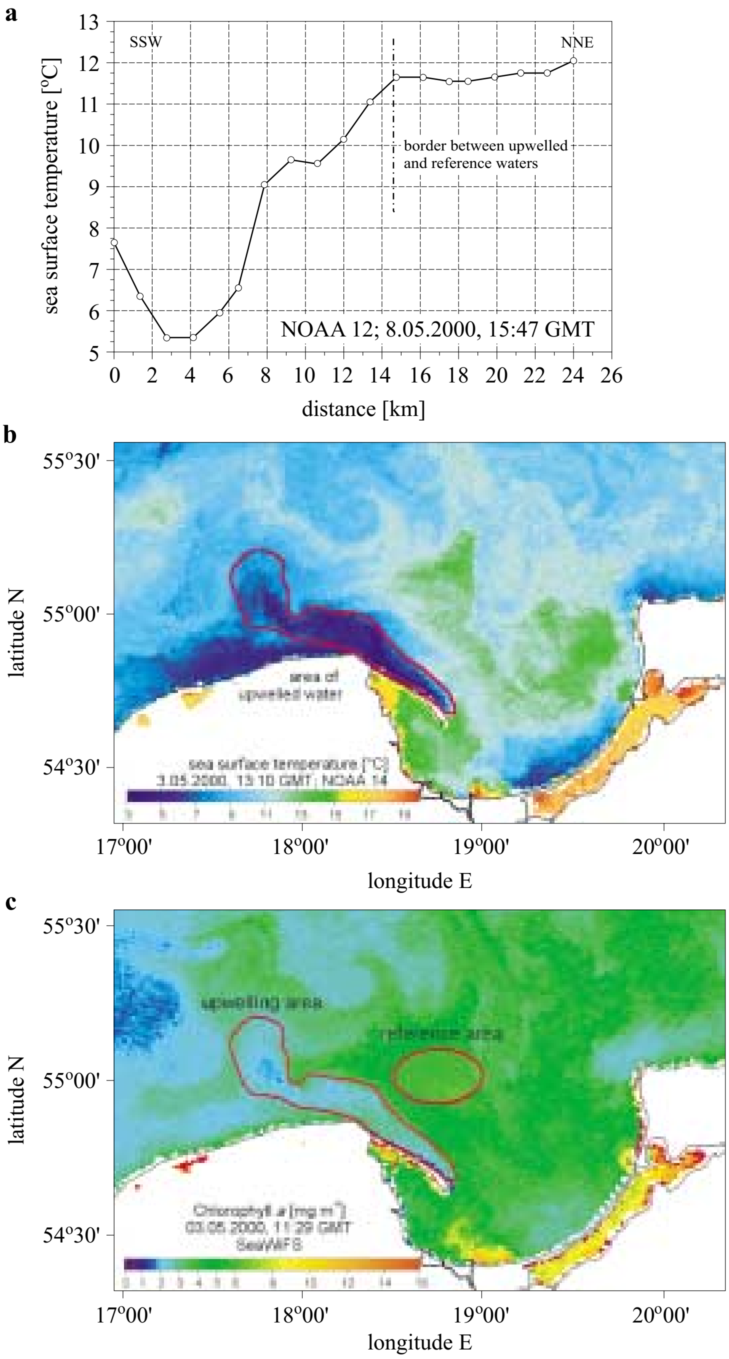

Fig. 4. Satellite-derived determination of the water plume range in the Hel region: example of temperature distribution in the cross-section of the upwelling plume (a), upwelling plume area determined on the basis of SST distribution analysis (b), areas for which mean chlorophyll a concentrations were calculated (c)

standard OC4 procedure, which for case 2 waters areas yields mainly negative values that are devoid of physical meaning and therefore useless for further analysis.

3. Producing maps of surface water Chl a concentration with regard to the atmospheric correction coefficient introduced in point 2.

Analysis of the sea surface temperature distribution determined the area of the upwelling plume. Transects were drawn across the plume of upwelled water (Fig. 4a), after which the area of the plume could be determined (Fig. 4b). The reference area was taken to be the area of stable surface temperatures situated a dozen or so kilometres towards the open sea from the upwelling plume (Fig. 4c). Statistical parameters of the surface chlorophyll concentrations were calculated for the areas so defined. In a non-upwelling period (no characteristic SST decrease in the area of upwelling occurrence), mean values were calculated for those areas where upwelling water is usually found (Fig. 2) (Krężel et al. 2005, this volume). Under partially cloud-free conditions, mean values were calculated only for the cloudless parts. The AVHRR sea surface temperature data were registered in the HRPT system. The method of data processing and the algorithms used have been described by Krężel et al. (2005, this volume).

4. Results and discussion

Satellite-derived data registered by a SeaWiFS radiometer were used to determine the ratio of Chl a concentration in the surface sea layer between the upwelling and reference areas in the warmer season of the year during upwelling and non-upwelling periods (Table 1). The Hel, Łeba and Kołobrzeg regions were analysed separately and some regularities were observed.

In the non-upwelling periods, the surface water Chl a concentration in the three regions specified above was generally higher than or close to that in the surrounding area (Table 1, Fig. 5a): the phytoplankton was flourishing in the sufficient abundance of nutrients and the higher, summer temperatures in shallow, coastal waters.

During an upwelling event, however, the situation becomes complicated. The rate of primary production can depend, among other things, on the rate of warming of cold, upwelled water. Particularly in spring, water temperatures rise rapidly and vast but shallow sea areas warm up more easily. Therefore, depth and bottom configuration cannot be ignored. The area of shallow water in the Łeba and Kołobrzeg regions is significantly greater than along the Hel Peninsula, where the depth increases rapidly with distance from the shore (Fig. 5b).

Consequently, in the Łeba and Kołobrzeg regions, upwelled waters are raised from shallower depths and warm up faster than those in the

Table 1. Relationship of chlorophyll a concentration at the sea surface between upwelling and reference areas derived on the basis of SeaWiFS data in upwelling and non-upwelling periods

Area	Events during upwelling				Events during absence of upwelling			
	+	±	−	∑	+	±	−	∑
Hel	10	4	13	27	14	11	2	27
	37	15	48	%	52	41	7	%
Łeba	12	5	1	18	18	10	3	31
	67	28	5	%	58	32	10	%
Kołobrzeg	10	3	0	13	18	7	4	29
	77	23	0	%	62	24	14	%
Sum	32	12	14	58	50	28	9	87
	55	21	24	%	58	32	10	%

The symbols denote: (+) – events with a higher concentration in the upwelling zone, (±) – events with insignificant differences between upwelling and reference area, (−) – events with a higher concentration in the reference area, ∑ – total number of events analysed.

Hel region. As a result of these favourable thermal conditions and the elevated nutrient concentrations during the upwellings in the former regions, phytoplankton were present in great abundance. This was manifested by an increase in surface Chl a concentration in comparison with the situation during non-upwelling periods (Table 1).

The changes affecting the Chl a concentration during an upwelling event off the Hel Peninsula are more complex. The Chl a concentration amplitudes in the upwelling area and its surroundings were wider in spring and summer than in autumn (Fig. 6). In spring, Chl a concentrations were usually lower in the upwelling area than in the reference area. In summer and autumn, the situation was reversed, although the differences between the two areas were smaller in summer than in autumn (Fig. 7).

Comparison of temperature and Chl a concentrations in the surface water measured from the coast through the upwelling centre (the coldest water area) and its plume to the surrounding area (Fig. 8) provides a good example of seasonal variability. In spring (e.g. 08.05.2000), the Chl a concentration in very cold water upwelled from a deeper sea layer (Krężel et al. 2005, this volume) was low, the lowest value being at the centre, which was coldest. However, temperatures and Chl a concentrations rose gradually with increasing distance from the upwelling centre. In autumn (e.g. 30.09.2000), in contrast, Chl a concentrations decreased with rising water temperatures, achieving much lower values in the surrounding area

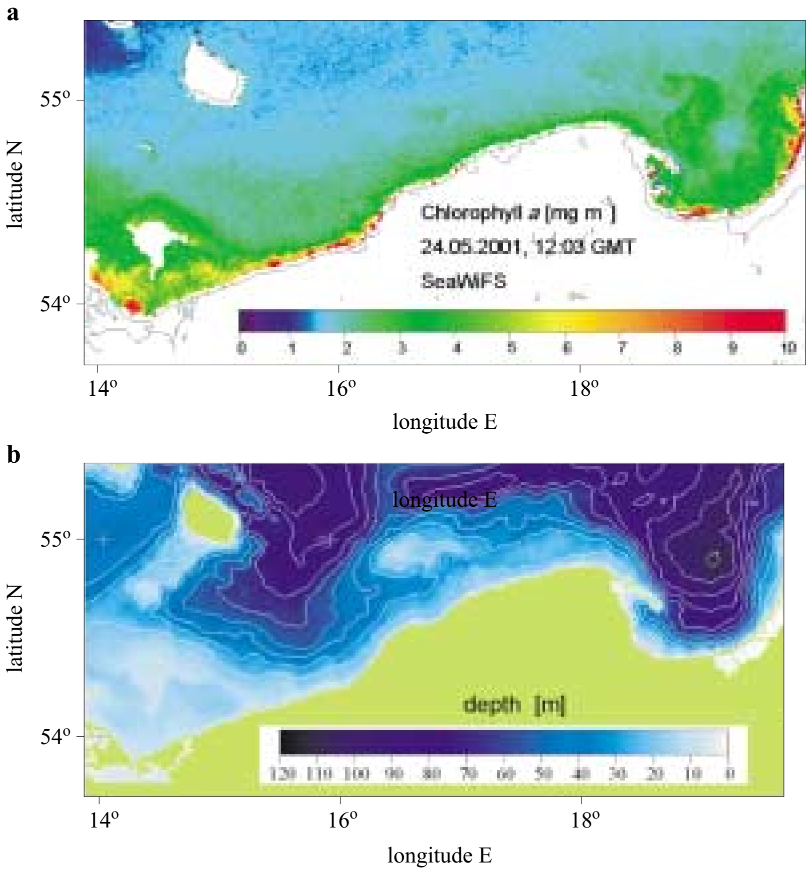

Fig. 5. The chlorophyll a concentration in the Polish coastal zone during a non-upwelling period (a), and the bathymetry of the region (b)

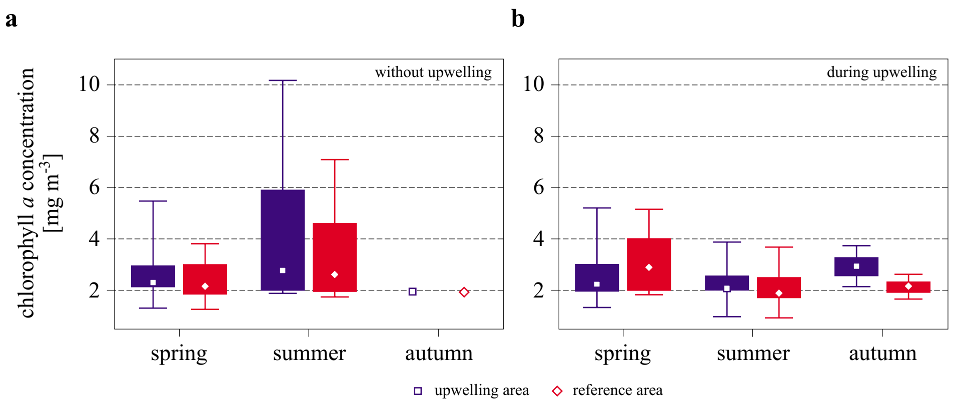

Fig. 6. Chlorophyll a concentration at the sea surface along the Hel Peninsula during non-upwelling (a) and upwelling periods (b)

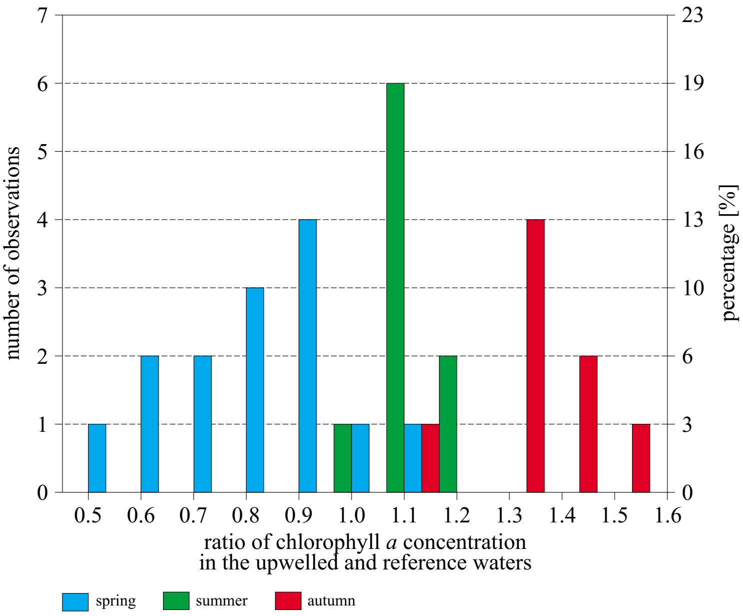

Fig. 7. Distribution of chlorophyll a concentrations in the upwelled-to-reference water ratio in the Hel upwelling region

than in the upwelling plume. Note that, as in spring, the Chl a concentration was lowest at the coldest point, i.e. the upwelling centre, which was sometimes only a few hundred metres in diameter.

The variations in temperature and Chl a concentration measured in time series during relatively long periods of upwelling off Hel, both in spring (May 2000) and in autumn (September–October 2000), are also indicative of seasonal changes (Fig. 9). During the evolution and gradual decay of cool upwelling waters in spring, the Chl a concentration in them was lower than in the reference area. In autumn, on the other hand, upwelling waters were characterised by higher Chl a concentrations during the whole upwelling period. It is important to note that in autumn, in both plume and reference areas, water temperatures were higher than in spring. In autumn Chl a concentrations in the above areas were relatively stable and only short-term (1–3 days) differences, c. 1 mg m^{-3}, were found. In spring the changes in Chl a concentration appeared earlier (1–2 days) and were more frequent, the difference being c. 3 mg m^{-3} during two days.

Comparison of absolute Chl a concentrations measured *in situ* (Zalewski et al., in press) with satellite-derived data shows them to be poorly correlated (Fig. 10). This is due to (a) imperfections in the Chl a algorithm for case 2 waters, (b) the fact that *in situ* and satellite measurements are not carried out contemporaneously, and (c) the fact that *in situ* point

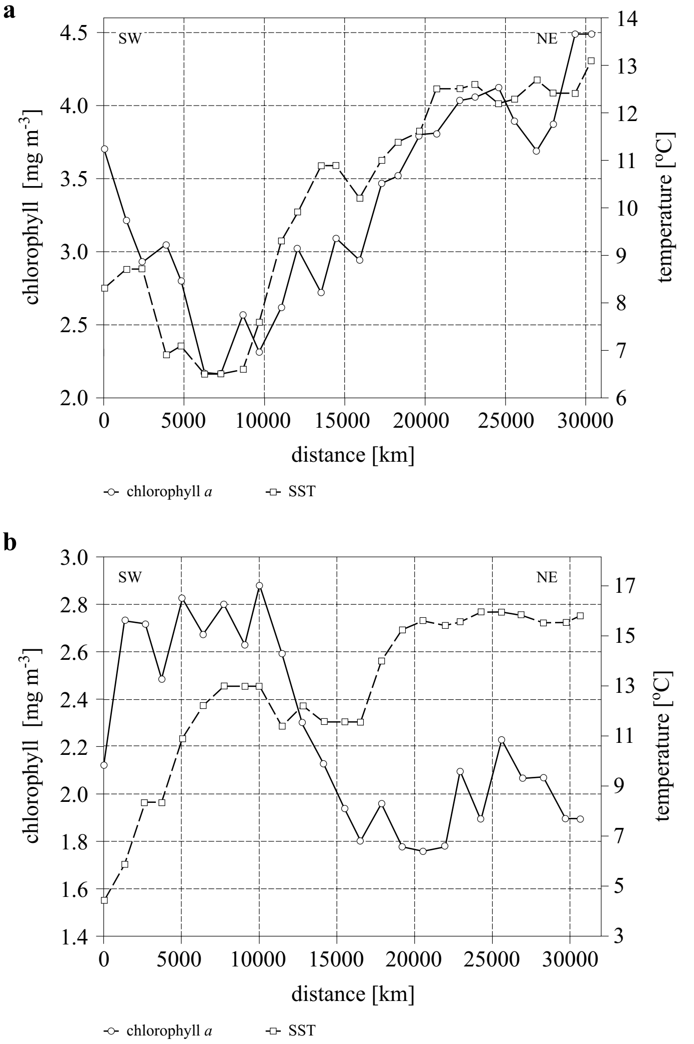

Fig. 8. Horizontal profiles of water temperature and chlorophyll *a* concentration at the sea surface in the Hel upwelling region: spring, 08.05.2000 (a) and autumn, 30.09.2000 (b)

values are compared with remotely sensed ones representing an average value within the whole pixel (~ 1 km^2). *In situ* spectrophotometric measurements indicated that irrespective of season, Chl *a* concentrations at upwelling centres were always lower than at the reference station. The lowest concentration (0.28 mg m^{-3}) was noted in the upwelling core and the highest (14.63 mg m^{-3}) at the reference station. The difference in Chl *a* concentration depended on upwelling strength and ranged broadly, from 1.2 to >40-fold at the reference station. In comparison to the above, the mean, minimum and maximum Chl a concentrations calculated on the basis of satellite data at the same or nearly the same periods did not show up such big differences between the upwelling water and the reference area (Table 2). Satellite imagery markedly simplifies the actual pattern of Chl a concentration. This is especially clear in the Hel upwelling region, where the water temperature gradient, over a range of some pixels, was steep (Krężel et al. 2005, this volume).

Table 2. Satellite-derived chlorophyll a concentration in the upwelling plume and the reference area

Date	Upwelling plume			Reference area		
	Min	Average	Max	Min	Average	Max
29.04.2000	1.605	2.001	2.603	1.796	2.287	3.647
18.09.2000	1.005	3.109	4.453	1.964	2.370	6.094
08.07.2001	1.472	3.557	5.570	2.713	3.522	5.758
28.09.2001	1.076	2.931	4.791	0.204	2.176	1.792
14.05.2002	1.316	1.958	2.883	1.443	2.006	2.945
02.08.2002	0.986	2.227	2.801	1.410	1.962	2.250
28.08.2002	0.862	0.969	1.157	0.842	0.908	1.183

Min – minimum value, Max – maximum value.

The methodology assumed that the upwelling area extended from its centre through the upwelled water plume to the boundary with surface water of a stable temperature (Fig. 4). The specific character of the Hel upwelling region lies in the fact that its centre is usually situated very close to the shore. Therefore, the low Chl a concentration at the centre is underestimated in satellite calculations since the coastal pixels are masked by the buffer applied. The good quality of a few autumn images enabled a small area upwelling core with a significant decrease in Chl a concentration to be identified among the pixels covering the whole upwelling plume. It was possible to select such a reference area on the satellite images where the influence of the upwelled waters could be excluded with a very high probability. The reference station chosen by *in situ* measurements was not so reliable, since the adopted criterion of maximum water temperature could result in its still being located in the plume area (Matciak et al., in press). For determining the centre of upwelling, field measurements were much more precise since they were carried out at the coldest site – in the upwelling core, which was often less than a few hundred metres in diameter. On the one hand, the resolution of satellite images enabled a situation to be described with a poorer accuracy than with *in situ* measurements but, on the other, considerably larger areas could be analysed. Nevertheless, the

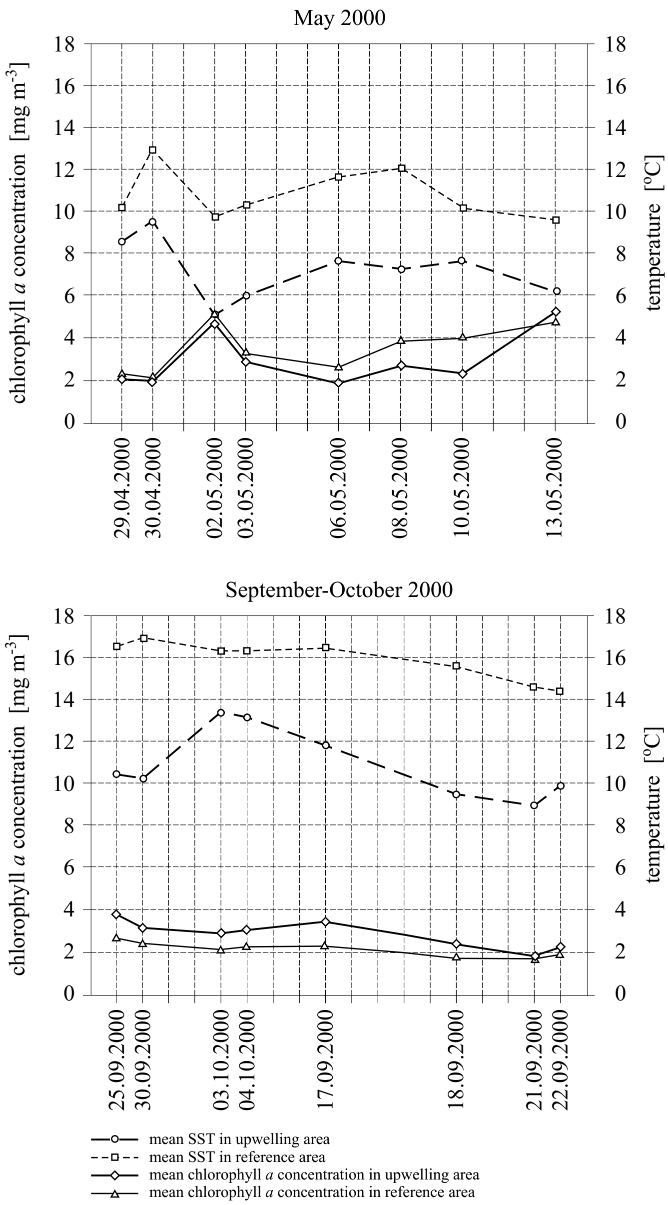

Fig. 9. Time series of chlorophyll a concentrations and water temperatures in Hel upwelling region during an upwelling event

results obtained by both methods led to a common conclusion, namely, that the Chl a concentration decreases rapidly and significantly in the cold upwelling core. However, as a result of their spreading across the surface (Burska & Szymelfenig, in press) nutrient-rich waters gradually warm up and primary production increases. Chl a concentrations were also reduced

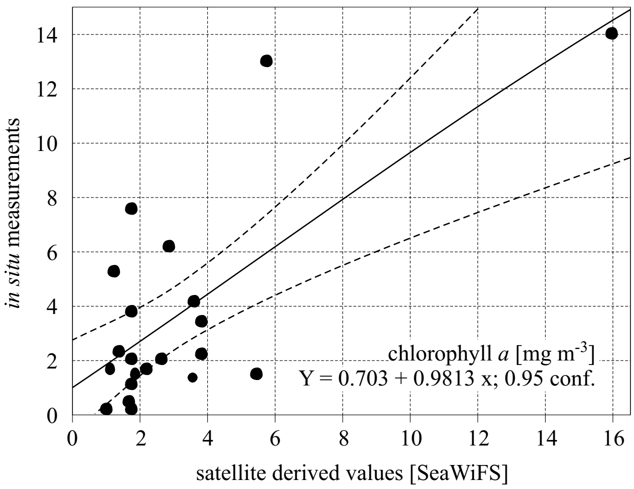

Fig. 10. Relationship between *in situ* (Zalewski et al., in press) and satellite-derived chlorophyll a concentrations at the sea surface in the Hel upwelling region

at the cold centres of upwelling areas off the coasts of Peru (MacIsaac et al. 1985), California (Dugdale & Wilkerson 1989) and south-west Africa (Shillington et al. 1990).

A clear relationship exists between the amount of nutrients available and phytoplankton productivity. Nutrient concentrations (nitrates, phosphates and silicates) were the highest at the upwelling centre and decreased towards the reference station (Burska & Szymelfenig, in press). Although the assimilation numbers calculated for the upwelling centre also indicate very good trophic conditions (Zalewski et al., in press), no increase in Chl a concentration was found. Presumably, phytoplankton abundance is reduced by very low water temperatures. The observed late-spring upwellings occurred in the period typical of the rapid growth of *Peridiniella catenata* (Wasmund et al. 2000, Gromisz & Witek 2001). This species requires a somewhat higher water temperature than diatoms, which appear earlier in the growing season. The higher Chl a concentration in the reference area could be explained by the large-scale occurrence of *P. catenata* (Gromisz & Szymelfenig, in press). In autumn, on the other hand, the higher Chl a concentration in the upwelling plume could have been influenced by the appearance of the typically autumnal phytoplankton community as early as mid-September (Gromisz & Szymelfenig, in press). Dominated by *Coscinodiscus granii*, this community is characteristic of the Gdańsk Basin in October and November (Gromisz & Witek 2001). The higher autumn Chl a concentration in the cool upwelling waters than in the reference area is probably the consequence of an earlier diatom bloom. Picked up on satellite images in spring and autumn, Chl a concentrations in the upwelling waters and their surroundings could be linked with the occurrence of characteristic phytoplankton communities.

In the Baltic Sea upwelling takes 6–24 hours to evolve given a suitable wind direction (Bychkova & Viktorov 1987). However, when the wind direction changes, downwelling can follow upwelling quite quickly (Kowalewski 1998). As a consequence, the previously upwelled waters return to greater depths. Satellite-derived Chl a concentrations may therefore be subject to rapid changes.

Upwelling periods recorded in the Baltic Sea have ranged from 12 hours to 30 days (Bychkova et al. 1988, Urbański 1995). The upwelling plume, in which changes in the Chl a concentration could occur, may persist for at least the same time. Such few satellite measurements of Chl a concentration as have been carried out in the southern Baltic lead to conflicting conclusions. According to Semovski et al. (1999), primary production is decreased by the Hel upwelling. On the other hand, the fertile Vistula waters flowing into the Gulf of Gdańsk elicit the opposite effect. These authors suggest that a decrease in Chl a concentration is brought about by the cool nutrient-poor upwelled waters. However, such a hypothesis seems doubtful in the light of the investigations by Burska & Szymelfenig (in press), who found higher concentrations of nutrients at the upwelling centre and in the upwelling plume than in the surrounding waters. The investigations of Semovski et al. (1999) took place in late spring (April, May), so their results are in agreement with the spring scenario observed in the present work. On the other hand, Siegel et al. (1999) concluded that in early spring (at the beginning of April) the upwelled nutrient-rich bottom waters in nutrients, contributes substantially to the increase in Chl a concentrations along the western Polish coast. They also assumed that a low nutrient concentration in upwelled waters along the Polish coast in summer could be evidenced by a marked reduction in Chl a concentration even in the Pomeranian Bay (Siegel et al. 1999).

As in the Baltic Sea (Bychkova et al. 1988, Kowalewski 1998), there is a marked differentiation in the evolution and duration of upwelling in waters much deeper than those along the Baltic coast, e.g. over continental shelves (Thomas et al. 2004). The differences concern not only the shape and area of the upwelling event but also the Chl a concentration. A characteristic feature of many upwelling events recorded on satellite images is the formation of tongues transporting organic matter produced over continental shelves for long distances – tens or even hundreds of kilometres (Brink & Cowles 1991, Gabric et al. 1993, Kostianoy & Zatsepin 1996, Barton et al. 1998, Álvarez-Salgado et al. 2001). The area of contact of oceanic waters with upwellings is markedly greater, because the tongues penetrate oceanic waters. Such a situation has also been observed in the Hel upwelling region (Krężel et al. 2005, this volume). Tongue formation tends to extend the areas of higher Chl *a* concentrations in oligotrophic oceanic waters (Davenport et al. 1999, Smyth et al. 2001). In the fertile waters of the southern Baltic, this effect is more complex. According to the autumn scenario, an increase in Chl *a* concentration is to be expected, but during the spring upwelling the area of lower Chl *a* concentration will increase because of tongue formation.

In spite of the many difficulties involved in the correct interpretation of satellite images, especially in the Baltic Sea (Darecki & Stramski 2004) as these are case 2 waters (Morel & Prieur 1977), the method does permit the rapid registration of the details of field shape and area as well as Chl *a* concentration (Joint & Groom 2000). Therefore, in the regions of powerful water dynamics like upwelling areas, estimating Chl *a* concentration from satellite images is a very useful and important tool in primary production studies (Acha et al. 2004, Thomas et al. 2004).

5. Conclusions

The following applies to upwelling plumes along the Polish coast of the Baltic Sea in the warmer part of the year:

1. The Chl *a* concentration increases, except in the waters along the Hel Peninsula.
2. Along the Hel Peninsula two scenarios were observed: Chl *a* levels fell in spring but rose in autumn.
3. According to *in situ* data, each upwelling event is characterised by the occurrence of a core with a minimum concentration of Chl *a*. In spring the area of this core is so vast that it is readily identified on satellite images. In autumn, however, the core area is small and so does not cause a general rise in the Chl *a* level in the upwelling plume.

References

Acha E. M., Mianzan H. W., Guerrero R. A., Favero M., Bava J., 2004, *Marine fronts at the continental shelves of austral South America: physical and ecological processes*, J. Marine Syst., 44 (1)–(2), 83–105.

Álvarez-Salgado X. A., Doval M. D., Borges A. V., Joint I., Frankignoulle M., Woodward E. M. S., Figueiras F. G., 2001, *Off-shelf fluxes of labile materials by an upwelling filament in the NW Iberian Upwelling System*, Prog. Oceanogr., 51 (2)–(4), 321–337.

Barton E. D., Arístegui J., Tett P., Cantón M., García-Braun J., Hernández-León S., Nykjær L., Almeida C., Almunia J., Ballesteros S., Basterretxea G., Escánez J., García-Weill L., Hernández-Guerra A., López-Laatzen F., Molina R., Montero M. F., Navarro-Pérez E., Rodríguez J. M., van Lenning K., Vélez H., Wild K., 1998, *The transition zone of the Canary Current upwelling region*, Prog. Oceanogr., 41 (4), 455–504.

Brink K. H., Cowles T. J., 1991, *The coastal transition zone program*, J. Geophys. Res., 96 (C8), 14637–14647.

Burska D., Szymelfenig M., *The upwelling of nutrients in the coastal area of the Hel Peninsula (the Baltic Sea)*, Oceanol. Hydrobiol. Stud., Suppl., (in press).

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

Bychkova I. A., Viktorov S. V., Shumakher D. A., 1988, *A relationship between the large-scale atmospheric circulation and the origin of coastal upwelling in the Baltic Sea*, Meteorol. Gidrol., 10, 91–98, (in Russian).

Darecki M., Kaczmarek S., Olszewski J., 2005, *SeaWiFS ocean colour chlorophyll algorithms for the southern Baltic Sea*, Int. J. Remote Sens., 26 (2), 247–260.

Darecki M., Stramski D., 2004, *An evaluation of MODIS and SeaWiFS bio-optical algorithms in the Baltic Sea*, Remote Sens. Environ., 89 (3), 326–350.

Davenport R., Neuer S., Helmke P., Perez-Marrero J., Llinas O., 2002, *Primary productivity in the northern Canary Islands region as inferred from SeaWiFS imagery*, Deep-Sea Res. Pt. II, 49 (17), 3481–3496.

Davenport R., Neuer S., Hernández-Guerra A., Rueda M. J., Llinas O., Fischer G., Wefer G., 1999, *Seasonal and inter annual pigment concentration in the Canary Islands region from CZCS data and comparison with observations from the ESTOC*, Int. J. Remote Sens., 20 (7), 1419–1433.

Dugdale R. C., Wilkerson F. P., 1989, *New production in the upwelling center at Point Conception, California: temporal and spatial patterns*, Deep-Sea Res., 36 (7), 985–1007.

Gabric A. J., Garcia L., Van Camp L., Nykjær L., Eifler W., Schrimpf W., 1993, *Offshore export of shelf production in the Cap Blanc (Mauritania) giant filament as derived from coastal zone color scanner imagery*, J. Geophys. Res., 98 (C3), 4697–4712.

Gordon H. R., Wang M., 1994, *Retrieval of water-leaving radiance and aerosol optical thickness over the oceans with SeaWiFS: a preliminary algorithm*, Appl. Optics, 33 (3), 443–452.

Gromisz S., Szymelfenig M., *Phytoplankton in the Hel upwelling region (the Baltic Sea)*, Oceanol. Hydrobiol. Stud., Suppl., (in press).

Gromisz S., Witek Z., 2001, *Main phytoplankton assemblages in the Gulf of Gdańsk and the Pomeranian Bay from 1994 to 1997*, Bull. Sea Fish. Inst., 2 (153), 31–51.

Joint I., Groom S. B., 2000, *Estimation of phytoplankton production from space: current status and future potential of satellite remote sensing*, J. Exp. Mar. Biol. Ecol., 250 (1), 233–255.

Joint I., Groom S. B., Wollast R., Chou L., Tilstone G. H., Figueiras F. G., Loijens M., Smyth T. J., 2002, *The response of phytoplankton production to periodic upwelling and relaxation events at the Iberian shelf break: estimates by the* ^{14}C *method and by satellite remote sensing*, J. Marine Syst., 32 (1)–(3), 219 –238.

Kostianoy A. G., Zatsepin A. G., 1996, *The West African coastal upwelling filaments and cross-frontal water exchange conditioned by them*, J. Marine Syst., 7 (2)–(4), 349–359.

Kowalewski M., 1998, *Coastal upwellings in a shallow stratified sea on the example of the Baltic Sea*, Ph. D. thesis, Institute of Oceanography, Univ. Gd., Gdynia, 83 pp., (in Polish).

Krężel A., 1985, *Solar radiation at the Baltic Sea surface*, Oceanologia, 21, 5–32.

Krężel A., 1997, *Recognition of mesoscale hydrophysical anomalies in a shallow sea using broadband satellite remote sensing methods*, Diss. and monogr., Univ. Gd., Gdynia, 173 pp., (in Polish).

Krężel A., Ostrowski M., Szymelfenig M., 2005, *Sea surface temperature distribution during upwelling along the Polish Baltic coast*, Oceanologia, 47 (4), 415–432.

MacIsaac J. J., Dugdale R. C., Barber R. T., Blasco D., Packard T. T., 1985, *Primary production cycle in upwelling center*, Deep-Sea Res., 32 (5), 503–529.

Matciak M., Burska D., Bradtke K., Kaluźny M., Szymanek L., Szymelfenig M., *Description of hydrological conditions in the Hel upwelling region (the Baltic Sea)*, Oceanol. Hydrobiol. Stud., Suppl., (in press).

Matciak M., Krężel A., 1991, *Green light penetration depth in Puck Bay*, Oceanologia, 31, 153–157.

Morel A., Prieur L., 1977, *Analysis of variations in ocean colour*, Limnol. Oceanogr., 22 (4), 709–722.

Ocean Colour European Archive Network, 1996, [http://marine.jrc.cec.eu.int/ index.php?module=pagemaster&PAGE_user_op=view_page&PAGE_id=19& MMN_position=25:22].

O'Reilly J. E., Maritorena S., Mitchell B. G., Siegel D. A., Carder K. L., Garver S. A., Kahru S. A., McClain C., 1998, *Ocean colour chlorophyll algorithms for SeaWiFS*, J. Geophys. Res., 103 (C11), 24937–24953.

Ruddick K. G., Gons H. J., Rijkeboer M., Tilstone G., 2001, *Optical remote sensing of chlorophyll a in case 2 waters by use of an adaptive two-band algorithm with optimal error properties*, Appl. Optics, 40 (21), 3575–3585.

Ruddick K. G., Ovidio F., Rijkeboer M., 2000, *Atmospheric correction of SeaWiFS imagery for turbid coastal and inland waters*, Appl. Optics, 39 (6), 897–912.

Sathyendranath S. (ed.), 2000, *Remote sensing of ocean colour in coastal, and other optically-complex, waters*, IOCCG Rep. No 3, 145 pp.

Sathyendranath S., Platt T., 1997, *Analytic model of ocean colour*, Appl. Optics, 36 (12), 2620–2629.

Semovski S. V., Dowell M. D., Hapter R., Szczucka J., Beszczyńska-Möller A., Darecki M., 1999, *The integration of remotely sensed, sea-truth and modelled data in the investigation of mesoscale features in the Baltic coastal phytoplankton field*, Int. J. Remote Sens., 20 (7), 1265–1287.

Shillington F. A., Peterson W. T., Hutchings L., Probyn T. A., Waldron H. N., Agenbag J. J., 1990, *A cool upwelling filament off Namibia, southwest Africa: preliminary measurements of physical and biological features*, Deep-Sea Res., 37 (11), 1753–1772.

Siegel H., Gerth M., Tiesel R., Tschersich G., 1999, *Seasonal and interannual variations in satellite derived sea surface temperature of the Baltic Sea in the 1990's*, Dt. Hydrogr. Z., 51 (4), 407–422.

Siegel H., Seifert T., 1985, *On the influence of the sea bottom on the spectral reflectance in the region of the Oder Bank (Southern Baltic Sea)*, Beitr. Meeresk., 52, 65–71.

Smyth T. J., Miller P. I., Groom S. B., Lavender S. J., 2001, *Remote sensing of sea surface temperature and chlorophyll during Lagrangian experiments at the Iberian margin*, Prog. Oceanogr., 51 (2)–(4), 269–281.

Solanki H. U., Dwivedi R. M., Nayak S. R., 2001, *Synergistic analysis of SeaWiFS chlorophyll concentration and NOAA-AVHRR SST features for exploring marine living resources*, Int. J. Remote Sens., 22 (18), 3877–3882.

Thomas A. C., Strub P. T., Carr M. E., Weatherbee R., 2004, *Comparisons of chlorophyll variability between the four major global eastern boundary currents*, Int. J. Remote Sens., 25 (7)–(8), 1443–1447.

Urbański J. A., 1995, *Upwellings of the Polish coast of the Baltic Sea*, Prz. Geofiz., 40 (2), 141–153, (in Polish).

Wasmund N., Nausch G., Postel L., Witek Z., Zalewski M., Gromisz S., Łysiak-Pastuszak E., Olenina I., Kavolyte R., Jasinskaite A., Müller-Karulis B., Ikauniece A., Andrushaitis A., Ojaveer H., Kallaste K., Jaanus A., 2000, *Trophic status of costal and open areas of the south-eastern Baltic Sea based on nutrient and phytoplankton data from 1993–1997*, Meereswiss. Ber., 38, 83 pp.

Zalewski M., Ameryk A., Szymelfenig M., *Primary production and chlorophyll a concentration during upwelling events along the Hel Peninsula (the Baltic Sea)*, Oceanol. Hydrobiol. Stud., Suppl., (in press).