Papers

A study of episodic events in the Baltic Sea – combined in situ and satellite observations*

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Abstract

A project was developed concerning the operational system of surveillance and the recording of episodic events in the Baltic Sea. In situ information was to be combined with multi-sensory satellite imagery to determine the extent of algal blooms, to track their evolution and that of rapid environmental events like hydrological fronts. The main element of the system was an autonomous Ferry Box module on a ferry operating between Gdynia and Karlskrona, automatically measuring temperature, salinity and chlorophyll *a* fluorescence. At pre-selected locations, discrete water samples were collected, which were subsequently analysed for their phytoplankton content, and algal hepato- and neurotoxins; they were also used in toxicity tests with *Artemia franciscana*.

1. Introduction

For a number of decades, ships-of-opportunity such as ferries have been used to collect hydrographic data in coastal and oceanic waters. In Norway the collection of salinity and temperature data on a ferry running along the coast started as early as the 1930s. In the Baltic Sea a joint project of the Finnish Institute for Marine Research and the Estonian Marine Institute, the Alg@line, initiated regular ferry-based observations on the distribution of algal blooms and nutrient concentrations in the early 1990s (Kahru & Leppänen 1991, Rantajärvi 2003), and between 2002 and 2005 a large EU Ferry Box project, including 11 partners operating on 9 shipping routes around Europe was conducted (http://www.ferrybox.org/eu_project_ferrybox/). At present, the ship-of-opportunity system is being implemented world-wide as a coastal module of the Global Ocean Observing System (GOOS 2005, Petersen et al. 2006). Increased interest in such unmanned systems led to the development of another component of the Europe-wide network of Ferry Box routes – the line between Gdynia (Poland) and Karlskrona (Sweden) was established at the end of 2007.

Ferry Box systems improve observational capacities as they provide detailed, regular and unique data with a high temporal and spatial resolution, which cannot be obtained on traditional oceanographic expeditions or even on regular monitoring cruises. Obtained in a very cost-effective way, the vast amount of data supplied by Ferry Box systems can be used for validating and calibrating models; they can also be related to observations provided by satellites or aircraft (remote sensing) to reveal the spatial scales of various phenomena, thereby enabling the better resolution and understanding of marine processes (Pulliainen et al. 2003, Ponsar et al. 2006).

In the Baltic Sea, seriously affected by eutrophication (HELCOM 2009), some locations suffer from frequent cyanobacterial blooms of potentially toxic species (Wasmund 2002, Wasmund & Uhlig 2003). The cyanobacteria form extensive summer blooms and are potentially toxic towards biota and human beings; they may also have adverse effects on fisheries and the recreational use of coastal areas. In order to discover the factors triggering these blooms and the environmental consequences of the latter, the dynamics of phytoplankton have to be studied with an appropriate spatial and temporal resolution.

This paper presents an outline and preliminary results of a project, developed to set up an operational system of surveillance and registration of episodic events (e.g. harmful algal blooms) in the Baltic Sea by combining in situ measurements from a Ferry Box with satellite information.

2. Material and methods

The project consisted of 3 major modules: Ferry Box, phytoplankton and satellite.

2.1. Ferry Box module

The main element of this module was an autonomous 'Ferry Box'[1] system, installed on a commercial passenger ferry plying daily between Gdynia (Poland) and Karlskrona (Sweden), a distance of ca 315 km across the middle of the Baltic Proper (Figure 1). The system initially operated

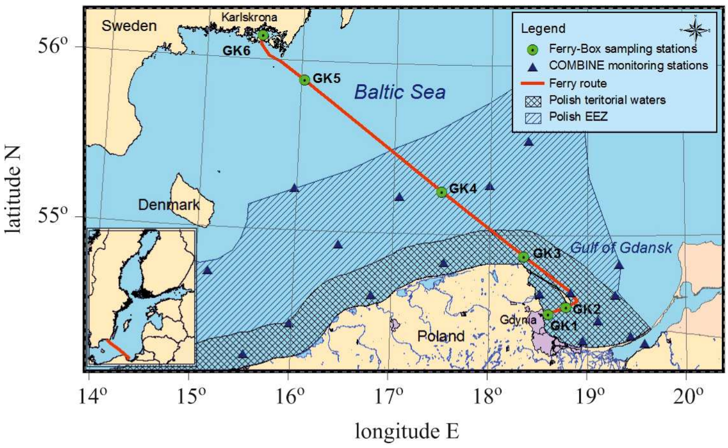

Figure 1. Provisional route of the 'Stena Nordica' passenger ferry between Gdynia and Karlskrona; circles mark sampling locations for discrete Ferry Box samples, triangles – marine monitoring stations

[1]The Institute of Meteorology and Water Management – Maritime Branch in Gdynia was provided with a Ferry Box system by HELCOM within the Baltic Sea Regional Project, a Large Marine Ecosystem project, funded by GEF of the World Bank.

(2006–2008) on board m/f 'Stena Nordica' but was transferred to m/f 'Stena Baltica' in early 2009.

This module provided flow-through measurements of temperature, conductivity [salinity], oxygen (oxygen results are not discussed here) and chlorophyll *a* fluorescence (Table 1). The water intake for flow-through measurements and discrete sample collection was situated at ca 2 m depth.

The Ferry Box sensors have a measurement resolution of 10 s (in that time the ferry travels ca 80–100 m), enabling them to collect a set of nearly 5 million records a year. The data, from automatic measurements by the relevant sensors, were stored in a data logger and transferred to land-based PC systems on a regular basis.

Discrete water samples were collected (WS 316 VAR autosampler; WaterSam, Germany) at 6 pre-selected or on-line triggered time intervals/geographical locations (Figure 1). The discrete water samples supplied material for phytoplankton analysis, as well as chlorophyll *a* and nutrient determination. The discrete water samples were collected during the daytime, usually on the voyage from Karlskrona to Gdynia, which takes < 10 h. The WaterSam autosampler is equipped with a cooler, so the samples could be stored at 4°C until the port of destination, where they were immediately transferred to a land laboratory for further processing. Discrete water samples were collected fortnightly on average, although the time interval varied depending on the environmental situation. The analytical methods conformed to the HELCOM COMBINE monitoring programme (HELCOM 1997).

2.2. Phytoplankton module

Within this module, phytoplankton structure, abundance and biomass analyses were conducted on discrete samples; algal toxins were determined and the toxicity of water was assayed on test animals.

Phytoplankton taxa, abundance and biomass were determined according to the HELCOM guidelines (HELCOM 1997).

A standard procedure of hepatotoxin analysis was applied with regard to algal toxins (Meriluoto & Codd 2005). Environmental samples were passed through GF/C Whatman filters. The material retained on the filters was treated with 90% methanol, homogenized in an ultrasonic bath for 15 min and then treated for 1 min with an ultrasonic disruptor equipped with a microtip probe. The aliquots were centrifuged for 10 min ($10000 \times g$). High performance liquid chromatography (HPLC, Waters, Milford, MA, USA) with a diode array detector (isocratic conditions; a single analysis took 10 min) was used to measure the nodularin concentration. The structure of the nodularin present in the cyanobacterial bloom material was confirmed

Table 1. Characteristics of the Ferry Box sensors for automated measurements of temperature, salinity, oxygen and chlorophyll *a*

Sensor	Manufacturer	Measuring range	Accuracy	Frequency	Resolution
conductivity	GO-Systemelektronik, GmbH, Germany	0–2000 μS	≤1% FS	≥1 s	1 μS cm^{-1}
temperature	GO-Systemelektronik, GmbH, Germany	0–80°C	≤1% FS	≥1 s	0.001°C
oxygen	GO-Systemelektronik, GmbH, Germany	0–200%; 0–20 mg L^{-3}	≤1% FS	≥1 s	0.001 mg L^{-3}
fluorescence	fluorometer SCUFA designs, USA	dynamic range – fluorescence: 4 orders of magnitude; dynamic range – turbidity: 3 orders of magnitude	chlorophyll*: 0.02 mg L^{-1} cyanobacteria* 150 cells mL^{-1}; turbidity*: 0.05 NTU		12 bit

*Detection limit of chlorophyll/cyanobacteria fluorescence.

using LC-MS/MS. The analytical system consisted of a QTRAP5500 MS/MS with a turbo-ion spray (Applied Biosystems MDS Sciex, Concord, ON, Canada) and an Agilent 1200 HPLC (Agilent Technologies, Waldbronn, Germany). Separation was performed on a Zorbax Eclipse XDB-C18 (4.6×150 mm; 5 μm) (Agilent, USA) at 35°C. Gradient elution was with a mixture of mobile phase A (5% acetonitrile containing 0.1% formic acid) and B (100% acetonitrile containing 0.1% formic acid). Mass spectra were acquired over a range of 50–1100 Da with a scan time of 1.0 s. The QTRAP instrument was operated in positive ion mode. Structures were elucidated using collision-induced dissociation (CID) with a collision energy ranging from 50 eV to 60 eV. Data were acquired and processed using Analyst QS 1.5.1 software.

The ecotoxicity of discrete water samples was determined using an Artoxkit M^{TM} (Artoxkit M 1990) test with the crustacean *Artemia franciscana* Leach (1918) as the test organism. The tests were done on *A. franciscana* in developmental stages II–III in multiwell test plates. The larvae, immersed in tested seawater, were incubated for 24 h in darkness. After this period dead organisms were counted in each test well. The animals were assumed dead if neither internal nor external movement was noticed during 10 s of observation. The mortality rate of the control group of test organisms should not exceed 10%.

2.3. Satellite module

The satellite module was included in the project to give spatial extension to the Ferry Box measurements. This module comprised the retrieval of data relating to chlorophyll *a* and surface seawater temperature (SST) from satellite images. Additionally, an in situ Ferry Box data was used for the validation of the MODIS data products.

Ocean colour satellite imagery of the Baltic Sea from MODIS Aqua scanner was acquired from the Goddard Space Flight Center, Distributed Active Archive Center, NASA. Raw satellite data from the MODIS Aqua instrument were processed with locally adapted atmospheric correction, which took into account the specific bio-optical conditions of water in the Baltic Sea. The radiometric calibrated and geo-located, 1 km spatial resolution satellite data (Level 1A data) were processed with the use of the SeaDAS software version 6.1 with implemented improved standard atmospheric correction (Stumpf et al. 2003, Mather 2004). This atmospheric correction procedure was recently evaluated and found to best suit turbid coastal waters, including the specific bio-optical conditions of water in the Baltic Sea (Jamet et al. 2011). After atmospheric correction the water-leaving radiance was utilized to retrieve the spatial distribution of the chlorophyll *a* concentration in subsurface layers. Retrieval was based mostly on the application of regional algorithms (Darecki & Stramski 2004, Darecki et al. 2005). However, for comparison, the standard chlorophyll *a* algorithm OC4 (O'Reilly et al. 2000) was also applied and this additional product was mapped.

The calculation of sea surface temperature (SST) maps from raw AVHRR data involved a number of processing stages. The initial stage related to the recording and archiving of the raw data received by the HRPT[2] receiving station at the Institute of Oceanography, University of Gdańsk, and the preliminary processing of selected scenes consisting of instrumental and geometrical correction with subsequent geographical registration and calculation of brightness temperature (NOAA 2003, Kowalewski & Krężel 2004). The subsequent evaluation of the real temperature of the sea surface was done using the nonlinear split-window algorithm NLSST (Woźniak et al. 2008). In the next stage, areas covered by clouds were masked using the information from IR and VIS spectral channels (Krężel & Paszkuta 2011). To limit errors resulting from the insufficient masking of hot-spots and thin clouds, thermal structures were analysed on the basis of SST maps plotted by applying the mosaic technique to scenes recorded on the same day by three satellites. The extents of fresh water plumes or upwelling extents were determined by the positions of thermal fronts. These fronts were mapped by spatial domain filtration (3×3 window size) and calculating the gradient towards the local maximum of SST change, after previous median filtering to eliminate noise (Cayula & Cornillon 1992, Belkin & O'Reilly 2009). The frontal zone was assumed to be an elongated, at least 5 km long, group of pixels with gradients over 0.2°C km^{-1}.

3. Results

3.1. Ferry Box module

The project commenced in 2008 and preliminary samples were collected from July to October. During this initial stage of the Ferry Box measurements a number of technical problems were encountered, one of the most annoying being severe fouling of the sensors by young forms of *Mytilus trossulus* and by *Balanus* spp.; malfunctioning of the WaterSam autosampler was also a common occurrence. The automatic measurements of temperature, salinity and chlorophyll *a* showed a variability of environmental factors over the period from 11 July to 9 October 2008 (Figure 2).

[2]High Resolution Picture Transmission

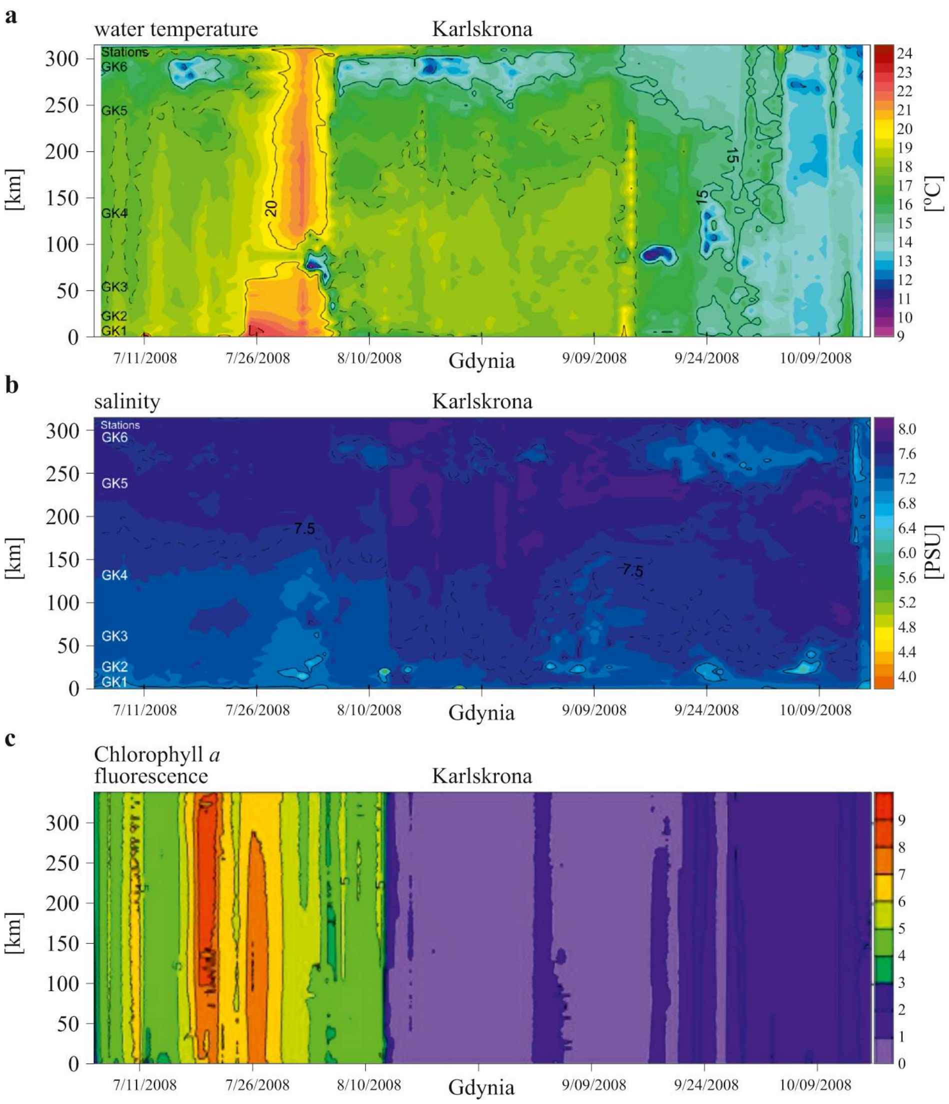

Figure 2. Variability of environmental parameters measured by Ferry Box between Gdynia and Karlskrona in 2008: seawater temperature (a), salinity (b), chlorophyll *a* (c)

Dissolved inorganic phosphate (DIP), oxygenated inorganic nitrogen (TO $\times$ N $= NO_3 + NO_2$), silicate, total phosphorus (TP) and total nitrogen (TN) were analysed in discrete seawater samples (TP and TN are not discussed here). Ammonia was not determined because the samples could not be treated with reagents immediately after sampling. Nutrient concentrations determined in discrete seawater samples depended on the station location and sampling date. Results from the off-shore station (GK4) are shown in Figure 3 to illustrate the observed fine changes in nutrient levels.

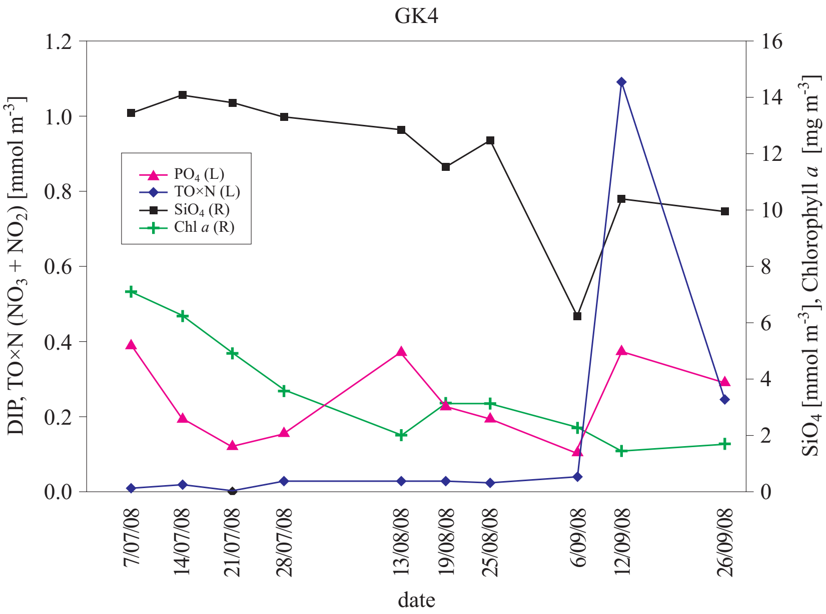

Figure 3. Changes in nutrient and chlorophyll *a* concentrations recorded at discrete station GK4 in 2008

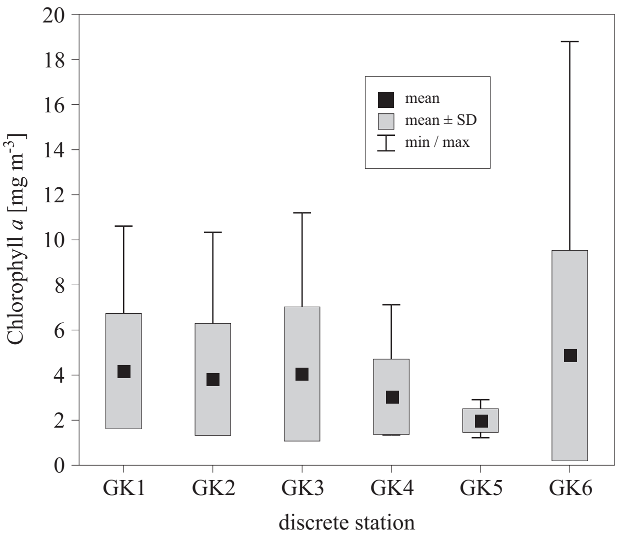

Figure 4. Variability in chlorophyll *a* concentrations at discrete sampling stations along the Gdynia-Karlskrona transect in 2008

From 7 July to 10 October 2008, chlorophyll *a* was measured in samples from discrete sampling stations on 11 occasions. The results showed considerable variability in chlorophyll *a* concentrations, depending on the location of the sampling station and sampling date (Figure 4).

3.2. Phytoplankton module

Phytoplankton species structure, abundance and biomass were determined in discrete samples on 3 occasions, between 7 and 28 July 2008 (Figure 5). The species structure showed considerable diversity (Figure 5). Flagellates were dominant in terms of both biomass and abundance, although there was also a marked presence of *Dinophyceae* in the biomass. The contributions of *Cyanophyceae* and *Bacillariophyceae* to the biomass were considerable in the off-shore part of the ferry route.

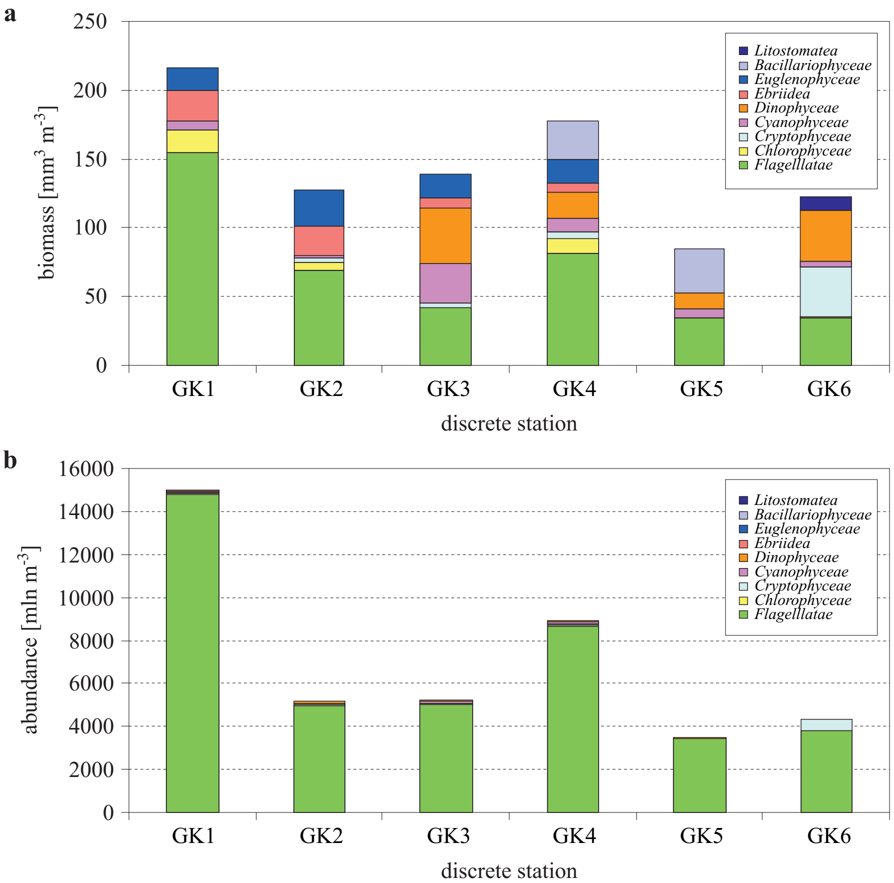

Figure 5. Biomass (a) and abundance (b) of the main phytoplankton groups in discrete samples collected on 28 July 2008

In fact, the biomass of the latter class consisted of a single diatom species – *Actinocyclus octonarius*. As for blue-green algae, the potentially toxic species *Nodularia spumigena*, accompanied by *Aphanizomenon flos-aquae*, were dominant among the *Cyanophyceae* in general (Figure 6), and *Aphanothece paralleliformis* was found to be dominant at a single station.

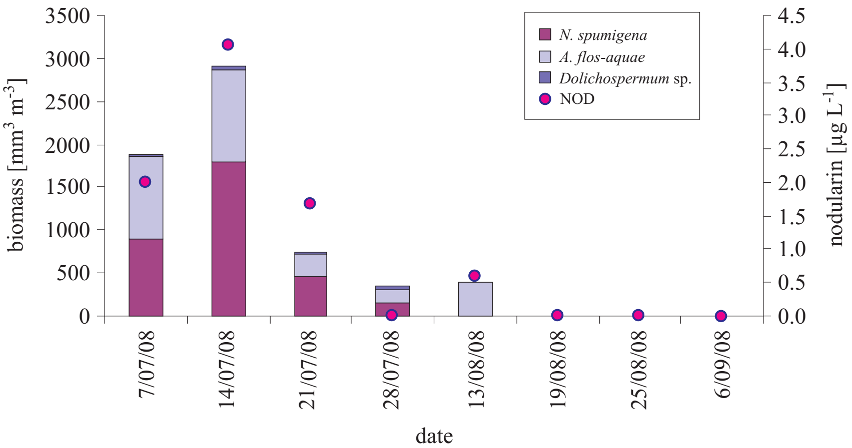

Figure 6. Biomass of diazotrophic cyanobacteria species dominating in phytoplankton versus hepatotoxin content at station GK1 in 2008

The presence of nodularin was detected in discrete samples collected between 7 July and 13 August. The amounts of toxin varied temporally and spatially. The coastal area of the Gulf of Gdańsk (station GK1) was characterized by the greatest accumulations of the toxin throughout the measurement period, with the highest mean (2.08 μg dm^{-3}) and variability

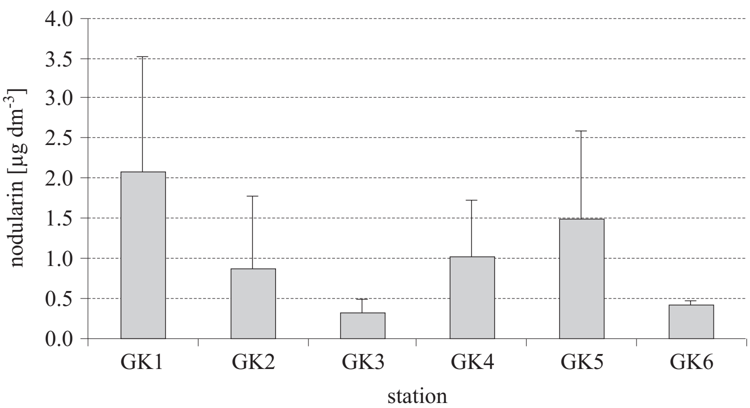

Figure 7. Mean concentrations and spreading of nodularin at discrete stations in 2008

(SD = 1.44 2.08 μg dm^{-3}) (Figure 7). The lowest concentrations were measured at station GK3, close to the tip of the Hel Peninsula (0.33 μg dm^{-3} on average), and at GK6 off the Swedish shore (0.41 μg dm^{-3} on average). The maximum concentrations of nodularin, 4.04 and 2.28 μg dm^{-3}, were recorded on 14 July at stations GK1 and GK5 respectively. Thereafter, nodularin concentrations decreased gradually and from 13 August onwards, they were below the HPLC detection limit (Figure 6).

According to the classification by Persoone et al. (2003), none of the discrete samples showed acute toxicity to *Artemia franciscana* in the toxicity tests.

3.3. Satellite module

The satellite module comprised the mapping of chlorophyll *a* and surface seawater temperature (SST). However, it was not possible to obtain high-quality images with respect to chlorophyll *a* between 16 July and 2 August 2008, but the satellite-retrieved chlorophyll *a* concentration data from 3 August (Figure 8) corresponds well with the chlorophyll *a* concentrations registered by the Ferry Box fluorometer (Figure 2c), showing the greatest concentration close to Swedish shores.

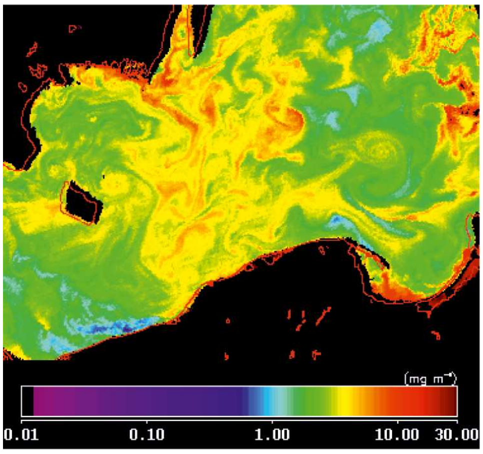

Figure 8. Satellite-retrieved chlorophyll *a* concentrations on 3 August 2008

Sea surface temperature derived from AVHRR data under clear skies were compared to values recorded by the automatic Ferry Box measurements. A strong correlation between in situ temperatures and satellite-derived values was found (Figure 9). The observed differences seem to be caused by discrepancies in time, depth and the spatial scale of the measurements. The standard error of the in situ water temperature estimates based on satellite data was 0.4°C.

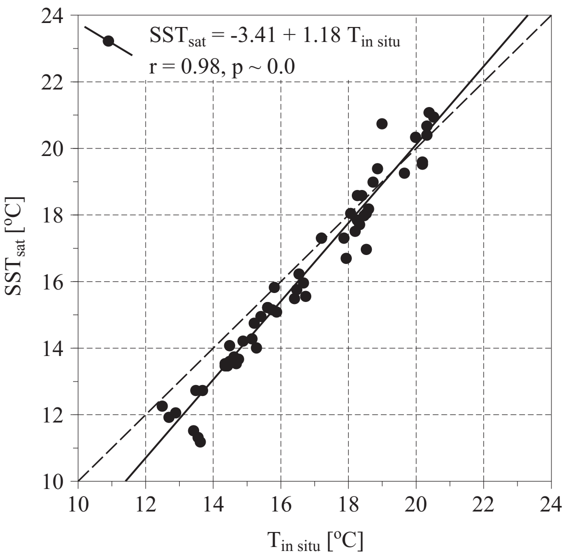

Figure 9. Linear correlation between seawater temperature measured by the Ferry Box at sampling stations GK1-6 and satellite derived values (data from 2008)

Satellite-derived SST data provided evidence of different thermal structures, like coastal upwelling events or river plumes (Figure 10).

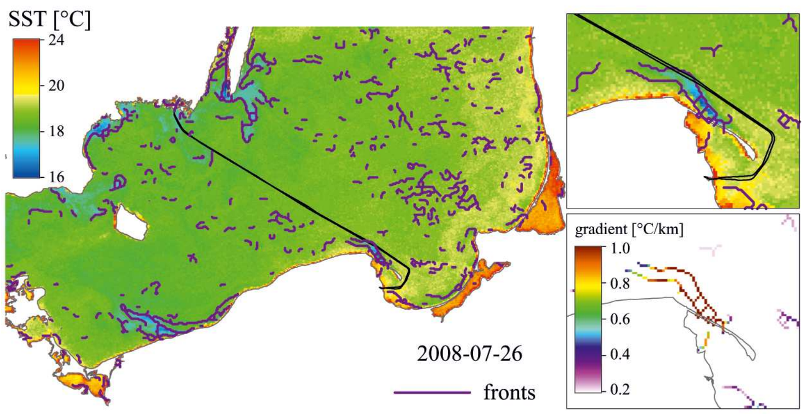

Figure 10. Surface sea water temperature and fronts derived from satellite data, 26 July 2008. The enlarged area near the Hel Peninsula shows SST gradients in frontal zones

4. Discussion

Ferry Box data from automatic measurements showed the warmest period, where seawater temperature is concerned, to be around 21–26 July and 7–8 August 2008 (Figure 2a). Salinity measurements showed rather weak variability throughout the measurement period (Figure 2b), and a conspicuous patch of colder and more saline water appearing at ca 70–80 km from Gdynia, off Cape Rozewie, indicated an upwelling event, also revealed by satellite imagery (Figure 10). A similar band of cold water appeared close to the Karlskrona shore for a much longer period, between 10 August and the beginning of September (Figure 2a) and reflected the general change in weather conditions at this time of the year in 2008 (Międtus et al. 2011). The spatial distribution of thermal structures on satellite-derived SST maps demonstrates well the considerable variability of the optical properties of water in this region (e.g. Figure 2), where relatively transparent waters upwelled from deeper layers met turbid waters advected from the Gulf of Gdańsk. Because of the complicated circulation system, the variability of optical properties along the ferry route transect could be difficult to explain without the spatial view. Analysis of the location of the frontal zone, its extent and strength between different water masses made it possible to interpret the rapid changes observed along the ferry route in the values obtained from the Ferry Box system (Figures 2b and 10).

Nutrient concentrations measured in discrete water samples showed levels typical of the season (Miętus et al. 2011). Oxygenated inorganic nitrogen (TO $\times$ N) values were very close to analytical zero (LOD_{NO_3} = 0.01 mmol m^{-3}, LOD_{NO_2} = 0.01 mmol m^{-3}) and the sum of inorganic nitrogen consisted mainly of nitrite, indicating the ongoing mineralization of organic matter. The fine changes observed at discrete stations (Figure 3) should be related to phytoplankton consumption and regeneration. Minimal phosphate and inorganic nitrogen concentrations coincided with good thermal conditions (Figure 2a).

The highest chlorophyll *a* concentrations, in excess of 10.0 mg m^{-3}, were measured at the stations closest to the coast: GK1 (7 July) and GK3 (21 July) in the Gulf of Gdańsk, and GK6 (10 October) in the vicinity of Karlskrona. During the study period, the variability in chlorophyll *a* concentrations was considerable as the coefficient of variation (%RSD) fell between 50 and 71%, with the exception of station GK5 (within the Swedish economic zone), where the RSD was only 25%. The Bartlett test (Doerffel 1989), conducted at confidence level p = 0.05 and f = 5 degrees of freedom, indicated that some areas represented by the discrete stations were more productive ($\chi^2 = 55.12 >> \chi^{*2} = 1.15$), and Students t-test for independent samples showed the area of station GK5, where the lowest chlorophyll *a* concentrations were measured, to be significantly ($t = 2.872$) different from the remaining stations. This observation conformed well to the data from the automatic measurements of temperature (Figure 2a) and satellite derived SST (Figure 10) – this specific sea area has a lower surface temperature for most of the year. However, a period of elevated temperature between 28 July and 13 August (Figure 2a) coincided well with the maximum chlorophyll *a* concentrations (2.5 mg m^{-3} and 2.4 mg m^{-3} respectively) specific to this area, measured in discrete samples and the corresponding satellite images (Figure 8).

The highest phytoplankton biomass (expressed as a biovolume), of the order of 242.2–522.3 mm^3 m^{-3}, was recorded on 21 July, corresponding to the warmest period in seawater temperature. A slightly different temporal and spatial pattern of phytoplankton biomass (max. on 21 July) and chlorophyll *a* development (max. on 7 July) was observed. This discrepancy could be related to differences in species structure and was also noticed in monitoring data (Vaiciute & Olenina 2009, Kraśniewski et al. 2011). A higher proportion of *Bacillariophyceae*, and especially *Chlorophyceae*, in the total phytoplankton biomass was found to be responsible for the higher chlorophyll *a* concentrations.

The project was conducted in a period (2008–2010) when blue-green algae blooms were not as pronounced as in earlier years (SMHI 2008); as a matter of fact, the ferry route crossed the Baltic Proper in a region not so subject to intensive blooms. Nevertheless, the discrete samples analysed between 7 and 28 July 2008 showed abundant *Cyanophyceae*. Their biomass varied from 660.0 mm^3 m^{-3} (max.) at station GK6 on 14 July to 99.33 mm^3 m^{-3} (min.) at station GK3 on 21 July, i.e. respective contributions to the total phytoplankton biomass of 83.0% and 41.0%. The toxic *Nodularia spumigena* was found in the majority of discrete samples from this period. The largest proportions of *N. spumigena*, 84.4% in the *Cyanophyceae* biomass and 66.7% in the total phytoplankton biomass, was recorded at station GK4 on 14 July. A high biomass of *N. spumigena* (18.0 mm^3 m^{-3}; 61.6% of the *Cyanophyceae* and 35.5% of the total biomass) was recorded at station GK1 on 14 July, when the maximum concentration of nodularin was also recorded (Figure 6).

The data on the proportion of cyanobacteria in the total summer phytoplankton biomass tally with the observations of increasing trends in the proportion of cyanobacteria in the Baltic phytoplankton (Wasmund & Uhlig 2003, Olli et al. 2011).

The ecological consequences of plankton blooms and their most harmful effects are linked to the occurrence of a high biomass of heterocystous species, which supply an additional load of nitrogen to the Baltic Sea ecosystem. *N. spumigena* is a cyanobacterium that forms vast blooms in the Baltic Sea during the summer (Kahru et al. 1994, Wrzołek 1996, Wasmund 1997, Finni et al. 2001). This phenomenon is both important and dangerous, as *N. spumigena* is capable of producing a potent toxin – nodularin (NOD) (Reinhart et al. 1988). A non-ribosomal cyclic pentapeptide of unusual structure, nodularin alters the liver's structure and function by inhibiting the activity of eukaryotic protein phosphatases (PP1 and PP2A) (Carmichael 1992). Incidents of poisoning involving domestic animals, cattle and birds are well documented (Edler et al. 1985, Sivonen & Jones 1999).

The concentrations of nodularin measured in discrete samples in 2008 (Figures 6 and 7) were comparable to those recorded in the Gulf of Gdańsk and the Baltic Sea in recent years; e.g. during the *N. spumigena* bloom in summer 2007, Kankaanpää et al. (2009) reported a NOD concentration of 2.45 μg dm^{-3}. The average NOD concentration in the Baltic Sea, determined by Mazur-Marzec et al. (2006), did not usually exceed 1 μg dm^{-3}. However, in coastal waters, including bathing areas, the concentration of the toxin can temporarily exceed 20 000 μg dm^{-3} (Mazur-Marzec et al. 2006).

The results, and also previously published data, indicate that the Baltic Sea, and especially its coastal waters, have to be considered as potentially endangered by cyanobacterial blooms. The highest NOD concentrations recorded were close to the provisional guideline level for recreational waters (2–4 μg dm^{-3}; first alert level) (Falconer et al. 1999). Such situations may pose a serious health threat to humans, and an effective early warning system should therefore be developed. Also, economic losses incurred as a result of the diminished recreational value of affected bathing sites as well as the poorer quality and smaller quantity of fish catches should be treated as important negative consequences of cyanobacterial blooms.

The seawater samples containing nodularin proved to be non-toxic to the test crustacean *Artemia franciscana*; nevertheless, the toxin released into the surrounding water during the lysis of cyanobacterial cells can persist in the aquatic environment for quite some time after the bloom, as it is a relatively stable chemical compound (Mazur-Marzec & Pliński 2009). The metabolites can take part in allelopathic interactions affecting the structure and dynamics of the phytoplankton community (Suikanen et al. 2004) and, via filter-feeding mussels, they can be passed on to vertebrates, which are thought to be more sensitive to the toxin.

With regard to SST, the overestimation and underestimation of temperature from satellite data in individual cases resulted, respectively, from the insufficient masking of hot-spots and thin clouds. However, the underestimation of Ferry Box temperature by satellite data seems to be due not only to the insufficient masking of clouds, as the statistical error is higher by more than 1°C in comparison to that calculated on the basis of BOOS data. The differences between satellite and in situ data indicated that the temperature measured by the Ferry Box was usually about 1.0°C higher than that derived from AVHRR data. Analysis of the location of frontal zones, their extent and strength between different water masses made it possible to interpret the rapid changes in the Ferry Box values along the ferry route.

Ultimately, the project envisages that the current satellite information, analysed by in situ Ferry Box-acquired data, will be processed and presented operationally in the form of maps of environmental parameters. This information, accompanied by quantitative information on the presence of toxic phytoplankton species, will enable the potential threat of HAB occurrence in the area of interest to be assessed. These products should be made available on the internet to various administrative bodies and scientific institutions as well as the general public. Additionally, discrete sampling should make it possible to track and investigate the changes in the phytoplankton community structure, both at a seasonal time scale (natural species succession) and over the years (as changes following eutrophication or the appearance of invasive species).

5. Conclusions

- The Ferry Box system installed on the cargo/passenger ferry between Gdynia (Poland) and Karlskrona (Sweden) was an effective tool for monitoring environmental changes, but the sensors have to be maintained in an undamaged condition and measurements checked against discrete readings.
- Interpretation of the rapid changes in environmental parameters observed along the ferry route as recorded by the Ferry Box system was possible as a result of the analysis of the location, extent and strength of frontal zones from satellite imagery. However, the satellite imagery regarding chlorophyll *a* turned out to be the weakest link in the system owing to a lack of good quality pictures corroborating the Ferry Box measurement data.
- The documented history of cyanobacterial blooms in the Baltic Sea and also the results of this project indicate that, in Polish coastal waters, a regular monitoring/warning system protecting users of recreational areas should be implemented in the summer.

- Both the biomass of *Nodularia spumigena* and nodularin concentration were moderate in 2008 compared to previous years.

Acknowledgements

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