Spatial phytoplankton pattern in the Baltic Sea

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Abstract

We try to give a comprehensive overview about the spatial distribution of phytoplankton biomass, groups, selected indicators and species for three selected years and different seasons in the entire Baltic Sea, based on the comprehensive CHARM phytoplankton data base. We analyse the interpolations with respect to the requirements of the European Water Framework Directive and compare the spatial phytoplankton pattern to the Baltic Sea Typology. The phytoplankton distributions are further compared with spatial interpolations of abiotic parameter and model results, to see if the model is potentially suitable to overcome short-comings in spatial phytoplankton data availability.

1   Introduction

In 2000, the European Water Framework Directive (WFD) (Directive 2000/60/EC) entered into force. The WFD establishes a comprehensive framework for European Community actions in the field of water and introduces new principles of modern water management. New is especially the spatial integration of river basins and coastal waters as well as the focus on biological ecosystem quality elements namely fish, macrozoobenthos, macrophytes and phytoplankton. The implementation of the WDF requires e.g. the development of a typology for coastal waters, reference conditions describing the very good ecological state of coastal ecosystems, a quality evaluation system for coastal ecosystems and finally a new monitoring strategy. An important aspect in the WFD is that it asks for spatial analyses and interpolations of all kind. The typology has a spatial focus and e.g. spatial distributions of biological elements are required for a comparison with the spatial distribution of types as well. With respect to abiotic data, spatial interpolations covering the entire Baltic Sea are well available e.g. in the Baltic Environmental Database (BED). Concerning biological elements, spatial analyses are partly available as well (WASMUND et al. 1999) but are less common. The first trial to compile coastal data from the different countries of the south-eastern Baltic Sea was made by WASMUND et al. (2000) for the years 1993-1997. However, a comprehensive attempt to present e.g. spatial phytoplankton distributions over large areas is lacking. The motivation for this study was to overcome this deficit.

The WFD has caused many activities and requires a lot of research. The EU project "Characterization of the Baltic Sea Ecosystem: Dynamics and Function of Coastal Types" (CHARM) was launched in 2001. Aim was to support the implementation of the WFD e.g. by developing a Baltic Sea typology (SCHERNEWSKI & WIELGAT 2004), by analyzing and evaluating biological data, or by suggesting reference conditions (SCHERNEWSKI & NEUMANN in press). All Baltic states (except Russia) participated in the project and contributed to a joint database on phytoplankton. The work described here is part of the CHARM project and utilizes this outstanding database.

Aims of this study are:

➢ To develop and validate a methodology, which allows the presentation and analysis of spatial phytoplankton pattern.

➢ To analyse the short-comings of the available phytoplankton data, to derive suggestions towards a reliable monitoring and to evaluate the value of the spatial phytoplankton data for the purposes of the WFD.

➢ To give a comprehensive overview about the spatial distribution of phytoplankton biomass, groups, selected indicators and species for three selected years and different seasons in the entire Baltic Sea and based on the best available data.

➢ To link phytoplankton pattern to spatial distributions of abiotic parameter and to compare it with model results (NEUMANN et al. 2002). The question is if models are suitable to overcome possible short-comings in phytoplankton data?

➢ To compare phytoplankton pattern with the typology. The present typology is based on three main factors surface salinity, water residence time and water depth, which corresponds to the mixing of the water column. The WFD assumes that the spatial pattern of these parameters reflect the biological parameters as well. The question is, if the spatial distribution of types can be validated with respect to phytoplankton.

Methods and a critical evaluation of the present spatial data for the purpose of the WFD are the focus of this study. This study shall not analyse phytoplankton pattern, their spatio-temporal behaviour or interdependencies in detail. Therefore this work is a first basis and leaves a lot of room for future detailed phytoplankton studies.

2   Methods

2.1   Data basis

The Baltic Phytoplankton Database of the CHARM-Project is based on monitoring data of the countries Denmark, Germany, Poland, Lithuania, Latvia, Estonia and Finland. Swedish data is lacking. The data was compiled and evaluated by phytoplankton experts and linked to abiotic data. The CHARM database mainly contained coastal data. To get a full coverage of the central Baltic Sea, the HELCOM data (Baltic Monitoring Program) were used additionally. The focus area of this study is given in Figure 1.

2.2   Data selection and aggregation

A full spatial documentation of phytoplankton pattern for many years is laborious and not necessary with respect to the aims of this study. We focussed our efforts on three years 1987, 1990 and 1997. These years show very different atmospheric conditions and one can expect that they caused very different phytoplankton developments and reflect the possible variability in the Baltic Sea fairly well.

1987 started with one of the twelve coldest winters of the century. The Baltic Sea showed a long-lasting and extensive ice cover. Spring and summer were too cold as well, followed by average conditions in autumn. The summer 1987 belonged to the four coldest of the century. Surface water temperatures were below the average all the year until November and reached only 12-14°C in July in the central Baltic Sea. The thermocline was relatively close to the surface and less pronounced compared to average years.

1990 was characterised by a very warm winter. The temperatures in the western Baltic Sea never dropped below 4°C. It followed a warm spring and a fairly normal summer with water temperatures close to the average. Altogether the year was outstanding sunny and dry.

1997 had an average winter. The spring was cool and the surface water temperatures increased only slowly. A thermal stratification was observed not before middle of Mai. In June a lasting heat period started and made the summer the warmest since 1890. In the central and western Baltic Sea surface water temperatures reached outstanding 23°C. The autumn was slightly colder than the average.

Figure 1: Study area as well as CHARM- and HELCOM sampling locations.

• CHARM station • HELCOM station

1987, March - May 1987, June - September

1990, March - May 1990, June - September
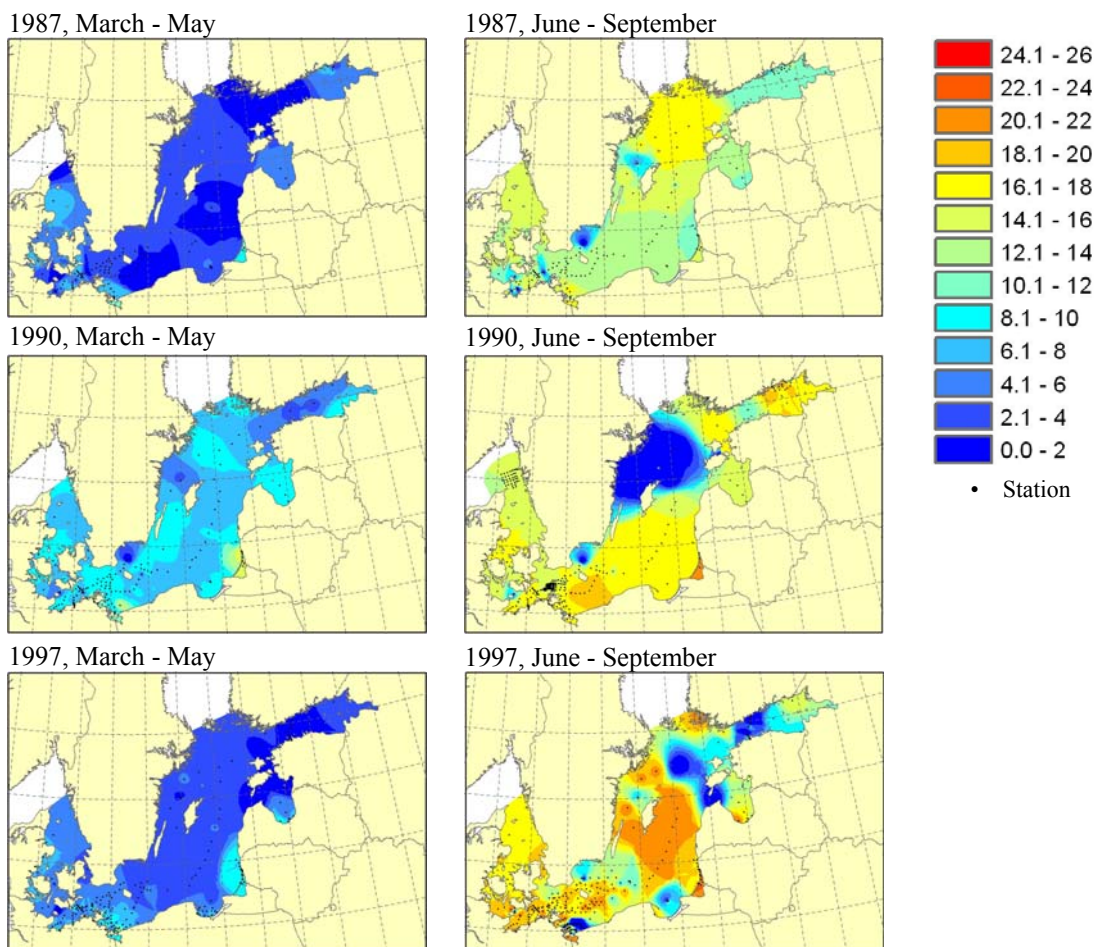
1997, March - May 1997, June - September

Figure 2: Seasonal average of temperature (°C) in the surface water (0-10 m) in 1987, 1990 and 1997 (Data: CHARM, HELCOM).

Usually, intensive phytoplankton developments (blooms) in the Baltic Sea are observed in spring, summer and autumn. Therefore, all biomass data was subdivided into seasons and averaged within these seasons. These seasons are defined according to the occurrence of phytoplankton blooms and differ between different regions in the Baltic Sea. In this study spring covers the month March until May and summer is represented by the period between June and September. This is in agreement with the definitions after HELCOM (1996) for the Baltic Proper. The coarse temporal resolution of the monitoring causes the situation that sampling hardly ever meets the peaks of the blooms (WASMUND et al. 1998).

2.3   Data processing and interpolation

According to the selected years and seasonal aggregations all relevant data was selected and compiled into a new data base. Data processing and statistics were carried out with the geographic information system (GIS) ArcView 3.3.

Table 1: Number of available data sets (DS) in the original data bases and the compiled data for his study.

		Nutrients	Phytoplankton	Stations
CHARM (BPDB)	DS altogether	14 365	309 881	
	DS 1987, 1990, 1997	2 032	45 077	
HELCOM (BMP)	DS altogether	25 269	74 128	
	DS 1987, 1990, 1997	2 327	13 445	
Compiled data	DS 1987, 1990, 1997 (without duplicates and averaged over 0-10 m)	4 004	45 964	304

Several interpolation programs and methods were applied and the results compared according to six pre-defined criteria (THAMM 2004). The relatively simple IDW-method (Inverse Distance Weighted) provided by the Spatial Analyst of ArcGIS 8.3 turned out to be most suitable. In all interpolations four neighbouring points, a weighting power of three and a search radius of 400 km was applied. Islands and the coastline were considered as boundaries. A disadvantage of the IDW method is the so-called 'Bull's-eye' effect in the direct vicinity of single measured data.

3   The annual phytoplankton dynamics

To understand spatial phytoplankton distributions, their seasonality and interannual variability requires a sound knowledge of the underlying processes and interactions. Therefore, the temporal phytoplankton dynamics in the Baltic Sea has to be briefly mentioned.

In winter (January, February), the essential nutrients have accumulated in the water, but light intensity is limiting excessive phytoplankton growth. In spring, light conditions improve continuously. The phytoplankton of the upper mixed layer receives suddenly a much higher integral light intensity if the mixing depth becomes lower than the euphotic zone, i.e. it is trapped in the illuminated upper water layers. This is the condition the phytoplankton needs for the outburst of its growth (WASMUND et al. 1998). Best adapted to these conditions are the diatoms (e.g. *Skeletonema costatum*), which form a spring bloom in most of the areas of the southern Baltic Proper in March. As soon as the nutrients (primarily nitrogen) are exhausted, the bloom disappears. After the diatom bloom, motile phytoplankton (e.g. *Mesodinium rubrum, Dictyocha speculum* and diverse dinoflagellates) develops, which is capable of vertical migration and therefore able to use nutrients from deeper water layers. In the central regions of the Baltic Sea, the spring bloom develops later (April, May) and is mainly composed of dinoflagellates (e.g. *Peridiniella catenata*). As nitrogen is the limiting nutrient in the Baltic Proper, nitrogen fixation by diazotrophic cyanobacteria may overcome the nutrient limitation. These nitrogen

fixing cyanobacteria (primarily *Nodularia spumigena* and *Aphanizomenon* sp.) may form extensive blooms in July and August and supply the fixed nitrogen also to other components of the ecosystem. Now, phosphorus becomes the limiting nutrient. Its exhaustion or a deeper mixing of the water column causes the end of the summer bloom. In the western Baltic, dinoflagellates (e.g. *Ceratium* spp.) develop slowly. As they are not heavily grazed due to their big size, they grow up to bloom concentrations until autumn. In October or November, thermal convection causes a deep circulation and brings new nutrients to the upper water layers, where a diatom bloom (e.g. *Coscinodiscus granii*) can develop again. The phytoplankton biomass decreases in November to the low winter level. The winter phytoplankton is frequently dominated by small flagellates (cryptophyceae), which obviously may grow under low-light conditions.

A detailed spatial analysis of phytoplankton pattern usually requires information on transport processes and flow pattern. With respect to the Baltic Sea the spatial resolution of the phytoplankton data is too coarse and spatial differences can hardly be explained by flow pattern.

4   Spatial phytoplankton pattern

4.1   Biomass

The increase in nutrient input, which is the main reason for eutrophication, leads directly to an increase in phytoplankton biomass. Therefore, phytoplankton biomass may serve as an indicator of the trophic state. A trophic classification scheme based on winter nutrient concentrations and annual means of phytoplankton primary production and biomass was developed by WASMUND et al. (2001) for the Baltic Sea including the outer coastal waters. According to this classification scheme, the river plumes of Oder, Vistula and the outflow of the Curonian Lagoon are eutrophic, whereas the open Baltic waters are mesotrophic. The inner coastal waters, exemplified by the Darss-Zingst bodden chain, an estuarine lagoon system of the German coast, may reach from the mesotrophic to the hypertrophic state (WASMUND 1990). We confirm that lagoons and river plumes contain a much higher phytoplankton biomass than open waters, as shown in Figure 3 for Szczecin Lagoon, Curonian Lagoon and the plumes of Newa, Oder, Daugava, Vistula rivers and of the outflow of Curonian Lagoon. This pattern is also found in the separate seasons (Fig. 4). As the river runoff is lower in summer than in spring, phytoplankton biomass in the plumes is also decreasing from spring to summer in some areas (eastern Gulf of Finland, Gulf of Riga, Gulf of Gdansk). The increase from spring to summer 1997 in the Pomeranian Bight and Gulf of Gdansk is caused by additional inputs owing to the exceptional floods (HUMBORG et al. 1998). Patches of very low phytoplankton biomass may also be caused by upwelling of deeper water, e.g. off the Lithuanian coast in summer 1990.

In general, the patterns of phytoplankton biomass are also found in the distribution of chlorophyll-a (Fig. 5). This pigment is a component of all phytoplankton cells. As it occurs in a more or less known percentage of the cell (e.g. HUNTER & LAWS 1981) it may serve as a proxy for total phytoplankton biomass. It may not used, if the species or phytoplankton groups are of interest.
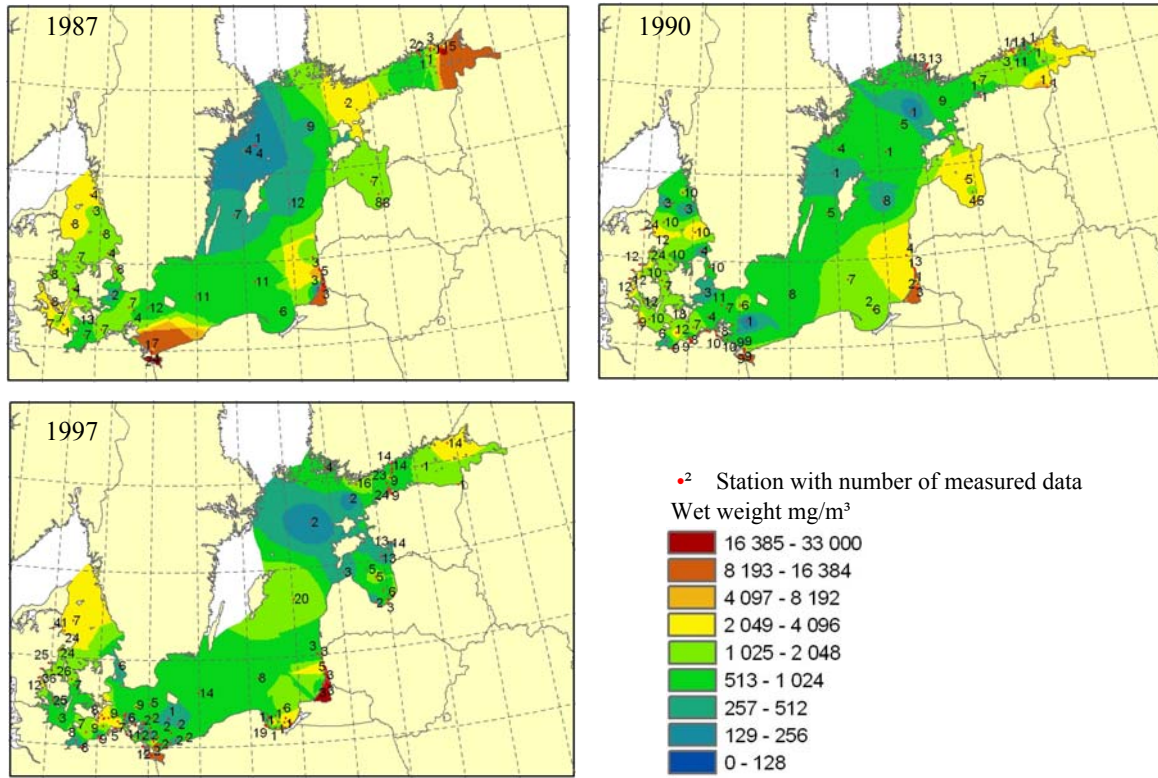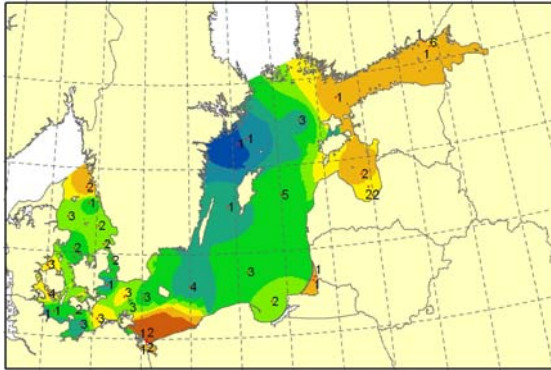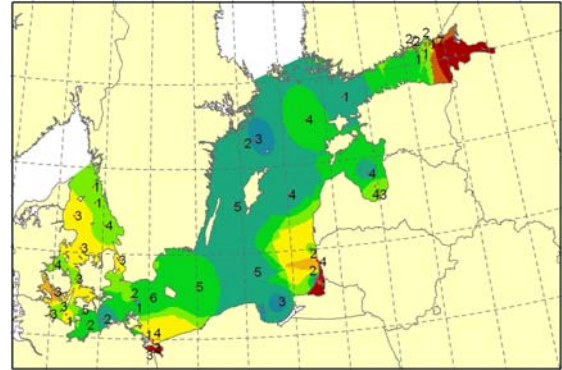
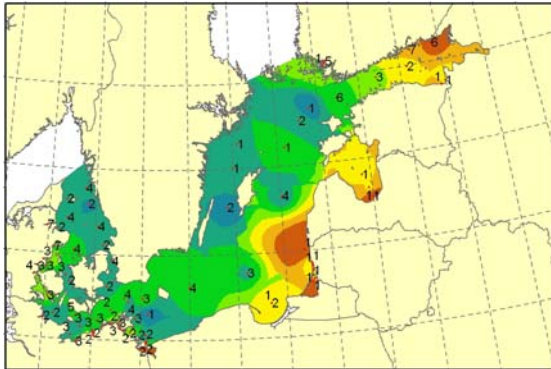Figure 3: Annual average of phytoplankton biomass in the surface water (0-10 m) in 1987, 1990 and 1997 (Data: CHARM, HELCOM).
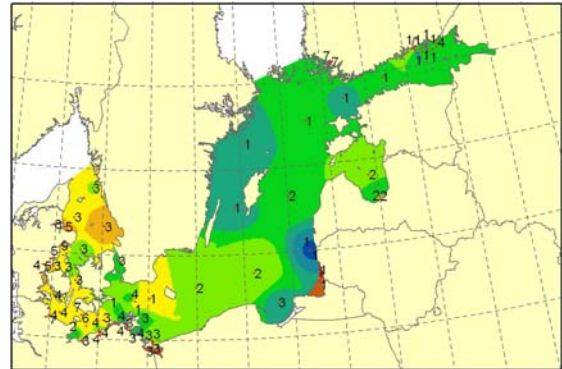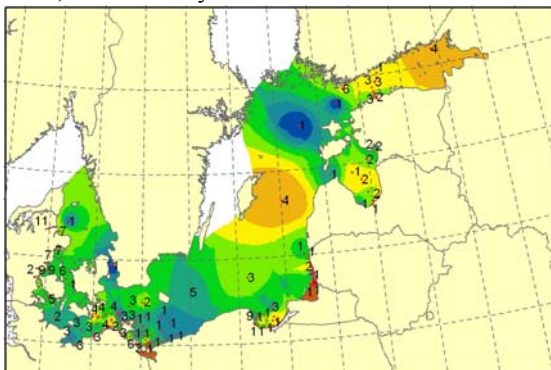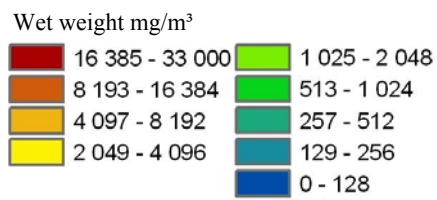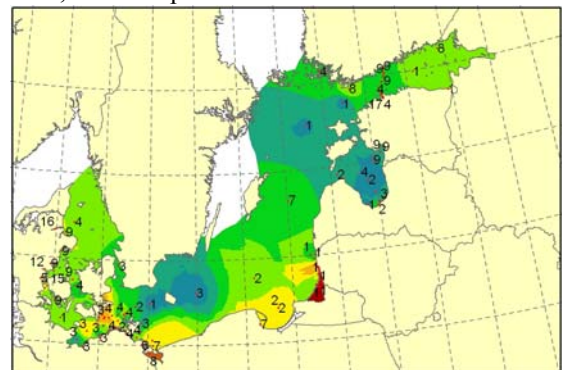
1987, March - May

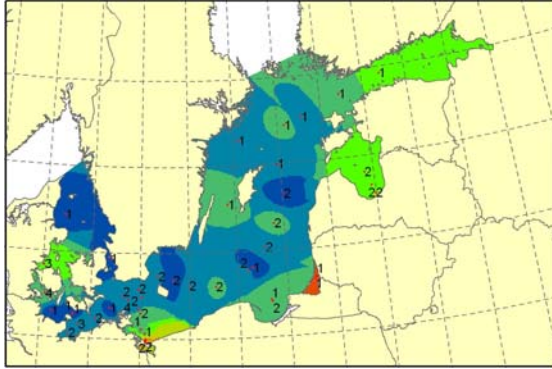1987, June - September

1990, March - May

1990, June - September

1997, March - May

1997, June - September

Wet weight mg/m³

■ 16 385 - 33 000	■ 1 025 - 2 048
■ 8 193 - 16 384	■ 513 - 1 024
■ 4 097 - 8 192	■ 257 - 512
■ 2 049 - 4 096	■ 129 - 256
	■ 0 - 128

•²   Station with number of measured data

Figure 4: Seasonal average of phytoplankton biomass in the surface water (0-10 m) in 1987, 1990 and 1997 (Data: CHARM, HELCOM).
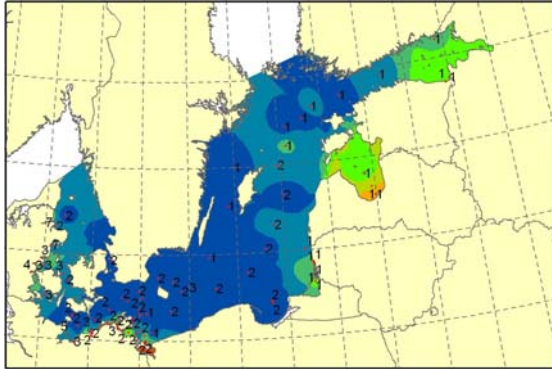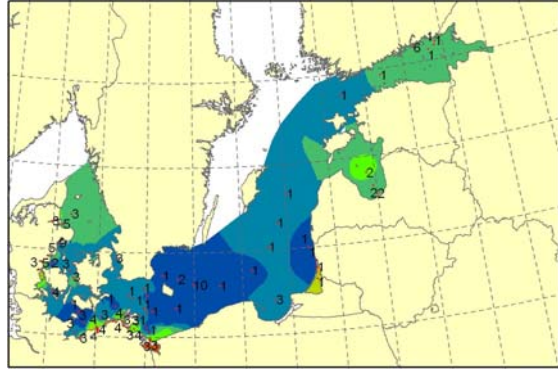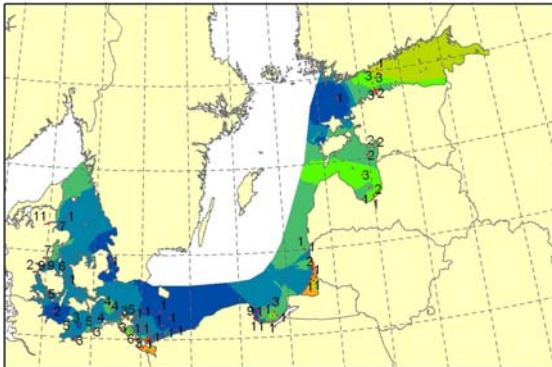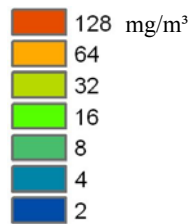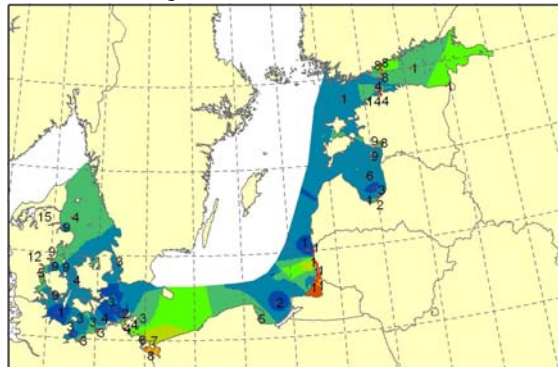
1987, March - May

1987, June - September

1990, March - May

1990, June - September

1997, March - May

1997, June - September

	mg/m³
128	
64	
32	
16	
8	
4	
2	
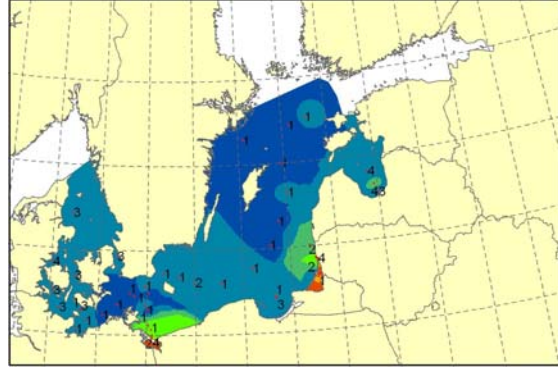
•² Station with number of measured data

Figure 5: Seasonal average of chlorophyll-a in the surface water (0-10 m) in 1987, 1990 and 1997 (Data: CHARM, HELCOM).

4.2   Phytoplankton groups

As already shown in chapter 3, non-motile algae (mainly diatoms) and motile algae (flagellates) have different preferences of environmental conditions owing to their different abilities. Diatoms prefer turbulent waters in order to keep suspended whereas flagellates need stratified waters if they want to benefit from their ability to choose their optimum water depth. Some cyanobacteria may also accumulate at specific water depths by buoyancy regulation and therefore dislike mixing of the water.
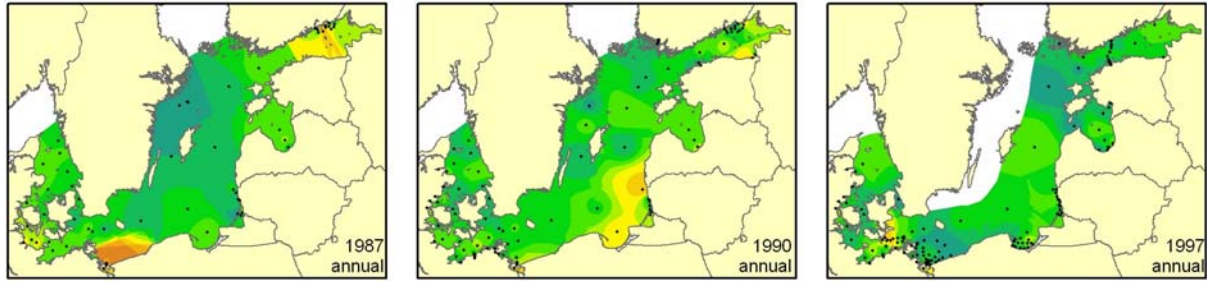
Dinoflagellates are the largest group of flagellates in the Baltic Sea. Therefore, their distribution is similar to that of the total flagellates, whereas the other flagellates are different from the total flagellate group (Fig. 6). Dinoflagellates are especially dominant in spring. Thus, their spring patterns are similar to the annual patterns. Moreover, the spring distribution of dinoflagellates (Fig. 6) resembles that of the total phytoplankton biomass in spring (Fig. 4) because they account for the biggest part of the spring biomass.

Diatoms are the second important part of the spring phytoplankton. Originally, they were the main component of the spring bloom, as shown in chapter 3. The year 1987 (Fig. 7) is typical for this situation. In the 1990s, they are strongly reduced, as exemplified by the years 1990 and 1997. Possible explanations for this trend are given by WASMUND et al. (1998). They think that the mild winters in the 1990s and the related non-appearance of deep mixing in the water column are responsible for the replacement of diatoms by dinoflagellates in the spring bloom. Concerning the composition of the spring bloom, the situation of the year 1987 can be assumed as a reference condition for the ecosystem.
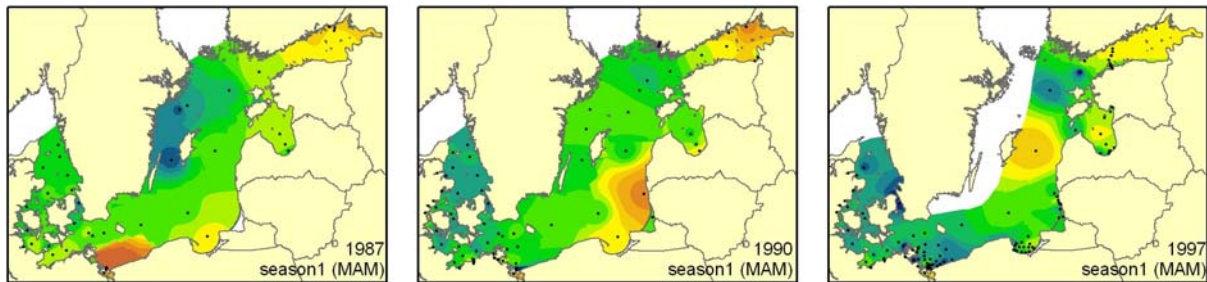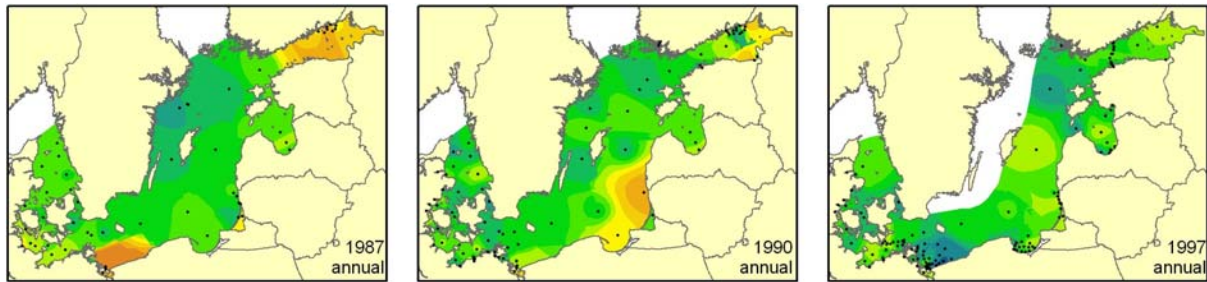
Cyanobacteria occur mainly in summer and may form big blooms. Therefore, the annual data shown in Figure 7 reflect mainly the distribution in summer (Fig. 10). The cyanobacteria blooms (e.g. *Microcystis* spp.) in the lagoons are related to high nutrient input and are promoted by high temperature. The big blooms in the open waters of the Baltic Sea (KAHRU et al. 1994) occur even at low nutrient concentrations (WASMUND 1997) because they meet their nitrogen demand from dissolved atmospheric nitrogen. This nitrogen fixation occurs in specialised cells, so-called heterocysts. These heterocystous cyanobacteria have to be strictly kept apart from cyanobacteria that are not able to fix nitrogen. They establish a well-defined functional group (Figure 8: "cyanobacteria with heterocysts"). Because of their impressive, sometimes toxic blooms they are of common interest and activate the question whether these blooms are increasing due to anthropogenic impact. As long as nitrogen is the limiting nutrient in the Baltic Proper, they cannot be related to eutrophication because they supply themselves with the nitrogen needed for growth. They are, however, limited by phosphorus. Consequently, increased phosphorus input into the ecosystem would promote the growth of nitrogen fixing cyanobacteria. FINNI et al. (2001) discussed that cyanobacterial blooms are known already from the mid of the 19th century but might have increased at least until the 1960s. During the last decades, they have established on a high level. Warm summer may support these blooms. Trends are however hard to be proved because of the high patchiness and therefore low representativeness of samplings in time and space. Satellite images (KAHRU et al. 1994) may supply additional information on distribution especially of the buoyant cyanobacterial blooms.

Other functional groups (Fig. 8) are less precisely defined than the cyanobacteria with heterocysts. The freshwater and brackish/marine spring blooms are not spatially separated as expected. Even those species considered as freshwater species are not only restricted to lagoons and river plumes but are also found in the open sea. They show a similar distribution as the mixotrophic and heterotrophic species. The spring and autumn bloom species are more evenly distributed in the sea, indicating that the blooms develop autochthonously in the whole sea areas. A few patches of low biomass, e.g. the autumn bloom in the Eastern Gotland Sea, are owing to low sampling frequency and therefore missing of the bloom.

Flagellates (all)

Dinoflagellates

Other flagellates

Wet weight mg/m³ • Station

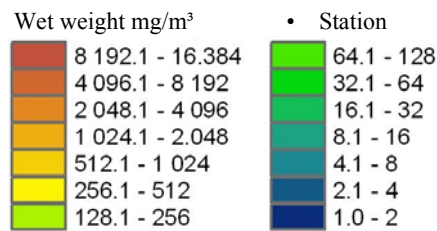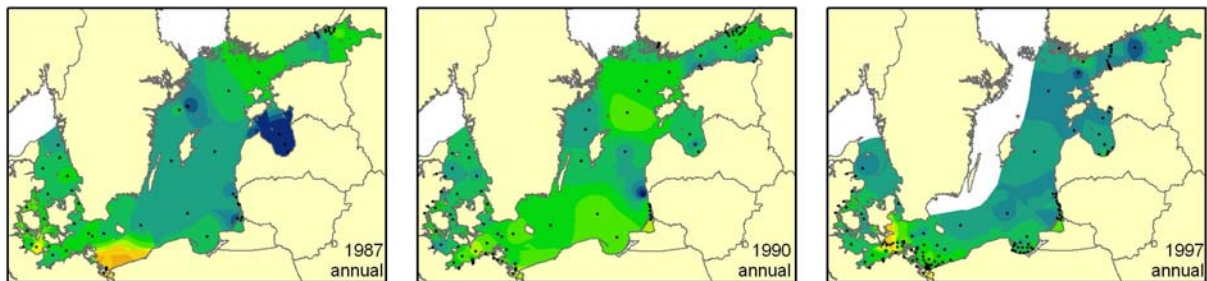|	
8 192.1 - 16.384	64.1 - 128
4 096.1 - 8 192	32.1 - 64
2 048.1 - 4 096	16.1 - 32
1 024.1 - 2.048	8.1 - 16
512.1 - 1 024	4.1 - 8
256.1 - 512	2.1 - 4
128.1 - 256	1.0 - 2

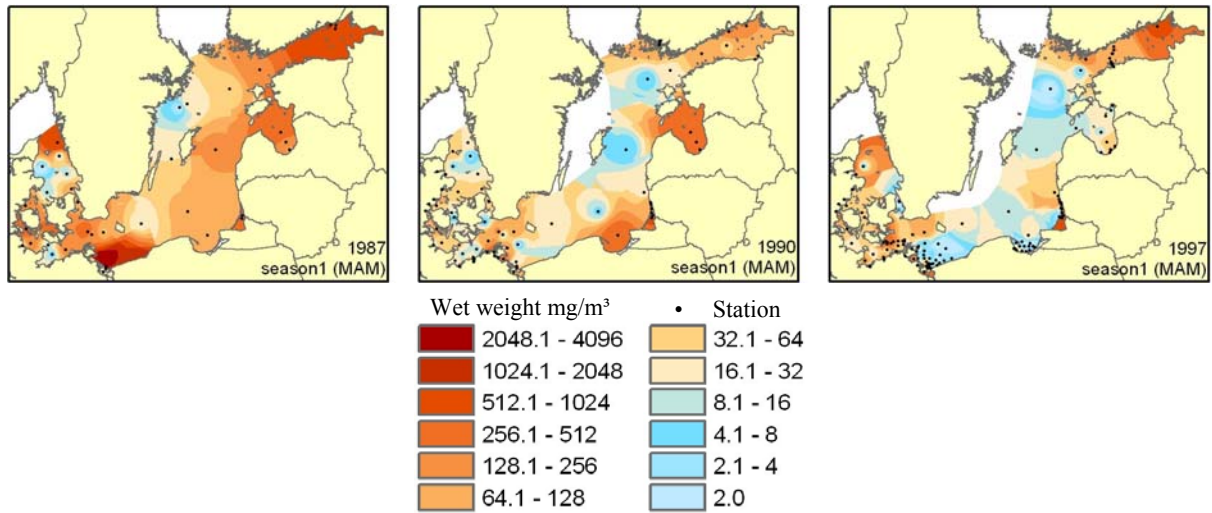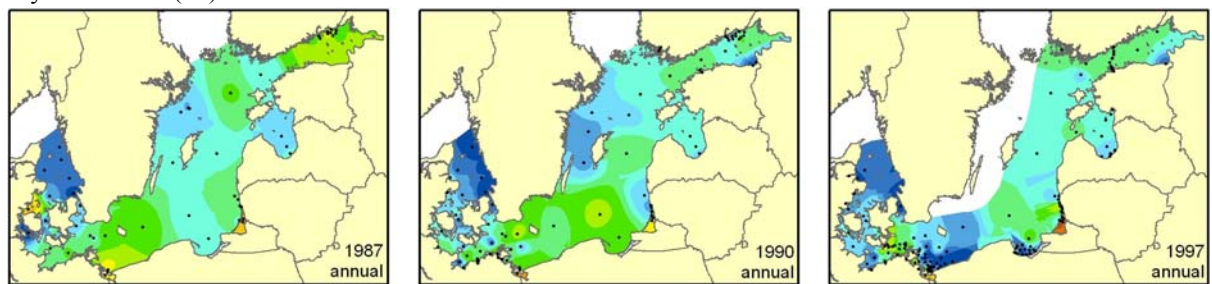Figure 6: Flagellates - seasonal average of biomass in the surface water (0-10 m) in 1987, 1990 and 1997 (Data: CHARM, HELCOM).

Diatoms

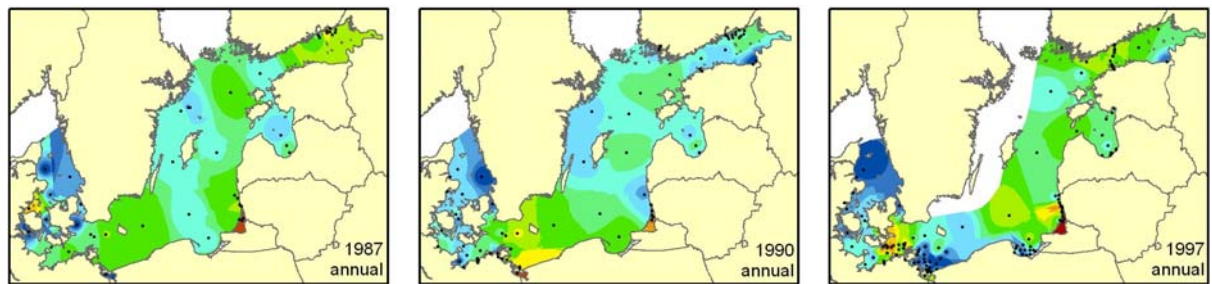Wet weight mg/m³ • Station

2048.1 - 4096	32.1 - 64
1024.1 - 2048	16.1 - 32
512.1 - 1024	8.1 - 16
256.1 - 512	4.1 - 8
128.1 - 256	2.1 - 4
64.1 - 128	2.0

Cyanobacteria (all)

Cyanobacteria with heterocysts

Freshwater cyanobacteria

Wet weight mg/m³ • Station

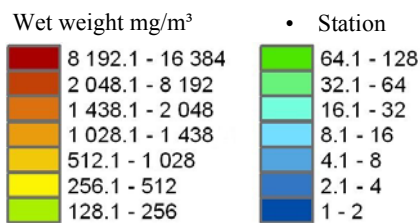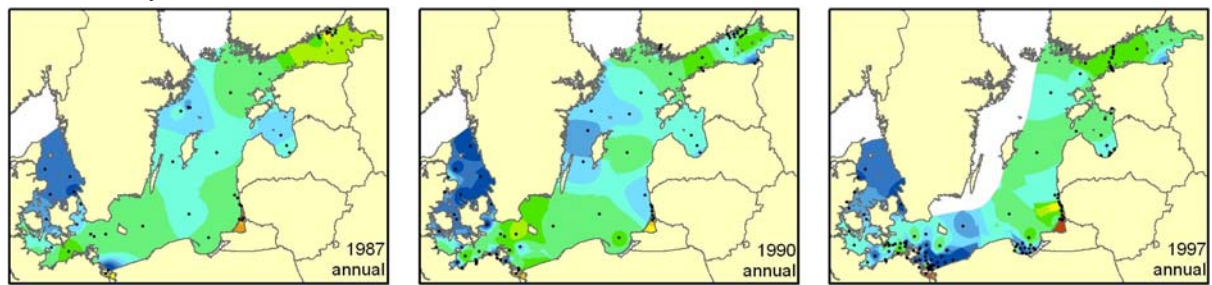|	
8 192.1 - 16 384	64.1 - 128
2 048.1 - 8 192	32.1 - 64
1 438.1 - 2 048	16.1 - 32
1 028.1 - 1 438	8.1 - 16
512.1 - 1 028	4.1 - 8
256.1 - 512	2.1 - 4
128.1 - 256	1 - 2

Figure 7: Diatoms and cyanobacteria - seasonal average of biomass in the surface water (0-10 m) in 1987, 1990 and 1997 (Data: CHARM, HELCOM).
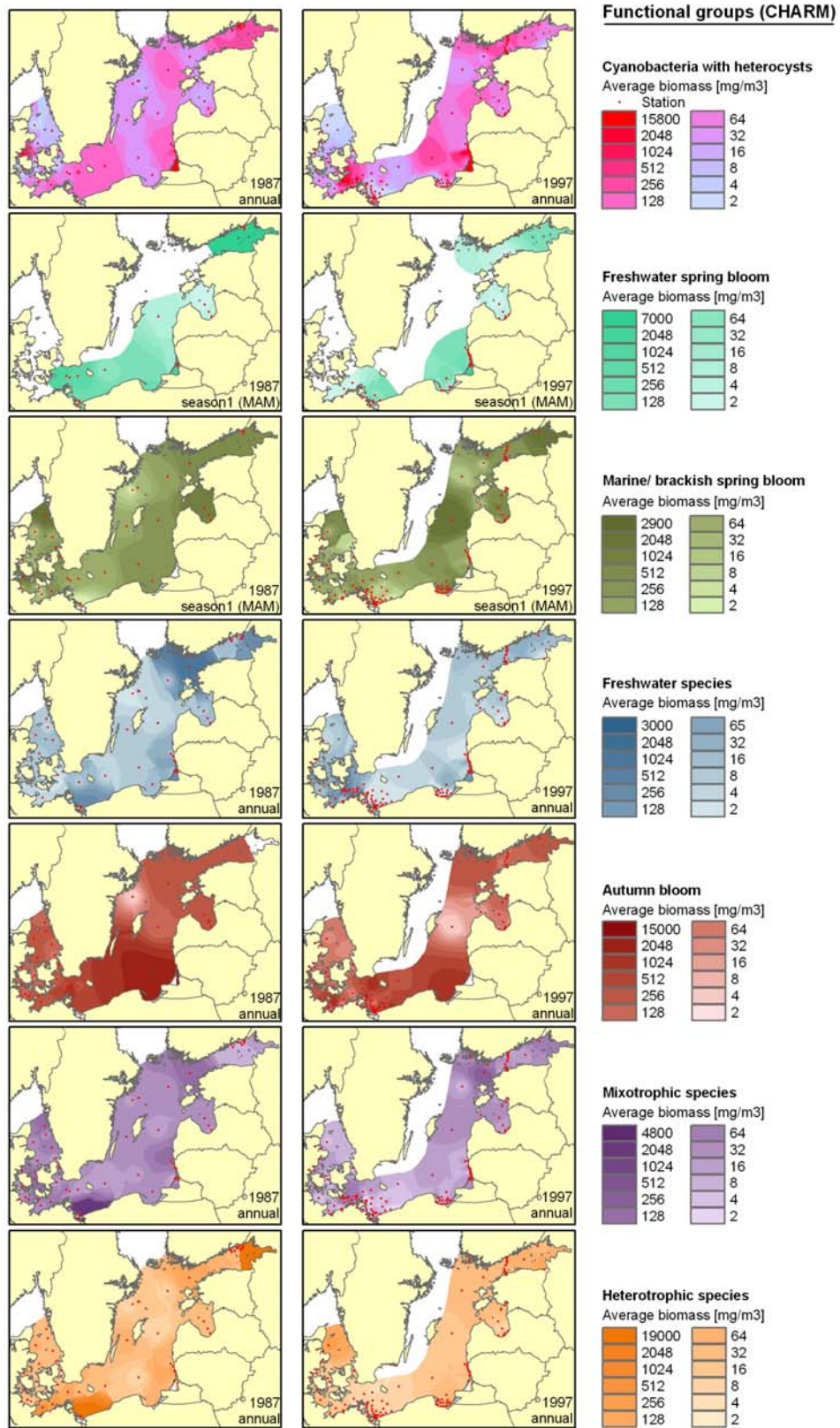
Figure 8: Functional groups - average of biomass in the surface water (0-10 m) in 1987, 1990 and 1997 (Data: CHARM, HELCOM).

4.3 Phytoplankton species

Only for the most abundant species, natural patchiness and methodological inaccuracy are low enough to design reliable distribution patterns. *Skeletonema costatum* is the dominant species in most of the spring diatom blooms. As it is mostly restricted to the spring period, annual and spring values show the same distribution patterns (Fig. 9). This species disappears by the end of spring due to nutrient limitation. Only in some coastal areas, where continuous nutrient input occurs, the species can survive until summer. This was especially noticed in the Kattegat/Belt Sea area and may be interpreted as an eutrophication indicator (HENRIKSEN pers. comm.). The high patchiness in this area reflects discrepancies between bloom growth and sampling scheme. Mixing of different water bodies causes different timing of the bloom in these areas and therefore patchiness is likely to occur even with synoptic sampling.

The patchiness is lower with the photoautotrophic ciliate *Mesodinium rubrum* (Fig. 9) because it is not as short-living as *Skeletonema costatum* but may dominate the phytoplankton for many months. There seems to be a shift of the peak occurrence from spring (in 1987) over spring/summer (in 1990) to summer (in 1997). Therefore, both spring and summer distribution patches appear in the annual means (cf. 1987 in Fig. 9).

4.4 Phytoplankton indicators

As shown above, phytoplankton composition and biomass changes in time and space. It is, however, hard to prove trends statistically because of high variability due to natural patchiness and insufficiencies in sampling. Nevertheless, WASMUND & UHLIG (2003) found a decrease in diatoms but an increase in dinoflagellates in spring and summer at most stations of the open sea. For summer cyanobacteria biomass, only a decrease could be found in the Bornholm Sea and in the Kattegat. This is supported also by our Figure 10. These trends may not be related to eutrophication because the trophic state did not change significantly in the investigation period. However, these trends show that something changed in the ecosystem. Therefore, at least the spring diatom biomass may be a useful indicator for environmental changes like global warming. It is supposed that warming reduces spring diatoms (WASMUND et al. 1998) but increases cyanobacteria (WASMUND 1997). Therefore, the biomass ratio of summer heterocystous cyanobacteria and spring diatoms should be a good indicator for the reaction of the phytoplankton to global warming. Figure 10 shows that it increases from 1987 to 1997. The high value of this ratio in front of Stockholm in 1987 is caused by the exceptionally low diatom biomass because the spring bloom was completely missed at this one station. This ratio cannot be applied in the Kattegat and river plumes (e.g. outflow of the Curonian Lagoon) because the heterocystous cyanobacteria do not occur there due to the unpleasant N/P ratios (Fig. 14) and salinities (Fig. 12).

Other indices proposed by the CHARM Phytoplankton WP, like the cyanobacteria/chlorophyta ratio, are less promising. Chlorophyta are mostly related to eutrophic freshwater. As also most of the cyanobacteria species prefer eutrophic freshwater, the ratio of these two components levels this specific feature off.

Skeletonema costatum
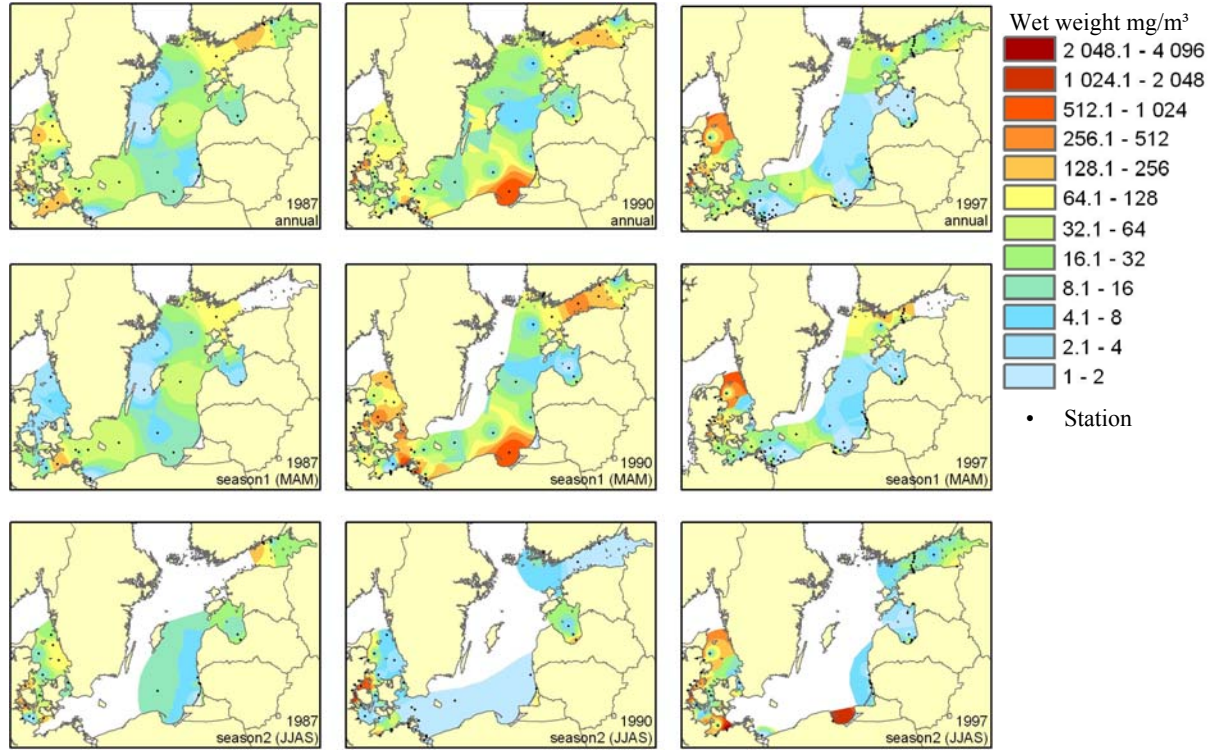
Mesodinium rubrum
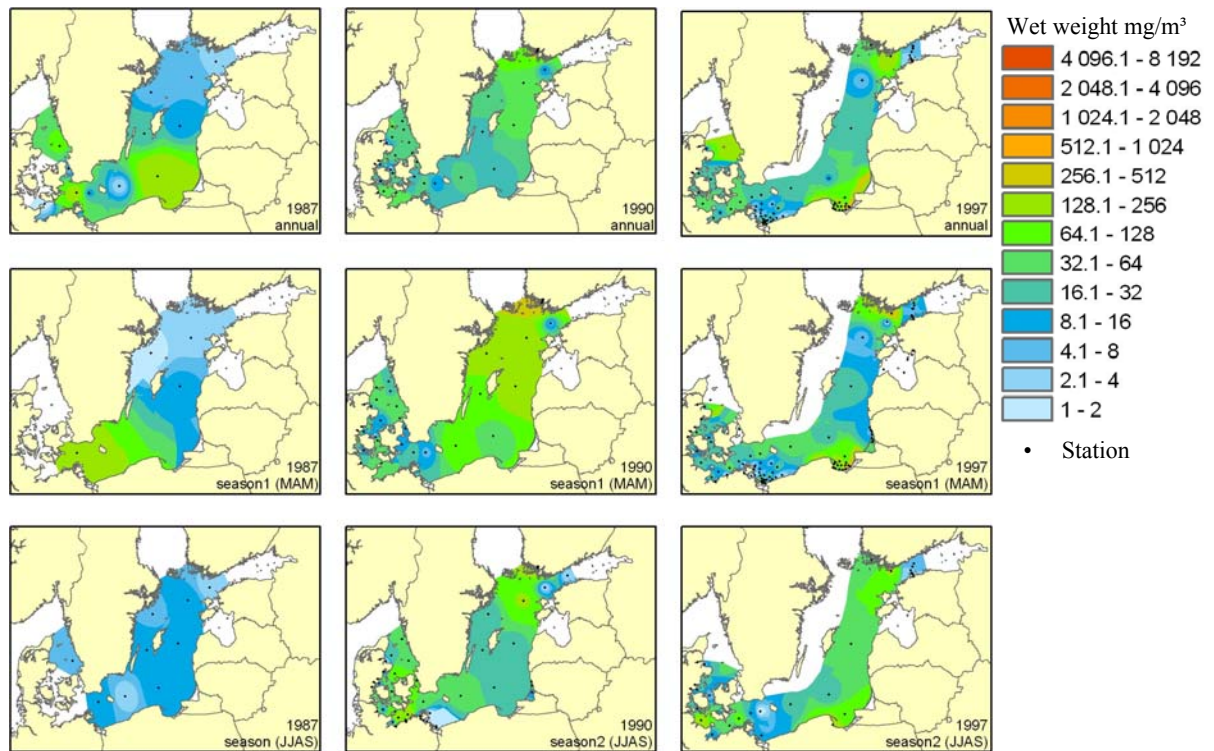
Figure 9: *Skeletonema costatum* and *Mesodinium rubrum* - average of biomass in the surface water (0-10 m) in 1987, 1990 and 1997 (Data: CHARM, HELCOM).
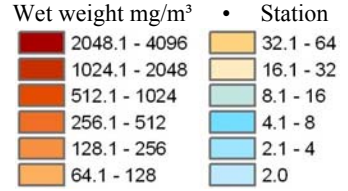
Diatoms

Cyanobacteria with heterocysts

Cyanobacteria with heterocysts (season 2) to Diatoms (season 1) ratio

Figure 10: Cyanobacteria with heterocysts to diatoms ratio - average of biomass in the surface water (0-10 m) in 1987, 1990 and 1997 (Data: CHARM, HELCOM).

Cyanobacteria (all)

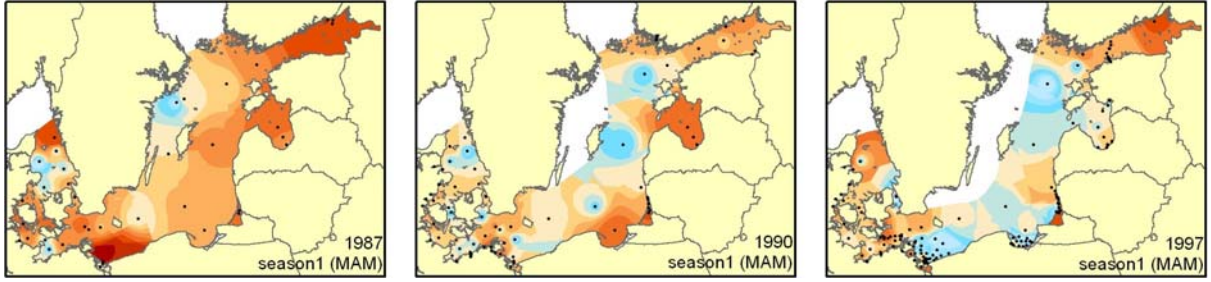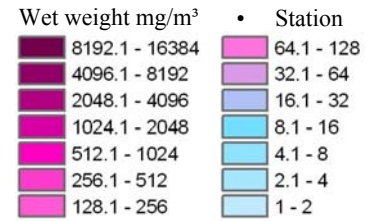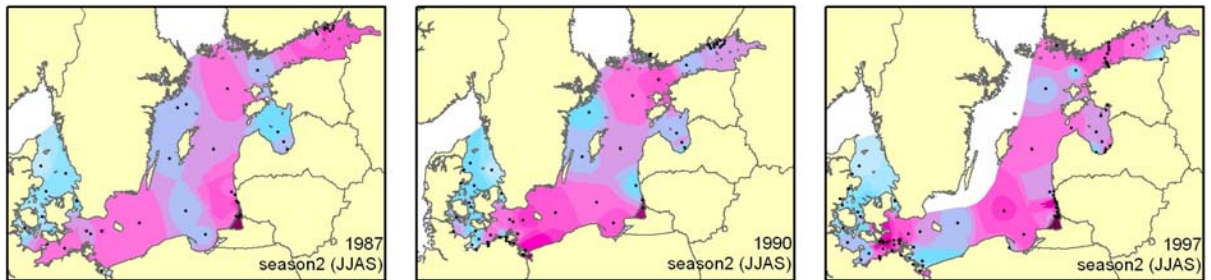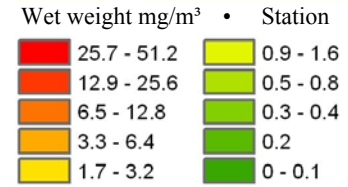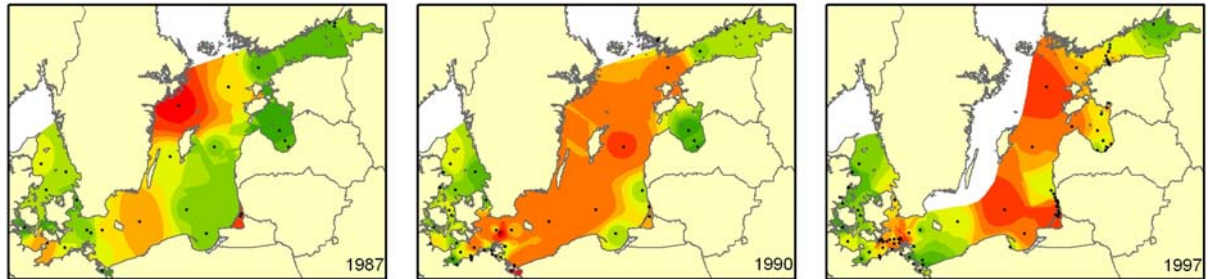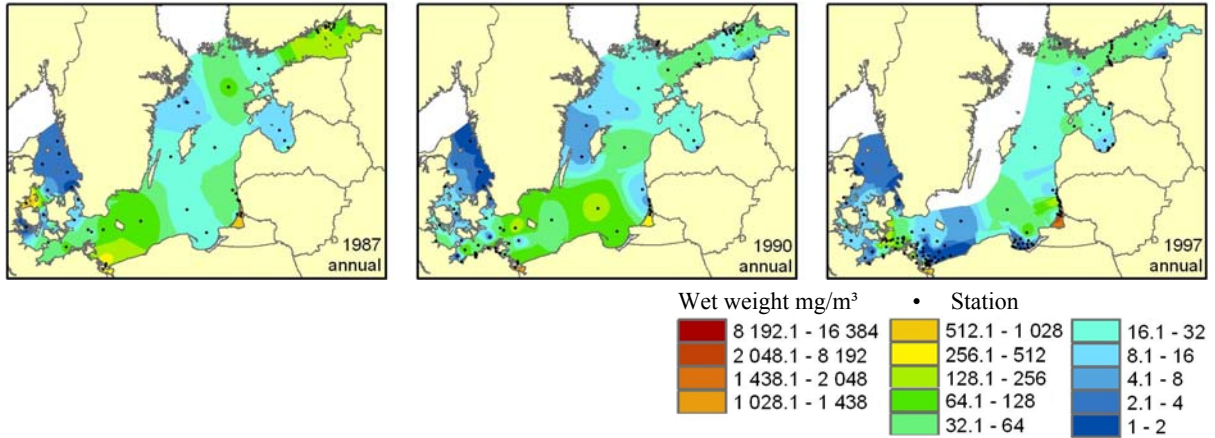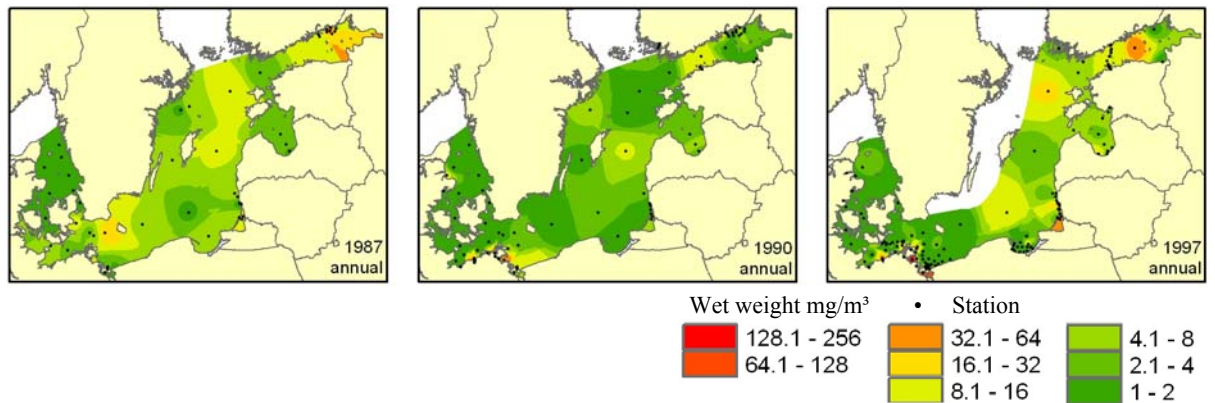Cyanobacteria Chlorophyta ratio

Figure 11: Cyanobacteria to chlorophyta ratio - average of biomass in the surface water (0-10 m) in 1987, 1990 and 1997 (Data: CHARM, HELCOM).

5   Spatial comparison with abiotic parameter

Several well known dependencies of the phytoplankton growth on abiotic parameters are reflected in the spatial distributions. Shallow mixed coastal waters show a larger relationship between euphotic and aphotic zone. It means that in average phytoplankton is potentially exposed to light for a longer time and can maintain a higher biomass compared to unstratified open waters with a comparable transparency. During summer open waters are stratified and phytoplankton is kept within a narrow mixed layer there as well. River plumes with their higher turbidity and small scale stratifications often show a very different behaviour with respect to light availability compared to other coastal waters. Especially in spring shallow areas warm up faster and allow an earlier development of phytoplankton in spring. This is true for the south-western part of the open Baltic Sea as well. These areas show the first diatom blooms in early spring and with increasing temperatures the blooms are propagating towards north-eastern parts of the open Baltic Sea. The positive influence of summer temperatures of at least 16°C on cyanobacteria growth is known, too, but their development depends on nutrients as well. River plumes are not only shallow (and warm up fast) but provide additional nutrients for an enhanced phytoplankton growth. All river plumes are well reflected in the spatial phytoplankton distributions.

If one tries to go further into detail, the strong spatial variability of the phytoplankton data and its insufficient spatial coverage restricts comparisons. Often, several abiotic parameters influence phytoplankton growth at the same time and prohibit simple evaluations on the basis of spatial interpolations. To be able to interpret spatial pattern, the temporal development usually has to be considered, too.

Generally, salinity is one of the major factor that determines the spatial distribution of species. In the Baltic Sea with its strong and large scale salinity gradients, this is clearly visible, as already shown by REMANE (1934) in his pioneering work. Blooms of nitrogen-fixing cyanobacteria, for example, develop at a salinity between 3.5 and 11.5 PSU (WASMUND 1997). Because of the high importance of salinity it is taken as the basis for the development of a typology according to the Water Framework Directive. The spatial salinity pattern in the Baltic Sea is fairly stable over the years (Fig. 12). High biomass is found in the high-saline Kattegat and the low-saline river plumes as well. If the biomass of large groups is considered rather than species, the influence of nutrients concentrations is much more relevant than the salinity because the nutrients are the factor that limits the phytoplankton growth.
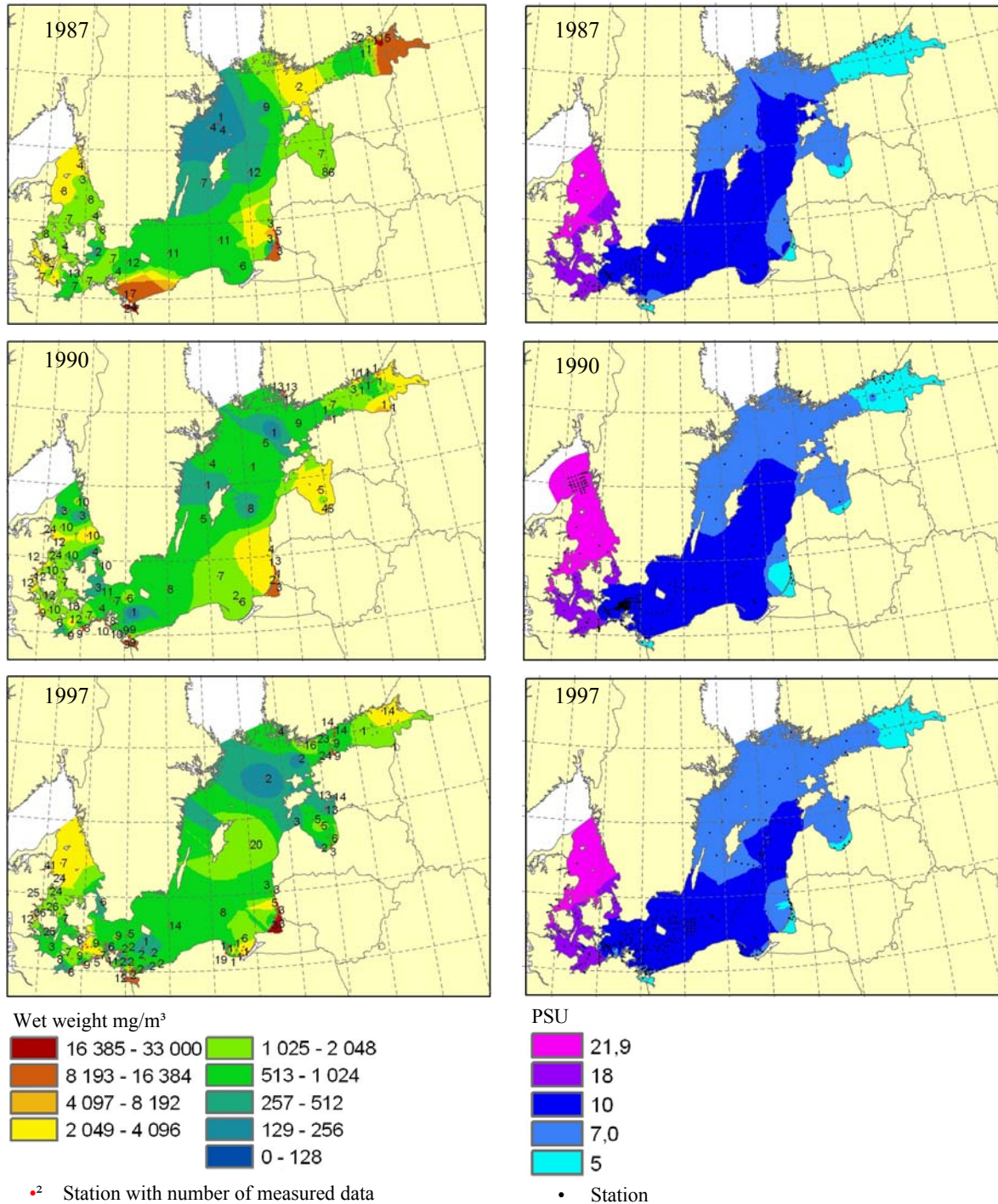
Figure 12: Annual average of phytoplankton biomass (left) and salinity (right) in the surface water (0-10 m) in 1987, 1990 and 1997 (Data: CHARM, HELCOM).
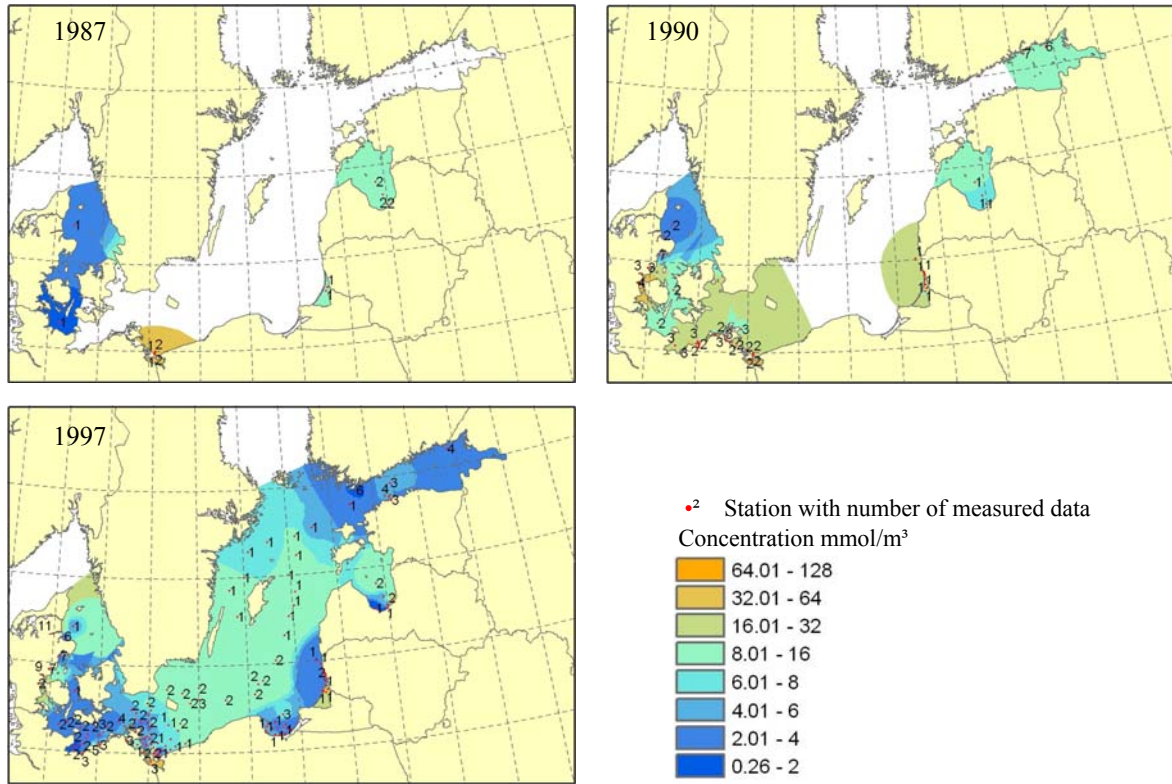
Figure 13: Average of silicate concentration in spring (March, April, May) in the surface water (0-10 m) in 1987, 1990 and 1997 (Data: CHARM, HELCOM).
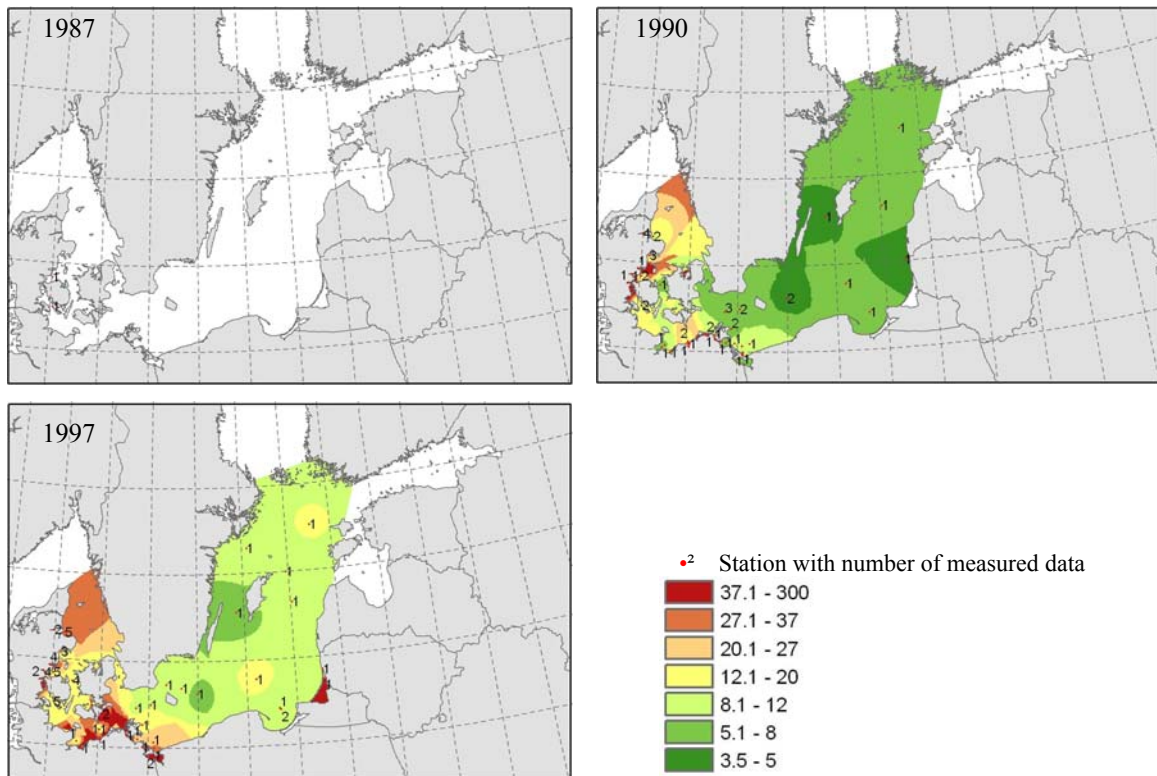

Figure 14: DIN to PO_4 molar ratio in winter (January, February) in the surface water (0-10 m) in 1987, 1990 and 1997 (Data: CHARM, HELCOM).

Silicate is needed for the growth of diatoms. As shown in Figure 13, there are rarely samplings of silicate in 1987 and 1990. Therefore, only spatial pattern of the year 1997 can be compared with distributions of the diatoms biomass. In river plumes and the western coastal Baltic Sea, average silicate concentrations in spring 1997 (Fig. 13) are very low, but significantly higher in the Baltic Proper. Several regions, like the western Baltic Sea, the Gulf of Finland and some river plumes show low silicate concentrations in spring 1997, which are linked to high diatom concentrations. Silicate in spring is already exhausted after the earliest diatom spring bloom and the concentrations remain low during the following time. High silicate concentrations in the Baltic Proper indicate that the diatom bloom has not taken place when the samples were taken. The figures indicate an inverse relationship between nutrient and diatoms concentrations. However, due to the limited data this relationship is not always reflected in large-scale spatial pattern. The results further show, that the sampling time and onset of diatom play an important role for the observed spatial distributions. Strong inter-annual variability in these processes cause very different spatial pattern from year to year.

During winter the nutrients nitrogen and phosphorus are mineralised and accumulate in the water body. The nitrogen/phosphorus ratio (N/P) indicates the general relative availability of these nutrients. It is assumed that nitrogen and phosphorus are taken up by phytoplankton according to the molar Redfield ratio of 16:1. The open Baltic Sea shows a ratio around 8, indicating that nitrogen is the scarce and potentially limiting nutrient. In the western Baltic Sea and in coastal waters the ratio is much larger and indicates a potential shortage of phosphorus (Fig. 14). A nitrogen limitation is common in open marine systems. The average biomass distribution fairly reflects the nutrient availability in the Baltic Sea. High nutrient concentrations in river plumes and near shore are usually linked to a higher phytoplankton biomass (Fig. 3). The N/P ratio resp. the limiting effect of nitrogen for phytoplankton growth is partly reflected in the concentration of cyanobacteria, which are able to overcome the nitrogen limitation.

6   Spatial comparison with results of the Baltic Sea Model (ERGOM)

Are models a suitable possibility to overcome the short-comings in phytoplankton data?

The Baltic Sea Model (ERGOM) is an integrated biogeochemical model linked to a 3-D circulation model and covers the entire Baltic Sea. The circulation model is an application of the Modular Ocean Model (MOM 3) code and includes an explicit free surface, an open boundary condition to the North Sea as well as riverine freshwater input. A thermodynamic ice model is used to simulate ice cover. A horizontally and vertically extending model grid was used. High horizontal resolution (3 nm) was applied in the south-western Baltic Sea. Towards north and east the grid size gradually increased. Altogether 30 vertical layers were assumed. The first 12 layers possessed a constant thickness of 2 m. Deep layers increased in thickness. The deepest layer (in the Gotland Deep) finally has a thickness of 36 m.

The biogeochemical model consists of nine state variables. The nutrient state variables are dissolved ammonium, nitrate, and phosphate. Primary production is provided by three functional phytoplankton groups: diatoms, flagellates, and cyanobacteria with heterocysts. Diatoms represent larger cells which grow fast in nutrient-rich conditions. Flagellates represent smaller cells with an advantage at lower nutrients concentrations especially during summer conditions. The cyanobacteria are able to fix and utilise atmospheric nitrogen and therefore, the model assumes phosphate to be the only limiting nutrient for cyanobacteria. Due to the ability of nitrogen fixation, the cyanobacteria are a nitrogen source for the system.

A dynamically developing bulk zooplankton variable provides grazing pressure on phytoplankton. Dead particles are accumulated in a detritus state variable. The detritus is mineralized into dissolved ammonium and phosphate during the sedimentation process. A certain amount of the detritus reaches the bottom, where it is accumulated in the sedimentary detritus. Detritus in the sediment is either bur-

ied in the sediment or resuspended into the water column, depending on the velocity of near-bottom currents. For a more detailed model description see NEUMANN (2000) and NEUMANN et al. (2002).

The most comprehensive data sets of river loads, atmospheric deposition, and meteorological data were available for the period between 1980 and 2000. This period was simulated and the results compared to measured data to evaluate the model performance. Validation results concerning chlorophyll, salinity and temperature are documented in NEUMANN et al. (2002). Altogether the model performance was satisfying and allowed the simulation of several nutrient load reduction scenarios on the trophic state of the Baltic Sea (NEUMANN et al. 2002; NEUMANN & SCHERNEWSKI in press; SCHERNEWSKI & NEUMANN 2002).The model was further applied to simulate reference conditions in the Baltic Sea according to the demands of the water framework directive. A spatial comparison of measured phytoplankton distributions with model results has not taken place so far.
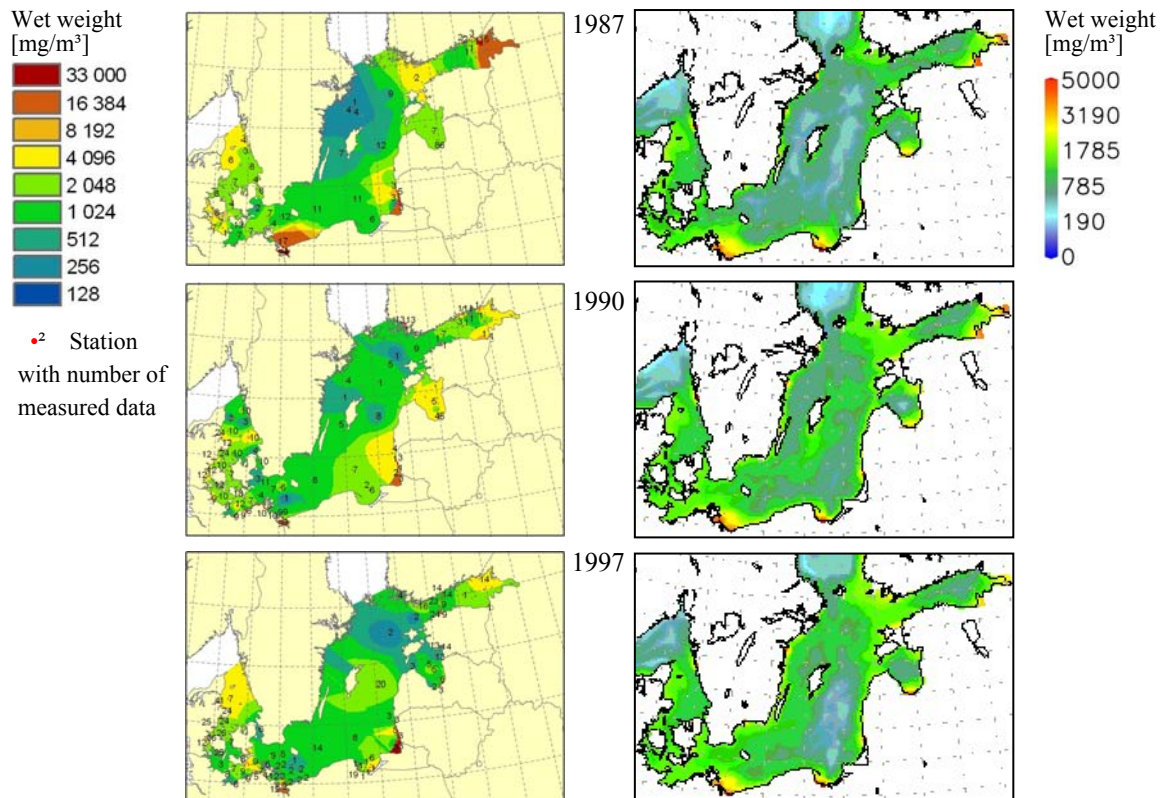
Figure 15: Annual average of phytoplankton biomass in the surface water (0-10 m) interpolated with monitoring data (left) and simulated with the Baltic Sea model ERGOM (right) in 1987, 1990 and 1997 (Data: CHARM, HELCOM, ERGOM).

The model phytoplankton biomass was calculated by using the C:N ratio of 106:16 (Redfield ratio), the assumption that half of the dry weight is due to carbon and converted to wet weight assuming a water content of 80 %.

The annual average of phytoplankton biomass shows the expected spatial distribution (Fig. 15). The highest concentrations in the river plumes are indicated in the interpolated as well as in the simulated maps. Differences in the distribution patterns between interpolation and simulation can be seen in the Baltic Proper. It is caused by the fact that the interpolation is a momentary view based on few data. Differences between station due to methodological errors or local phytoplankton patches create large scale pattern. The model calculates large amounts of data and is not affected by methodological problems or small scale patchiness. Therefore, the model gives a much smoother general picture, but basic

elements in both pictures are well in agreement. A problem is the difference in the range of concentrations between the model and the observations. In reality, much higher values are observed in some regions than predicted by the model.

The spatial patterns of the nitrogen-fixing cyanobacteria between interpolation and model differ partly significantly (Fig. 16). This is especially true for the eastern coastal Baltic Sea and the Gulf of Gdansk. 1997 is known as the year with the most extensive surface accumulation of cyanobacteria (KAHRU et al. 2000; SIEGEL & GERTH 2000). This fact is well reflected in the model but not well visible in the interpolation. This clearly indicates the limited reliability of the data for spatial analysis.

Data together with spatial model applications might complete the spatio-temporal phytoplankton distribution in the Baltic Sea. The model ERGOM is potentially a suitable model for this purpose, but will require a further development.

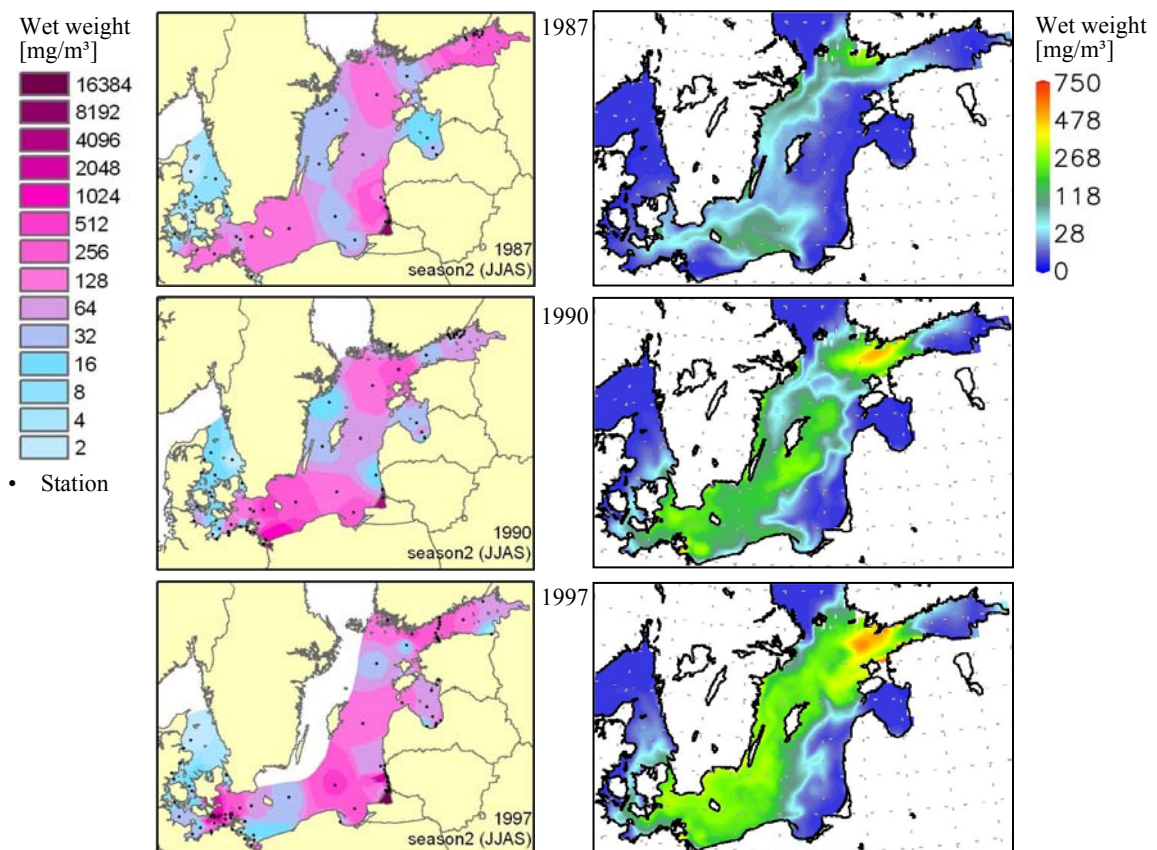Figure 16: Average of cyanobacteria with heterocysts biomass in summer (June, July, August, September) in the surface water (0-10 m) interpolated with monitoring data (left) and simulated with the Baltic Sea model ERGOM (right) in 1987, 1990 and 1997 (Data: CHARM, HELCOM, ERGOM).

7   Spatial comparison with the Baltic Sea Typology

The first step in the implementation of the Water Framework Directive in marine systems is the development of a coastal water typology. A typology is a classification system, which divides all transitional and coastal waters into types, based on physical factors. A typology always is accompanied by a map showing the spatial distribution of the types. It is of outstanding importance and forms the basis for all other Directive activities. The implementation of the WFD and the development of national typologies are the responsibility of national authorities. As a result, every country has already developed an independent typology. The WFD defines the Baltic Sea as one Ecoregion. The coastal waters have an international character but national typologies will cause interceptions at country borders and different national typologies will complicate large scale comparisons across the Baltic Sea. Further, the definition of coastal waters in the WFD of 1 nm off the baseline is artificial. The division between

coastal waters and open waters is not in agreement with morphological, physical, chemical or biological parameters. Therefore, a joint typology, not only for the Baltic coastal waters, but the entire Baltic Sea was suggested within the CHARM project (SCHERNEWSKI & WIELGAT 2004). It serves as an umbrella, which allows the integration of the national typologies and a further subdivision according to regional demands.

Salinity was used as the main obligatory factor in this Baltic Sea typology. Residence time and depth/mixing conditions were additionally used. It is expected that these abiotic parameter control the biology of coastal waters. Therefore, the spatial distribution of these abiotic types should be reflected in biological spatial pattern as well. The question is: Are the phytoplankton distribution and the spatial distribution of types in agreement? Are the abiotic types a mirror of spatial phytoplankton distributions?
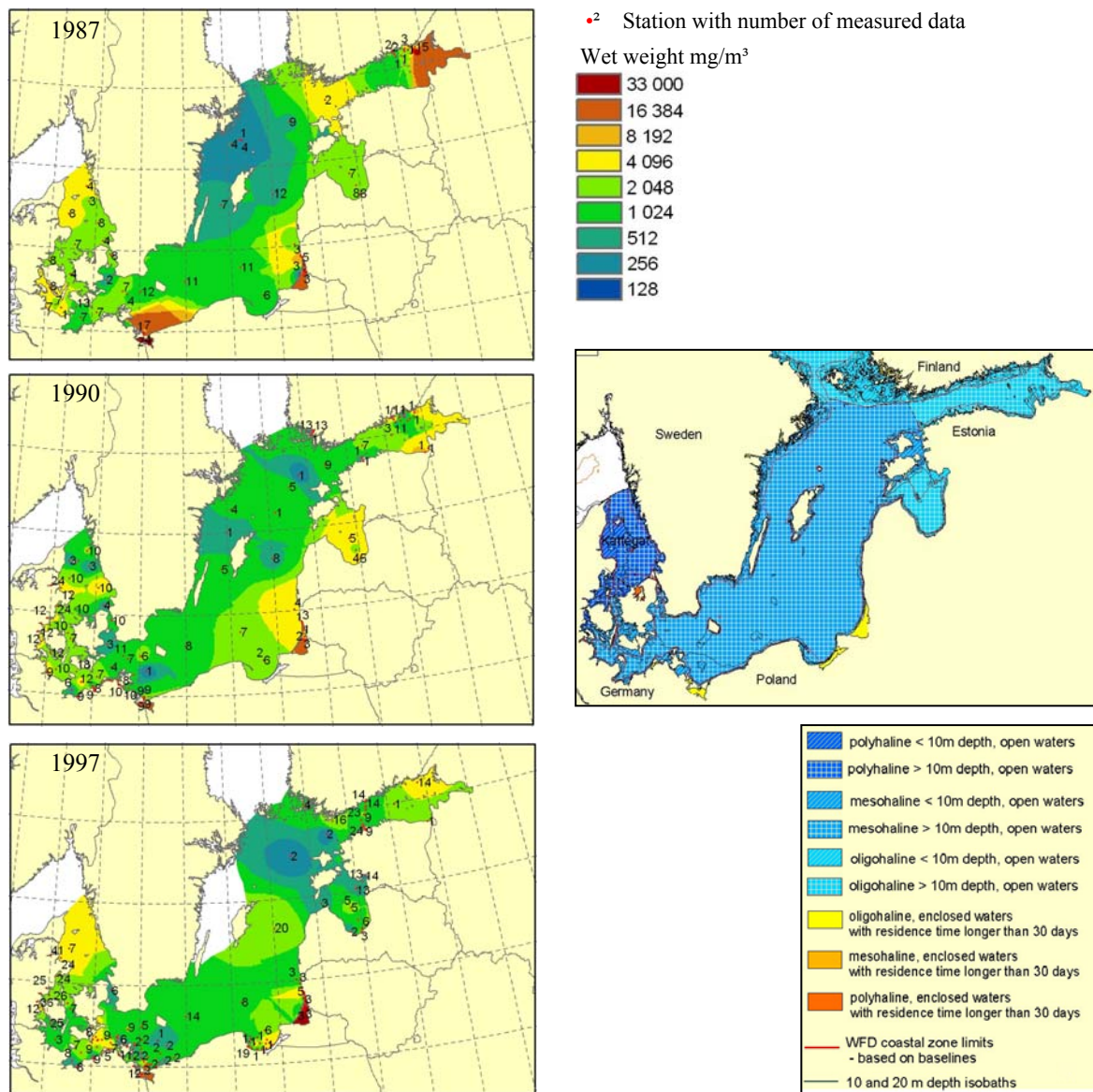
Figure 17: Comparison of annual average of phytoplankton biomass in 1987, 1990 and 1997 and Typology of the Baltic Sea (Data: CHARM, HELCOM, SCHERNEWSKI & WIELGAT 2004).

A general comparison between the average annual phytoplankton biomass and the spatial distribution of types shows a good agreement in all oligohaline bays and lagoons as well in oligohaline regions of the open sea (Fig. 17). The Gulf of Finland and the large Riga Bay are separate types and they are in

reality characterised by higher phytoplankton biomass. However, this can be an effect of higher nutrient loads as well.

The biomass in the open Baltic Sea shows a strong spatial and interannual variability. This certainly is a result of the coarse spatial resolution of the data and methodological problems linked to the sampling. The shown spatial distributions do not allow a subdivision of the open Baltic Sea and it is therefore reasonable to define it as one large type, as done in the typology. The tendency to higher biomass in the polyhaline Kattegat is well reflected in a separate type as well.

Apparent disagreements between the typology and phytoplankton biomass distributions occur near large rivers and their plumes. River plumes with their elevated nutrient concentrations are a result of anthropogenic pressures. According to the WFD these pressures shall not be reflected in a typology, because they are not permanent. The river plumes and their special features are covered by another concept, which allows a subdivision of types, the water body concept. The typology, subdivided according to external pressures into water bodies, is well able to cover river plumes (SCHERNEWSKI & WIELGAT 2004).

The comparison between the phytoplankton groups, diatoms (Fig. 7), flagellates (Fig. 6) and cyanobacteria (Fig. 7), and the typology show a very reasonable agreement. The regular occurrence of different groups in the western Arkona Sea as well as in the central Arkona Sea and the Bornholm Sea suggests treating these parts of the Baltic Sea as a separate type. This is in agreement with HELCOM, who calls this region the southern Baltic Proper. River plumes and the western Arkona Sea reflect the anthropogenic influence and suggest separate water bodies.

The two analysed species S*keletonema costatum* and *Mesodinium rubrum* are very patchy and can hardly be compared with the typology. Altogether, the basic average phytoplankton biomass distribution is well reflected by the Baltic Sea typology.

8 Discussion and conclusion

In this study we apply and validate interpolation methods, which allow the presentation and analysis of spatial phytoplankton pattern. The relatively simple IDW-method (Inverse Distance Weighted) turned out to be most suitable. However, the interpolation methods were not the major problem in this study. Nearly all phytoplankton interpolations clearly show the short-comings of the available phytoplankton database. The sampling frequency and spatial coverage is often not suitable to allow a reliable spatial phytoplankton distribution. Methodological problems, especially when considering single phytoplankton groups decrease the reliability of the data further. Temporal data aggregation into seasons is necessary. However, the used database is outstanding and by far the most comprehensive in the Baltic Region. This database allows a certain overview about the spatial distribution of phytoplankton biomass, groups, selected indicators and species for three selected years and different seasons in the entire Baltic Sea. Linking phytoplankton pattern to spatial distributions of abiotic parameter clearly shows that detailed interpretations always require time series for different regions. The knowledge of the temporal development of processes in different regions is imperative for an interpretation. We limit ourselves to the spatial aspect. Our work therefore remains in a preliminary stage and can to be regarded as basis for further analysis and interpretations.

One aim was to compare phytoplankton pattern with the typology according to the Water Framework Directive. The typology is based on three main factors surface salinity, water residence time and water depth, which corresponds to the mixing of the water column. The WFD assumes that the spatial pattern of these parameters reflect the biological parameters as well. In general, this typology reflects basic properties of the spatial phytoplankton distribution. In detail, several modifications of the typology might be useful, but due to the uncertainty of the phytoplankton data a very detailed spatial comparison is hardly possible. Altogether the existing amount and quality of phytoplankton data is not sufficient to meet all requirements in the Water Framework Directive.

How could a phytoplankton monitoring for the Baltic Sea look like? To increase the number of sampling stations and the temporal frequency of sampling significantly is necessary but hardly realistic due to financial restrictions. Measurements based on frequently travelling ferries are certainly one solution to increase the temporal data resolution and the spatial density of data along this ferry route. Several additional automatic recording moored stations in several locations are another possibility to increase the temporal data density. Together with satellite data, covering large areas and contributing the spatial aspect, an improved spatio-temporal picture of phytoplankton distributions in the Baltic Sea might result. Finally, models are another possible solution. Data together with spatial model applications might complete the spatio-temporal phytoplankton distribution in the Baltic Sea. The model ERGOM is potentially a suitable model for this purpose, but will require a further development.

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