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Phytoplankton spring bloom intensity index for the Baltic Sea estimated for the years 1992 to 2004

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Abstract

We introduce an index for estimating the annual phytoplankton spring bloom intensity in the Baltic Sea. It is based on chlorophyll *a* estimates calculated from automatically sampled fluorescence and chlorophyll *a* measurements on board cargo ships from 1992 to 2004. The intensity is described by an index including information on the chlorophyll *a* concentration and duration of the spring bloom period. In all of the years studied, the spring bloom was most intense in the Gulf of Finland. In the Gulf of Finland and the Northern Baltic Proper there was a slight tendency for the bloom to start earlier in the spring.

Introduction

Developing indicators to describe different aspects of the environment is a key to monitoring changes over long time periods. The phytoplankton spring bloom is an annual phenomenon in the Baltic Sea regulated by winter nutrient reserves, and thus an excellent indicator of eutrophication. The intensity of the bloom can be described as the concentration of chlorophyll *a*, the most abundant pigment in the spring phytoplankton community (Piippola & Kononen, 1995; Bianchi et al., 2001). However, the peak of the bloom is short and patchy both in space and time, and high sampling resolution is essential (Leppänen et al., 1994). In this study we introduce a spring bloom intensity index based on continuous fluorescence and chlorophyll *a* measurements made by automatic sampling systems on board ferries (Rantajärvi & Leppänen, 1994). Although chlorophyll *a* fluorescence is known to have a diurnal variation (Prézelin & Ley, 1980; Dandonneau & Neveux, 1997), transferring fluorescence into chlorophyll *a* gives a relatively accurate description of the phytoplankton biomass (Kuparinen, 1985).

The phytoplankton community of the Baltic Sea is characterized by a yearly succession. The winter biomass is low, especially in ice-covered areas where light is the limiting factor for growth. The annual maximum is reached in April–May, with a peak up to 10 times higher than the subsequent summer level. This spring bloom maximum consists mainly of diatoms and dinoflagellates, the succession proceeding from the Southern Baltic towards the Northern Baltic (Hällfors et al., 1981; Nömmann & Kaasik, 1992; Lignell et al., 1993; Wassmund et al., 1998). It is suggested that the start of the bloom is mainly related to available light. The entire course of the bloom is also affected by the winter nutrient reserves and the development of vertical stratification, which prevents the plankton from mixing into deep layers (Svedrup, 1952; Wassmund et al., 1998; Fennel, 1999). The bloom declines rapidly at the end of May as the nutrients are depleted, and is followed by a summer minimum (Hällfors et al., 1981; Kivi et al., 1993). In late summer another phytoplankton maximum develops, caused by cyanobacteria. The autumnal phytoplankton community is dominated by diatoms, which increase toward the late autumn (Niemi, 1973).

Materials and methods

The data used in the study were collected with an automatic flow through sampling system on board the cargo ships Finnjet (from 1992 to 1997) and Finnpartner (from 1998 to 2003) travelling across the Baltic Sea between Helsinki (60°N, 25°E) and Travemünde (54°N, 11°E) (Fig. 1). The time spent on one transect was about 2.5 days, and two to three voyages were made every week.

The water intake depth of the system was approximately 5 m. Fluorescence measurements were made by a Turner Design Model 10-AU fluorometer along the ships' whole route every 100 to 300 m during the period from February/March to October/November. In addition, 24 water samples were taken on 1 voyage a week for *in vitro* chlorophyll *a* and inorganic nutrient analyses. Chlorophyll *a* was filtered from samples on Whatman GF/F fibreglass filters and extracted in ethanol for 24 h, after which its amount was measured with a Jasco FP-750 spectrofluorometer or a Perkin-Elmer LS2-b fluorometer with an exitation wavelength of 413 nm and emission wavelength of 668 nm. The chemical analyses were made with a Lachat QC 8000 analyser, using the Lachat QuikChem Method 31-115-01-3-A for phosphate, Lachat QuikChem Method 31-114-27-1-A for silicate and a modified Lachat QuikChem Method 31-107-04-1-A for nitrate and nitrite. The sampling and analyses are described in Leppänen & Rantajärvi (1995) and Ruokanen et al. (2003).

A validation coefficient was calculated between the *in vivo* fluorescence and *in vitro* chlorophyll *a* using linear regression, the chlorophyll *a* concentration being obtained for most fluorescence measurements. During the spring, the fit was good ($R^2 > 0.7$), although in some cases of low chlorophyll *a* concentration the fit was decreased ($R^2 > 0.5$).

The spring bloom was estimated from a chlorophyll *a* 7-day running average curve. The running average was calculated from median chlorophyll *a* biomass per area per day. Missing day medians were substituted by interpolating adjacent medians.

A chlorophyll *a* threshold level of 5 μg l^{-1} was set to determine the beginning and end of the spring bloom. The threshold level was estimated through testing the chlorophyll *a* data. 5 μg l^{-1} was found to be suitable for the Baltic area; it was

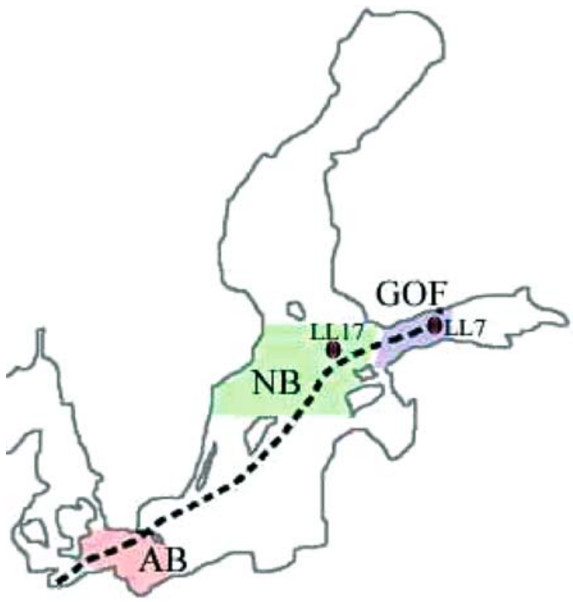

Figure 1. A map of the study area. The Arkona Sea (AB), Northern Baltic Proper (NB) and western Gulf of Finland (GOF) sub-areas are shaded. The route of the ship is presented with a broken line and the positions of the HELCOM sampling stations (LL7 and LL17) are shown.

low enough to detect the start of the bloom and high enough not to include fluctuations in the summer minimum as part of the bloom.

The intensity index was calculated by an approximation of a time-intensity integral for the days where the chlorophyll *a* 7-day running average exceeded the threshold value of 5 μg l^{-1} (Fig. 2), using the following equation:

$$Index = \sum_{i=1}^{n} h_i,$$

where i is the number of the day, n is the number of bloom days and h_i is the 7-day running average of the chlorophyll *a* daily median. The length, peak and mean chlorophyll *a* level of the bloom were also calculated.

If the chlorophyll *a* value descended below the threshold level in the middle of the bloom, the bloom was regarded as consisting of two separate periods. Thus the intensity index and the length of the bloom were calculated using only the periods exceeding the threshold level (Fig. 3). If the spring bloom did not exceed the threshold level, the intensity index was zero, as were the length, peak and mean values (Fig. 4). If the data did not cover the beginning of the bloom (i.e., data collection had started too late), the calculated intensity index, as well as the length and mean values, appeared smaller than in reality

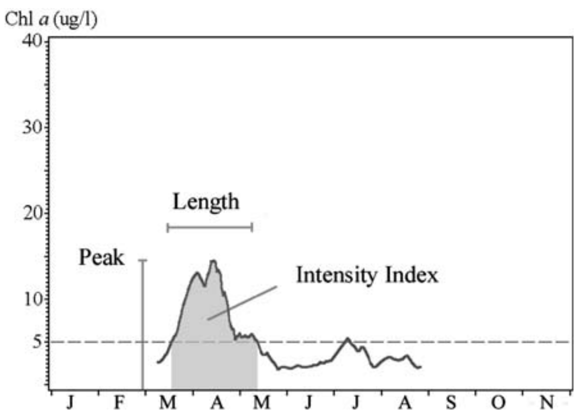

Figure 2. Seven-day running average of chlorophyll *a* in 2003 for the Northern Baltic Proper. The shaded area indicates the spring bloom, for which the intensity index is calculated; the spring bloom threshold is shown with a broken line. The peak and length of bloom are also presented.

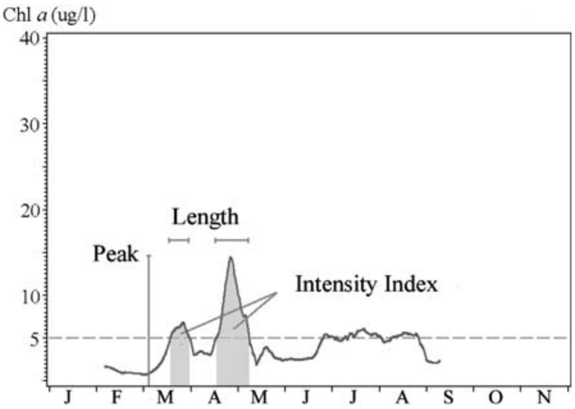

Figure 3. Seven-day running average of chlorophyll *a* in 2003 for the Northern Baltic Proper, in which the spring bloom consists of two periods.

(Fig. 5). In Tables 1, 2 and 3 these years are marked with an asterisk.

The spring bloom was studied in three areas of the Baltic Sea: the western Gulf of Finland (59°N to 60°N and 23°E to 25°E), the Northern Baltic Proper (58°N to 60°N and 18°E to 23°E) and the Arkona Basin (54°N to 55°30′N and 12°E to 15°E). These areas are used in the Algaline Joint Operational Unattended Phytoplankton Monitoring programme (Rantajärvi et al., 1996).

A nutrient value (*Nutr*) was calculated as the geometric mean of nitrate + nitrite, silicate and phosphate concentrations for each sub-area to describe the combined winter nutrient level. The geometrical mean was used because it is sensitive to the level of each nutrient, reacting to changes in the nutrient limiting phytoplankton growth. The value was calculated using the following equation:

$$Nutr = \sqrt[3]{conc(NO_2NO_3) * conc(PO_4) * conc(SiO_4)},$$

where $conc(NO_2NO_3)$, $conc(PO_4)$ *and* $conc(SiO_4)$ were the mean concentrations of nitrite + nitrate, phosphate and silicate of the sub-area, measured on a voyage in January or February, at a minimum of 3 weeks before the initiation of the spring bloom.

Observations from two monitoring stations carrying out frequent sampling for CTD profiles

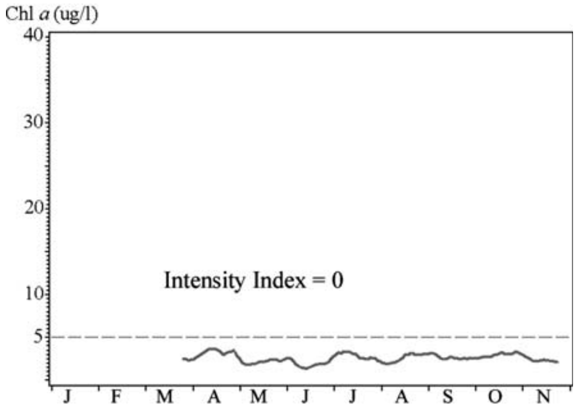

Figure 4. Seven-day running average of chlorophyll a in 2003 for the Northern Baltic Proper. In this case the spring bloom chlorophyll *a* level does not exceed the threshold.

were used for reference data on the hydrographical conditions of the northern sub-areas. Observations from March to May during the study period were investigated in order to determine the depth of the mixed surface water layer and the strength of the thermocline. The strength was described as the difference in temperatures above and below the thermocline. Station LL17 (59°01′N, 21°02′E) was used to represent the Northern Baltic Proper and station LL7 (59°50′N, 24°50′E) the western Gulf of Finland (Fig. 1).

Results

Values for the years 1992–2004 varied from 0 to 1060. The peak of the bloom varied from absent to 33.9 μg l^{-1} and the duration varied from 0 to 78 days. During some of the years the data collection started too late to cover the entire bloom and thus the index was calculated for only part of the bloom. This was the case, for example, in 1999 which was a high bloom year but which got an index value close to the long-term mean in all areas (Tables 1, 2 and 3).

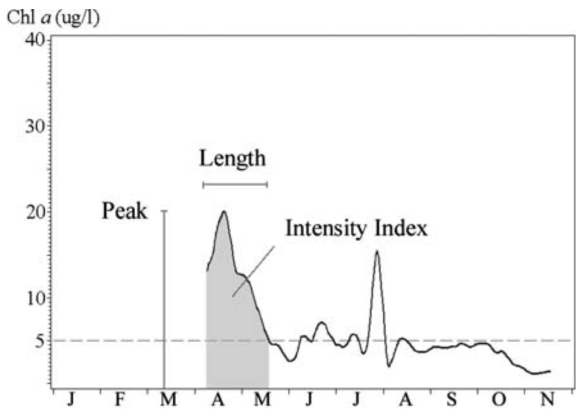

Figure 5. The curve for seven-day running average of chlorophyll *a* in 2003 for the Northern Baltic Proper. In this case the data do not cover the beginning of the bloom.

The bloom was most intense in the Gulf of Finland, with a weakening trend toward the south. Both the maximum and the duration of the bloom were considerably higher in the north than in the south. In the Arkona Basin the bloom was completely absent during two of the years. There was a high yearly variation in the intensity of the bloom, but no distinct long-term change could be detected. The lowest value occurred in 1997 and the highest in 2003 in all of the study areas (Fig. 6).

The spring bloom usually started in late March – early April in the Southern Baltic, reaching the Gulf of Finland 12 days and the Northern Baltic Proper 16 days later, on average. The lag between the starting date in the southern (Arkona Sea) and the northern sub-areas (Western Gulf of Finland and Northern Baltic Proper) varied from 0 to 19 days except during 2004, when the bloom started first in the Gulf of Finland. Over the period from 1992 to 2004 there was a slight tendency toward an earlier start in the spring (Fig. 7).

The bloom intensity was found to correlate with the winter nutrient concentration in the entire

Table 1. Spring bloom estimates for the Arkona Basin from 1992 to 2004. Parameters: spring bloom intensity index, mean chlorophyll *a* during bloom, length of bloom, highest peak of the bloom and the starting day of the bloom

Year	Index	Mean (μg l^{-1})	Length (days)	Peak (μg l^{-1})	Start day (Julian)
1992	0		0		
1993	131	7.7	17	9.7	82
1994	143	7.2	20	8.9	88
1995	228	7.1	32	10.4	85
1996	197	6.0	33	8.9	101
1997	0		0		
1998	99	6.6	15	7.6	80
1999*	241	7.8	31	14.8	100
2000*	202	6.7	30	9.7	87
2001*	152	7.2	21	8.6	78
2002	173	7.9	22	10.9	81
2003*	307	8.3	37	13.4	70
2004	108	6.0	18	6.8	86
Mean	156	7	22	10	85
SE	91.43	0.69	12.19	2.23	9.53

Years in which data have not covered the beginning of the bloom are marked with an asterisk.

study area from 1993 to 2004 (Fig. 8), though the regression fit was poor ($R^2 = 0.27$).

The density stratification developed in the Northern Baltic Proper and the western Gulf of Finland in the second half of May. The stratification consisted mainly of an intense temperature gradient, but during the years 1998 to 2004 in the Gulf of Finland a change in salinity was also involved. The depth and strength of the thermocline varied between years and areas, the gradient being clearly stronger in the Gulf of Finland than in the Northern Baltic Proper. In the Gulf of Finland a slight tendency toward a strengthening of the thermocline toward the end of the study period could be detected (Table 4).

Table 2. Spring bloom estimates for the Northern Baltic Proper from 1992 to 2004

Year	Index	Mean (μg l^{-1})	Length (days)	Peak (μg l^{-1})	Start day (Julian)
1992	277	6.9	40	9.2	101
1993	307	10.2	30	15.0	104
1994	294	8.2	36	12.7	103
1995	375	8.7	43	12.6	105
1996	477	9.0	53	17.1	96
1997	140	6.1	23	7.5	115
1998	287	8.2	35	14.4	81
1999*	367	11.8	31	15.1	101
2000	296	9.9	30	13.6	100
2001	451	11.3	40	17.3	86
2002	303	9.5	32	13.2	94
2003	522	9.3	56	14.5	81
2004	220	8.1	27	11.2	94
Mean	315	9	36	13	101
SE	97.04	1.80	9.13	3.23	9.63

Parameters same as in Table 1.

Table 3. Spring bloom estimates for the western Gulf of Finland from 1992 to 2004

Year	Index	Mean ($\mu g\ l^{-1}$)	Length (days)	Peak ($\mu g\ l^{-1}$)	Start clay (Julian)
1992	638	13.3	48	24.5	92
1993	652	12.8	51	25.4	101
1994	710	11.4	62	19.0	90
1995	759	13.5	56	25.4	98
1996	755	12.2	62	24.8	99
1997	241	8.3	29	12.8	110
1998	508	9.1	56	18.4	80
1999*	551	13.1	42	20.0	102
2000	413	10.9	38	15.4	97
2001	839	16.1	52	33.9	78
2002	576	12.8	45	21.8	93
2003*	1060	14.5	73	28.8	71
2004	722	9.3	78	16.2	59
Mean	642	12	51	23	93
SE	210.68	2.19	11.89	5.84	11.27

Parameters same as in Table 1.

Discussion

The spring bloom intensity index

The spring bloom intensity index is a mathematically simple tool that can take advantage of high resolution data. It is easily included as a part of the statistical routines on automatic sampling systems. The index takes into account both the chlorophyll *a* concentration and the duration of the bloom; these are the important factors in evaluating primary production responses to the environment (Leppänen et al., 1994). The above qualities make the index an efficient indicator for use in monitoring and long-term environmental assessments; it has been included in the HELCOM indicator report since 2003. Due to its numerical nature it is also suitable for modelling purposes.

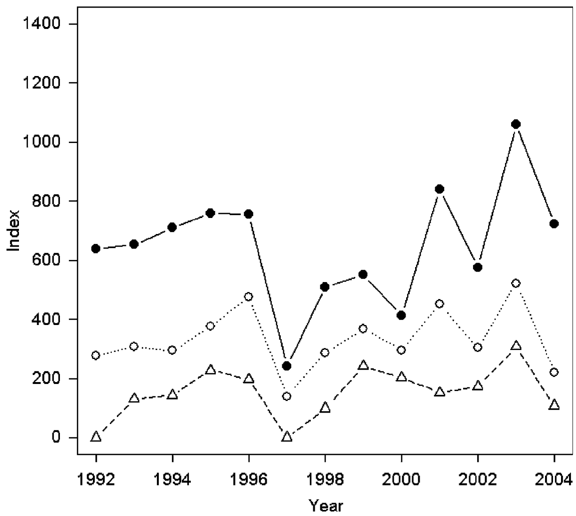

Figure 6. Development of the spring bloom intensity from 1992 to 2004 in the Arkona Basin (Δ), the Northern Baltic Proper (●) and the western Gulf of Finland (○).

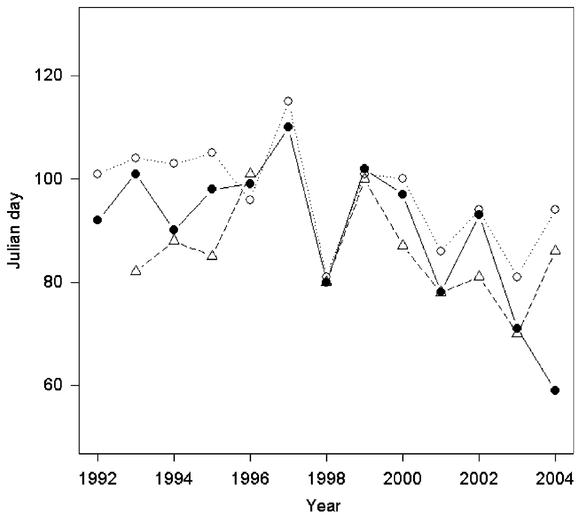

Figure 7. Changes in the spring bloom starting day from 1992 to 2004 in the Arkona Basin (Δ), the Northern Baltic Proper (●) and the western Gulf of Finland (○).

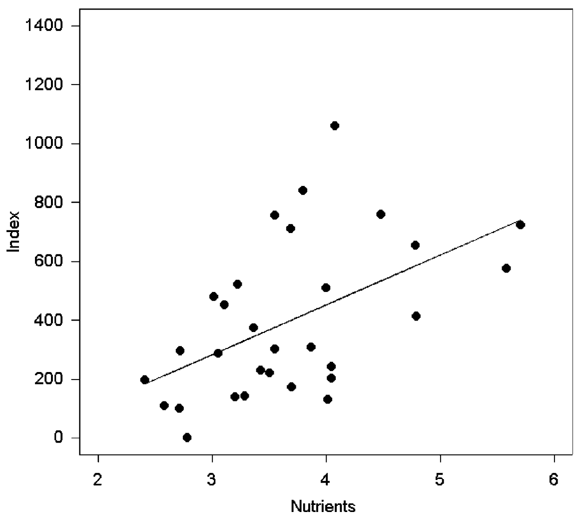

Figure 8. The relationship between the spring bloom intensity index and winter surface nutrients (nutrients calculated as described in Materials and methods). Fit of regression line: $R^2 = 0.27$.

The spring bloom threshold of 5 μg l^{-1} was set as the background level of chlorophyll *a*. This level is considered to be specific to the Baltic, and should be redetermined for other sea-areas. A lower threshold could have been used in the Southern Baltic, where the spring chlorophyll *a* level was never as high as in the northern Baltic. Keeping a constant threshold, however, allowed the intensity indices to be compared between sub-areas.

In certain years the data collection started too late to cover the beginning of the spring bloom, due to ice in the Northern Baltic. This was considered to be a problem only in the Arkona Basin sub-area, where 4 of the 12 indices were estimated from inadequate data (years 1999, 2000, 2001 and 2003 in Table 1.). In the northern sub-areas this concerned only the year 1999, where the spring bloom intensity was estimated to be close to the long-term mean (Tables 2 and 3). It is difficult to approximate the real intensity of the bloom in this case, but visual estimation from the chlorophyll *a* 7-day running average curve (Fig. 5) would lead to a value no more than 1.25 times the intensity estimated by the index. In further development of the method one could take into account the missing data, possibly by approximating a starting date using information about the progress of the bloom and its beginning during previous years.

Changes in the spring bloom

From 1992 to 2004 there was a considerable yearly variation in the intensity of the spring bloom. We found a connection between the intensity and winter surface nutrient levels. Other authors have shown that the role of available nutrients is significant throughout the bloom succession (Lignell et al., 1992; Kivi et al., 1993; Leppänen et al.,

Table 4. Estimates describing the temperature stratification in the second half of May in the Northern Baltic Proper (NB) and the Western Gulf of Finland (GOF), Parameters: depth of thermocline (mixed = no thermocline), temperature difference above and below the thermocline (ΔT)

	NB		GOF	
	Depth (m)	ΔT (°C)	Depth (m)	ΔT (°C)
1992	25	1	20	2
1993			15	5
1994			10–20	2–5
1995	Mixed	0	15	0–3
1996	25	1	12	2
1997	Mixed	1	35	2
1998	20	2	10–20	1–4
1999			10	2–5
2000			15	5
2001	25	1	15	5
2002	15	1	10–15	5–7
2003	10	5		
2004			10–20	6–7

1994; Tamminen, 1995; Kuuppo et al., 1998). The bloom seems to be controlled by other factors as well, especially by the depth of the mixed surface water layer (Kahru & Nömmann, 1990; Wassmund et al., 1998; Fennel, 1999). Naturally the extent of the ice cover in the northern sub-areas has an effect on both the amount of solar radiation available in the water column and the vernal convection. The 1997 spring bloom was delayed and insignificant, especially in the Gulf of Finland. That year the winter nutrient level was average, the winter was warmer than normal and the ice season was mild (Seinä et al., 2001). However, the mixed layer was considerably deeper than usual, and this could have had an effect on the spring bloom.

No distinct long-term change was found from 1992 to 2004. In the Arkona Basin the 1999, 2000, 2001 and 2003 spring bloom intensities were underestimated due to lacking data; had they been estimated higher, a slight increasing trend might have been detected.

The spring bloom started earlier in the southern than the northern sub-areas; this was most likely caused by the latitude-dependant differences in the amount of available solar radiation as well as by differences in the winter conditions (Svedrup, 1952; Hällfors et al., 1981).

The spring bloom was most intense in the western Gulf of Finland sub-area, as a result of both longer duration and higher chlorophyll *a* levels. It was surprising that the bloom also started earlier in the Gulf of Finland than in the Northern Baltic Proper. This could be due to the shallowness of the mixed layer in the Gulf compared to the deeper Baltic Proper (Kahru & Nömmann, 1990; Wassmund et al., 1998; Fennel, 1999).

The observed long-term tendency towards an earlier starting date in the northern sub-areas could indicate slight changes in the climate. Warm weather results in a strong and early stratification, which in turn enhances the spring bloom (Fennel, 1999). However, strong winds would tend to cause a deeper mixed layer and delayed spring bloom, as seems to have happened in 1997.

Conclusion

The spring bloom intensity index is a practical tool for estimating the annual variation in phytoplankton dynamics in the Baltic Sea. It is based on data collected by an unattended sampling system and is simple to calculate. It is thus a suitable indicator for inclusion in Baltic environment monitoring routines.

The spring bloom was most intense in the Gulf of Finland. The starting date of the bloom has become slightly earlier from 1992 to 2004 in the Gulf of Finland and the Northern Baltic Proper.

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