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A novel earth observation based ecological indicator for cyanobacterial blooms

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ABSTRACT

Cyanobacteria form spectacular mass occurrences almost annually in the Baltic Sea. These harmful algal blooms are the most visible consequences of marine eutrophication, driven by a surplus of nutrients from anthropogenic sources and internal processes of the ecosystem. We present a novel Cyanobacterial Bloom Indicator (CyaBI) targeted for the ecosystem assessment of eutrophication in marine areas. The method measures the current cyanobacterial bloom situation (an average condition of recent 5 years) and compares this to the estimated target level for 'good environmental status' (GES). The current status is derived with an index combining indicative bloom event variables. As such we used seasonal information from the duration, volume and severity of algal blooms derived from earth observation (EO) data. The target level for GES was set by using a remote sensing based data set named Fraction with Cyanobacterial Accumulations (FCA; Kahru & Elmgren, 2014) covering years 1979–2014. Here a shift-detection algorithm for time series was applied to detect time-periods in the FCA data where the level of blooms remained low several consecutive years. The average conditions from these time periods were transformed into respective CyaBI target values to represent target level for GES. The indicator is shown to pass the three critical factors set for marine indicator development, namely it measures the current status accurately, the target setting can be scientifically proven and it can be connected to the ecosystem management goal. An advantage of the CyaBI method is that it's not restricted to the data used in the development work, but can be complemented, or fully applied, by using different types of data sources providing information on cyanobacterial accumulations.

1. Introduction

Recurring harmful phytoplankton blooms can be found in many of the world's largest estuarine, coastal and freshwater areas (Paerl and Otten, 2013). In the Baltic Sea, the observed increase in cyanobacterial blooms is attributed to severe eutrophication and a subsequent change in nutrient balance caused by anthropogenic nutrient enrichment, in particular from urban areas, agriculture and industry (Vahtera et al. 2007; Conley et al. 2009; HELCOM 2009; Andersen et al., 2011). Cyanobacterial mass occurrences are considered harmful in two fundamental ways; through their toxicity and through high biomass accumulation that have multitude effects on ecosystem functioning (Glibert et al., 2005). Cyanobacterial toxins can affect organisms both through indirect and direct exposure. As well as being transferred through the food web, they can be acutely poisonous for protists, invertebrates and vertebrates, including humans (Landsberg, 2002; Karjalainen et al., 2007). On the other hand, high biomass blooms can potentially degrade ecological habitats, decrease biodiversity and increase bottom anoxia. Furthermore, through their unique ability to utilise dissolved molecular nitrogen, they may introduce new biologically available nutrients and carbon into the system in otherwise nitrogen-limited conditions (e.g. Paerl and Otten, 2013).

The EU Marine Strategy Framework Directive (MSFD; Anonymous, 2008) is the main initiative to protect the seas of Europe. It requires that "*human-induced eutrophication is minimized, especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algae blooms and oxygen deficiency in bottom waters*" (Anonymous, 2008, p. L 164/34). However, even though the increase of algal blooms are in the MSFD noted among the main adverse effects of eutrophication, the development of quantitative bloom assessment methods is lagging

Abbreviations: AB, algae barometer value; CSA, cyanobacterial surface accumulation; CyaBI, cyanobacterial bloom indicator; ECDF, empirical cumulative distribution function; EO, earth observation; FCA, fraction with cyanobacterial accumulations; GES, good environmental status; HELCOM, Baltic Marine Environment Protection Commission; MSFD, EU marine strategy framework directive; SYKE, Finnish Environment Institute

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behind. The challenges encountered in the development are common for many biological indicators: the inherent complex characteristics of the phenomenon and its complicated relationship to environmental pressures, as well as challenges in setting target values for GES in the absence of quantitative historical information (Borja et al. 2011, 2012). These issues have hindered phytoplankton indicator development work and to the best of our knowledge, an indicator on harmful algae blooms with identified target levels, has so far not been developed.

The central objective of the MSFD is to achieve or maintain GES in marine areas. The environmental indicators involved in the MSFD are binomial; good environmental status is either reached or not. The boundary value between these two classes defines the environmental target value to which current status is compared. Quantitative series of spatially extensive cyanobacterial bloom observations that reach back in time to the period when the Baltic Sea ecosystem was unaffected by anthropogenic pressures do not exist. A paleolimnological study of sediment pigments provides information on the occurrence and intensity of cyanobacterial blooms in the past century (Poutanen and Nikkilä, 2001), but this study is restricted to a few distinct sampling locations and does not provide sufficient spatial coverage for our purpose. Kahru and Elmgren (2014) present the longest spatially extensive time series on the quantity of cyanobacterial surface accumulations in the Baltic Sea, based on satellite images. Their time series covers the years 1979–2014 and constitutes the most suitable data source for the target setting of cyanobacterial bloom indicators in the area in question.

Cyanobacterial blooms in the Baltic Sea can be rapid or prevailing, and their occurrence may vary from local to basin-wide scales (e.g. Kutser et al., 2006; Reinart and Kutser, 2006; Kahru et al., 2007). Blooms are thus difficult to describe with conventional phytoplankton sampling methods, i.e. by collecting discrete water samples. Earth observation data are considered to have great potential for cyanobacterial bloom monitoring due to its extensive spatial and temporal coverage (e.g. Ferreira et al., 2011; Mouw et al., 2015; Palmer et al., 2015). However, converting images of this visually distinctive phenomenon into direct quantitative information usable in environmental assessments is challenging (cf. Kahru and Elmgren, 2014). This is mainly because the satellite sensors such as MODIS (MODerate Resolution Imaging Spectroradiometer by NASA) suitable for operative large scale monitoring, have spectral band configurations too coarse or inappropriately located to facilitate the separation of cyanobacterial biomass measurements from other phytoplankton groups (Kutser et al., 2006). The MERIS instrument (MEdium Resolution Imaging Spectrometer by European Space Agency; lifespan 2002–2012) showed potential to measure biomass of cyanobacteria by using the absorption of cyanobacteria-specific pigment phycocyanin (Simis et al., 2007; Wynne et al., 2008; Binding et al., 2011). Even though, Woźniak et al. (2016) presented a phycocyanin algorithm adapted to spectral bands of the recently launched Ocean Land Color Imager (OLCI) in the Sentinel-3 satellite by European Space Agency, a generally applicable algorithm exclusive to cyanobacterial biomass that is independent from the satellite instrument has so far not been developed. The cyanobacterial bloom characteristics, typically presented as the areal and temporal coverage or intensity of blooms, have proven to be useful in ecosystem assessment studies (e.g. Kahru et al., 2007; Klemas, 2012; Öberg, 2013; Huang et al., 2015; Palmer et al., 2015). These characteristics, typically presented as the areal and temporal coverage or intensity of blooms are mainly based on the measurements of chlorophyll a concentration or the increased turbidity from the satellite images. The use of cyanobacterial bloom characteristics in describing the cyanobacteria blooms has certain benefits. This information can be estimated not only from majority of optical EO data, but also from other environmental observations including automated measurements, transect data or citizen observations.

In this study, we describe the novel Cyanobacterial Bloom Indicator (CyaBI). The indicator evaluates the current ecological status by combining information on cyanobacterial blooms into an index. The indicator is presented applying seasonal algal bloom characteristics information derived from satellite images. In the target level setting for GES, we applied the satellite based FCA data by Kahru and Elmgren (2014) that has different approach for interpreting bloom accumulations when compared to CyaBI method.. The assessment of the ecosystem state, compares the current status and set target levels. The CyaBI method was tested in four of the open sea sub-basins covering the central and north-eastern parts of the Baltic Sea. We evaluate the indicator according to three general requirements set for marine indicators (Samhouri et al., 2012), namely 1) the ability of the used measurements to describe the current status, 2) the suitability of the GES boundary setting, and 3) how the indicator articulates with ecosystem management goals. The indicator is demonstrated by using satellite derived data, but can be complemented, or even fully applied, with other data sources. The indicator was originally referred to as the Cyanobacterial Surface Accumulation (CSA) index during its development (e.g. Anttila et al., 2015).

2. Study area and materials

2.1. Study area

The Baltic Sea, a non-tidal, semi-enclosed brackish water estuary in northern Europe, is one of the most nutrient-enriched seas in the world. Starting with deforestation and agriculture, anthropogenic activities have affected the Baltic Sea with nutrient inputs for almost 2000 years (Zillén and Conley, 2010), possibly even longer (cf. Odén, 1980; Wassmann, 2004). However, as shown by sediment investigations, the drastic increase in nutrients and productivity started only in the 1950s–1960s (Struck et al., 2000; Poutanen and Nikkilä, 2001).

Blooms of nitrogen-fixing cyanobacteria are considered to be a natural feature of the Baltic Sea, dating as far back as about 7000 years ago (Bianchi et al., 2000; Poutanen and Nikkilä, 2001; Westman et al., 2003). Early phytoplankton investigations show that already in the early 1900s, cyanobacteria occasionally occurred in great quantities in both the coastal (e.g. Levander, 1908) and the open Baltic Sea (Ostenfeld, 1931). However, during the 20th century, their occurrence became extensive and frequent, and since the 1960s cyanobacterial blooms have become common in the Baltic Proper and the Gulf of Finland (Finni et al., 2001; cf. Poutanen and Nikkilä, 2001). Today large-scale surface blooms are an annually occurring phenomenon (Reinart and Kutser, 2006; Kahru and Elmgren, 2014). The predominant bloom type during the warm water period (July–August) in the Baltic Sea is caused in particular by the filamentous nitrogen-fixing species *Aphanizomenon flos-aquae* and *Nodularia spumigena* (Hällfors, 2007). Several other phytoplankton groups may also form surface accumulations or visible discoloration of the water in summer, but these blooms are usually confined to coastal waters and are more local and transient in character (Lindholm, 1995).

The CyaBI indicator is presented by using data from four sub-basins of the Baltic Sea, namely the Gulf of Finland, Northern Baltic Proper, Western Gotland Basin and Eastern Gotland Basin (Fig. 1). The delineation of the sub-basins is based on the open sea assessment areas of the Baltic Marine Environment Protection Commission (HELCOM, 2014).

2.2. Data sets

The main data source used in the indicator development was the satellite data based daily algal bloom product of the Finnish Environment Institute (SYKE), which is in turn derived from the respective chlorophyll *a* and water turbidity products (Appendix A). All of the products constitute a part of the Finnish operative EO monitoring of the Baltic Sea (www.syke.fi/earthobservation). Since cyanobacterial blooms typically occur in the Baltic Sea during the warm water period, the earth observation data sets for years 2003–2015 constituted data

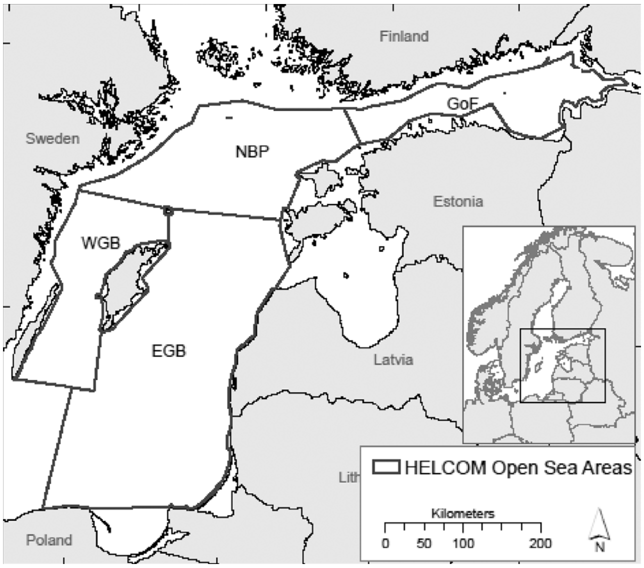

Fig. 1. The four HELCOM open sea assessment areas (sub-basins) in the Baltic Sea used in the study; Gulf of Finland (GoF), Northern Baltic Proper (NBP), Western Gotland Basin (WGB) and Eastern Gotland Basin (EGB).

from the 20 June to 31 August (79 days of each year).

The algal bloom product detects potential areas of algal accumulations based on the chlorophyll *a* concentrations and water turbidity from the satellite data. The method used for deriving the algal bloom product is described in Appendix A, but generally the procedure is as follows: first the chlorophyll *a* and water turbidity products are separately generalized and classified into four classes using empirically derived concentration values as class boundaries classes (no algal surface accumulations [0], potential algal surface accumulations [1], likely algal surface accumulations [2] and evident algal surface accumulations [3]; Fig. 2). Finally, the algal bloom product combines the two classifications by using the highest surface accumulation class for each pixel. The EO instruments used in deriving the chlorophyll *a* information were MERIS for the years 2003–2011 and MODIS for 2012–2015. The validation of the algal bloom product against the regular surface algal observations made by the Finnish Border Guard resulted in evident or good correspondence in 77% of the cases (n = 93; Appendix A). During different service provision projects for remote sensed information, accuracy assessments of SYKE's MERIS chlorophyll *a* products against different in-situ data sources have resulted coefficient of determination (r^2) value in range of 0.47–0.64 (Alasalmi et al., 2013; Attila et al., 2013) and for the SYKE's MODIS chlorophyll a product a r^2 value of 0.82 was achieved (RMSE 5.8 μg/l, n = 41), although with a limited amount of high concentration values (Simis et al., 2013). Respective accuracy assessments for SYKE's MERIS based turbidity product resulted in r^2 values between 0.76–0.83 with RMSEs of 0.73-0.86 FNUs (Attila et al., 2013). According to Simis et al. (2013), SYKEs MODIS based turbidity product resulted in r^2 of 0.49 with RMSE 0.56 FNU.

The temporal and spatial coverage of the EO data used was extensive. The data set gave annually observations on an average of 49% of days during the studied seasons. The temporal coverage was generally higher for the Gulf of Finland (56%) and Northern Baltic Proper (63%) than for the Western Gotland Basin (37%) and Eastern Gotland Basin (41%). Spatial coverage, basically the average cloud-free area in satellite images during the studied seasons, varied between 18 and 31% in the four sub-basins. On a cloud free day, the number of observations derived by EO was very high. For example, in the Gulf of Finland, one MODIS (1000 m spatial resolution) or MERIS (300 m spatial resolution) based algae bloom product gave 11 805 and 32 705 observations, respectively. Cloudiness is the main factor affecting the temporal and spatial coverage. It must be emphasised that the above mentioned numbers are average estimates and that there is great variation within and between different summers.

The Fraction with Cyanobacterial Accumulations (FCA) ratio by Kahru and Elmgren (2014) was used to derive the boundary values for GES. The FCA data for the years 1979–2014 were provided personally by Mati Kahru for use in this study. The FCA is, defined as the ratio between the number of turbid (detected surface accumulations) and valid (no surface accumulations detected) pixels during a two month period (July–August) observed from several satellite sensor data covering the studied area. For the derivation of the boundary values for GES, we calculated the CyaBI index for the converging time periods (July–August) and areas as used in the FCA calculations, since the sub-basin boundaries slightly differed from the ones used in this study. The method for retrieving the FCA ratio and the data used are described in detail by Kahru and Elmgren (2014).

3. Methods and results from the method testing

3.1. Aggregating the EO observations

The remote sensed daily algal bloom products were first spatially aggregated by calculating a so-called algae barometer value (*AB*) for each sub-basin and day during the period 20 June–31 August 2003–2015. The algae barometer value is a weighted sum of the proportion of positive algae bloom estimations in the three potentiality classes (1–3) observed in an area (Eq. (1); Rapala et al., 2012).

$$AB = \frac{1}{n_{tot}}(n_{\#cl1} + n_{\#cl2} \times 2 + n_{\#cl3} \times 3) \quad (1)$$

where n_{tot} is the total number of observations, and $n_{\#cl1}$, $n_{\#cl2}$, and $n_{\#cl3}$ are the number of algae bloom observations in classes 1–3. A problem in using this method with an extensive number of observations available from satellite data (i.e. pixels) was detected. Even a single pixel with a positive algae observation increases the daily algae barometer to a value above zero and has an effect on the bloom characteristics estimation described below. To tackle this problem, we set very low algae barometer values (< 0.002) as zero under the assumption that these do not represent significant algal blooms or, more likely, are caused by erroneous observations (e.g. caused by small clouds).

3.2. Determining the indicative bloom event variables from EO data

As indicative variables for the CyaBI index we used seasonal characteristic information, namely the duration, volume, and severity of algal blooms. These characteristics were estimated for each sub-basin and year by using an empirical cumulative distribution function (ECDF; e.g. Gentle, 2009). The ECDFs, that give the cumulative proportion of the observations, were derived from the daily algae barometer values (Fig. 3). The bloom characteristics were defined from the ECDFs as follows: i) seasonal bloom volume, i.e. the areal coverage above the ECDF functions, ii) duration of the algal surface accumulation period, i.e. the horizontal lines in Fig. 3 representing the percentage of observations with algae barometer values above 0.002, and iii) bloom severity, i.e. the 90th percentile of the algae barometer observations indicated by the vertical line in Fig. 3.

3.3. Estimating the current ecosystem status

Our method combines the indicative bloom event variables into the CyaBI index by averaging the normalised time series from each of them. In this study, the included variables were considered equally important, and a simple average was used, but optionally the indicative variables can be weighted based on their information value. The time series of indicative variables describing the bloom characteristics, as well as the FCA estimates used in the validation, were normalised according to Eq.

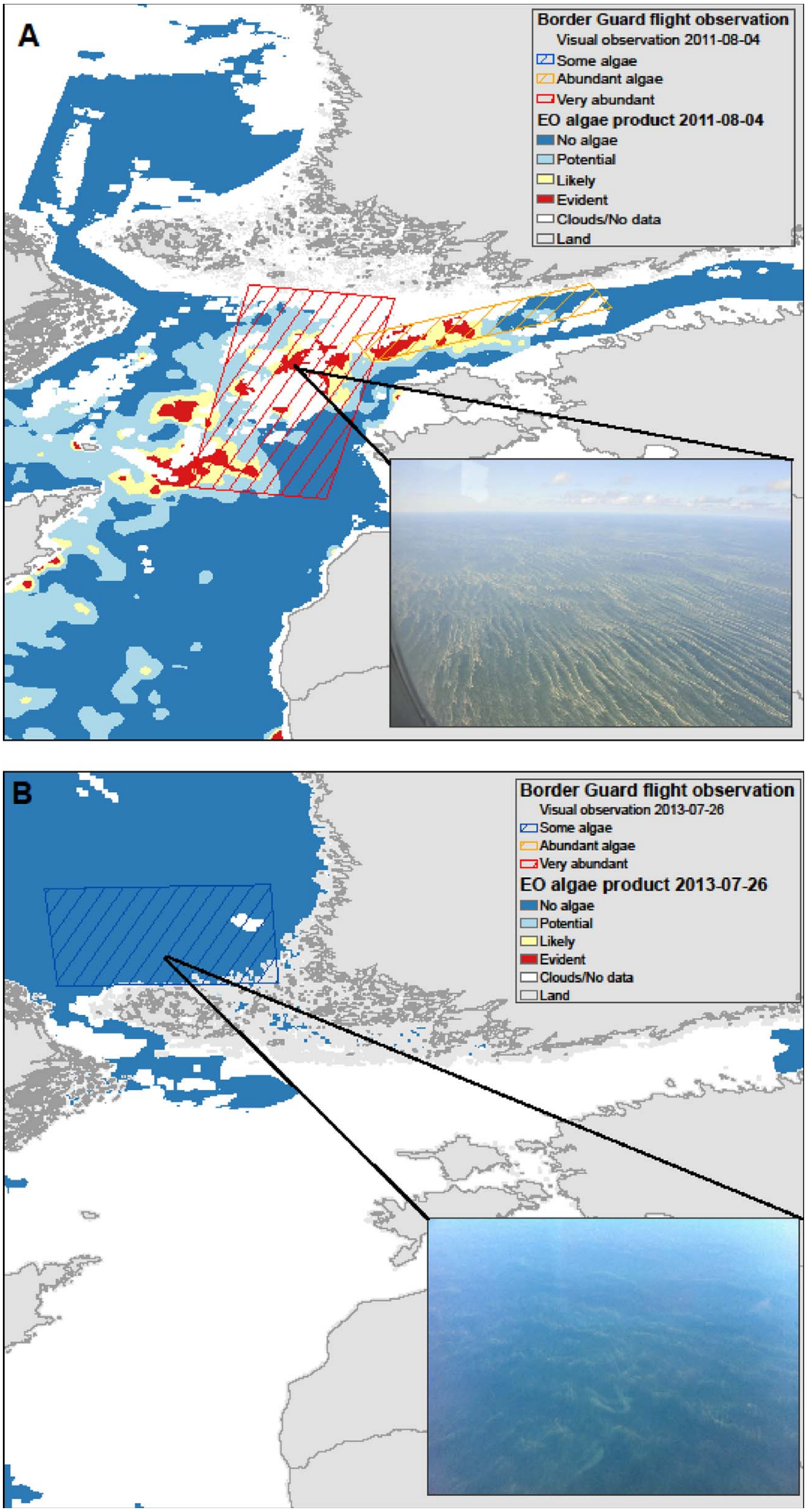

Fig. 2. Examples of surface algae bloom products together with digitized algae observation made by the Finnish Border Guard that were used in the validation of the satellite data (Appendix A). Fig. 2B illustrate the comparison from 4.8.2011 when a good correspondence was found and 2 B the situation on 26.7.2013 when no correspondence was determined. Photographs taken during the border guard flights on the marked locations are included.

(2).

$$P_{norm,y} = (P_y - P_{max})/(P_{min} - P_{max}) \quad (2)$$

where $P_{norm,y}$ is the normalized value of a parameter for year y and P_y is the actual parameter value for the year. $P_{\min}$ and $P_{\max}$ are the minimum and maximum values of time series with annual time steps.

The time series for the normalised indicative var iables and their combination to form the CyaBI index for the four sub-basins are presented in Fig. 4. The results show improved and relatively stable algal bloom conditions in the Gulf of Finland, Western Gotland Basin and Eastern Gotland Basin during the years 2009–2015 when compared to preceding years. In the Northern Baltic Proper, however, the CyaBI-index shows deterioated conditions in the recent years.

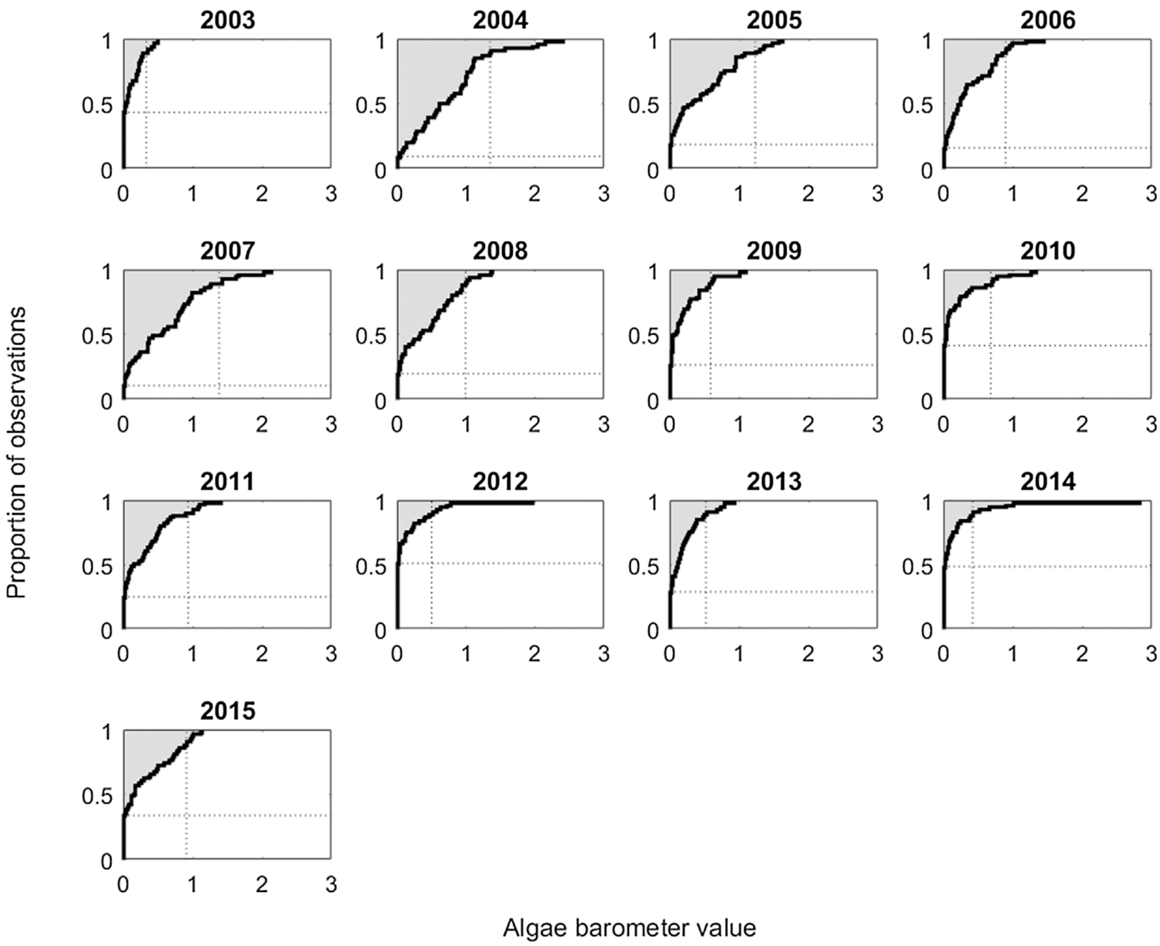

Fig. 3. Empirical cumulative distribution functions (ECDF) derived from the **daily** algae barometer values of the years 2003–2015 from the Gulf of Finland (bold black line). The bloom volume for each season is derived from the area above the ECDF function (marked in grey). Horizontal dashed lines indicate the duration of the algal bloom period and vertical dashed lines indicate bloom severity.

3.4. Setting the target levels for GES

Cyanobacterial blooms are a natural phenomenon in the Baltic Sea (Bianchi et al., 2000; Poutanen and Nikkilä, 2001; Westman et al., 2003), but during the last decades they have first become more and more common and then extensive and frequent (Finni et al., 2001). Knowing this, we did not aim to set our target level at pristine conditions, but at the best observed status in the longest available spatially representative algal bloom data set, i.e. the FCA data by Kahru and Elmgren (2014). Thus, for each sub-basin, we identified break points in the FCA time series according to the method presented by Rodionov (2004) and Rodionov and Overland (2005). The highest average FCA value (i.e. the lowest level of observed algal accumulations) in a time period without break points was used as the target value representing the FCA GES level for cyanobacterial blooms. The applied break-point method performs a sequential *t*-test with set significance level, starting from the first observation of the time series, aiming to detect if the next observation significantly differs from the mean value of the previous observations. When a significant difference is found, it must remain for the following *n* years (determined by the user) in order to be valid as a break point. As *n* we used seven years and as significance level 20%, which were considered feasible to detect the time periods with sufficiently similar FCA values and for the purpose of setting the GES levels. The identified target periods occurred in the early phases of the time series in all sub-basins (Fig. 5). The standard error of the FCA value during the target periods was used as one uncertainty source for the target setting described in Eq. (3). In each sub-basin, the FCA GES level was transformed into the respective CyaBI values by using a linear model between the two data sets. The linear model was based on the respective values from the two data sets from the four sub-basins and the years 2003–2014. In the combined data set, the CyaBI index showed a significant linear relationship with the FCA ratio (p value of F-stat $< \; < \; < 0.05$) with n = 48, r^2 = 0.59, RMSE = 0.18, slope = 0.66 with standard error of 0.08 and intercept = 0.26 with standard error 0.05. The highest differences in the data sets occurred in Eastern Gotland Basin and Western Gotland Basin and in years 2008 and 2014. The two uncertainty sources for the target setting, namely the standard error of the target period and the standard error of slope coefficient in the linear model, were combined according to the error propagation rule (Eq. (3); Rouaud, 2013).

$$\Delta e = \sqrt{s^2(\Delta t)^2 + t^2(\Delta s^2)} \qquad (3)$$

, where s refers to the slope coefficient of the linear model, t to the target value and Δt and Δa to the respective errors.

The identified FCA GES levels transformed into respective CyaBI GES levels resulted in CyaBI values ranging from 0.74 (Northern Baltic Proper) to 0.90 (Gulf of Finland) (Table 1). The confidence estimates for the GES boundaries indicated good confidence for the Gulf of Finland and Western Gotland Basin, but can be considered low especially for the Northern Baltic Proper (Table 1).

3.5. Ecosystem status assessment with the CyaBI

For the evaluation of the current bloom status, we compared the CyaBI GES target levels to the average CyaBI values of the years

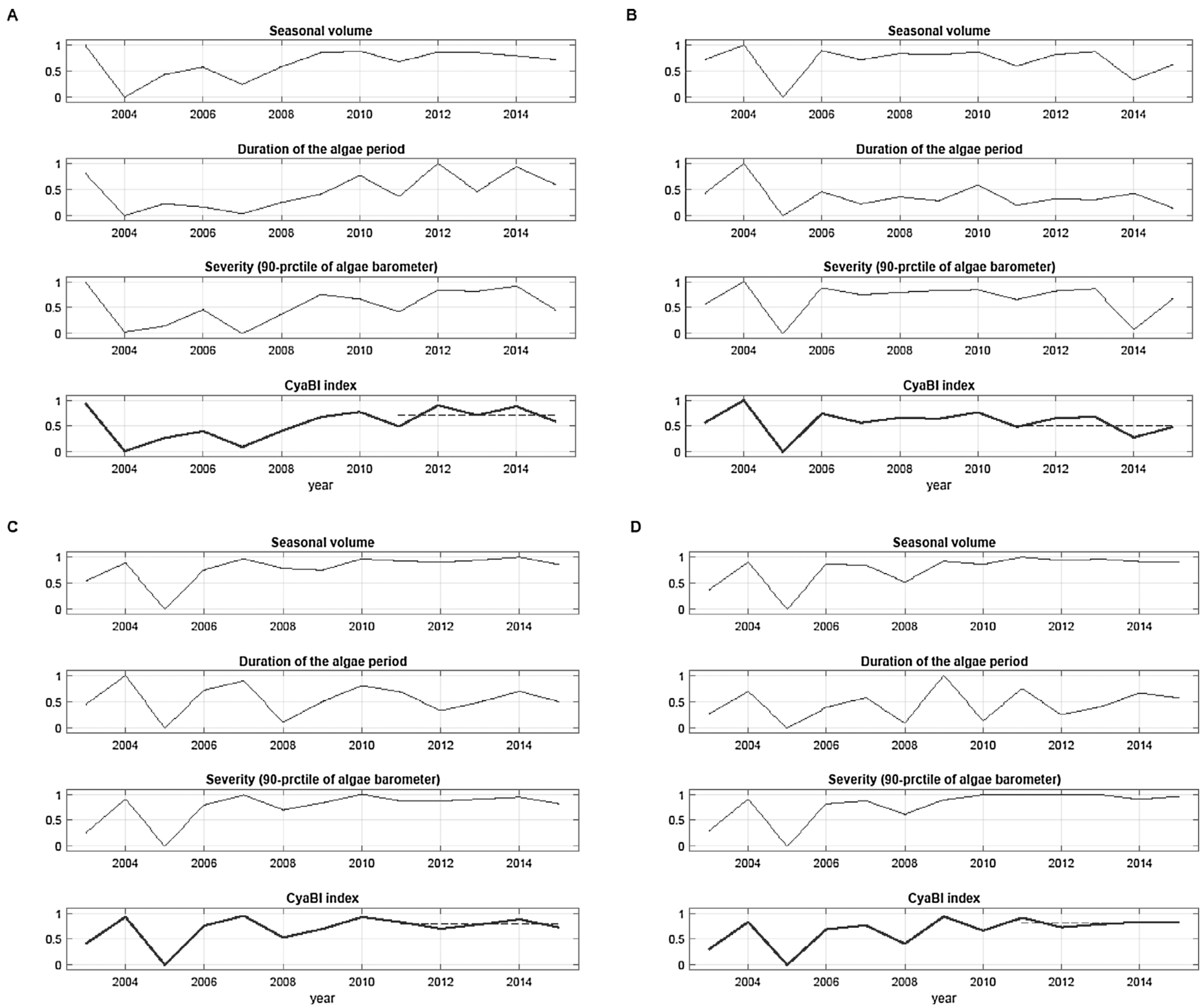

Fig. 4. The normalised indicative variables and their combination into the CyaBI index for (a) the Gulf of Finland, (b) the Northern Baltic Proper, (c) the Western Gotland Basin and (d) the Eastern Gotland Basin. Time series in each figure from the top are seasonal bloom volume, duration of the cyanobacterial bloom period, severity of the cyanobacterial bloom period, and all of these combined to form the CyaBI index. The lower the CyaBI index value, the more substantial the cyanobacterial blooms. The dashed lines in CyaBi-index figures represents the current status estimate i.e. the average conditions of years 2011–2015 (see section 3.5 and Table 1).

2011–2015 (Table 1). GES was reached only in the Eastern Gotland Basin, but here the confidence estimate for this GES boundary was also high. In the Northern Baltic Proper the current status was furthest from the GES.

4. Discussion

4.1. The performance of the current cyanobacterial bloom status estimation

Cyanobacterial blooms in the Baltic Sea can be rapid or prevailing, they show great variation on the spatial scale and can be caused by several phytoplankton species (e.g. Kutser et al., 2006; Reinart and Kutser, 2006; Kahru et al., 2007). The data and measurements on cyanobacteria blooms are obviously also affected by these variation sources. This makes the accuracy assessment of cyanobacterial bloom products challenging. We assessed the ability of the presented CyaBI index in describing the current status of cyanobacterial blooms from three perspectives. Firstly, the validation of SYKE's algal bloom product against the Finnish Border Guard flight observations shows reasonable accuracy [evident or good correspondence in 77% of comparison pairs, n = 93; and even 80% for cases where only MERIS data were used, n = 39 (Appendix A)]. Secondly, the temporal and spatial coverage of the used data can be considered high. The EO data set gave observations on average every second day, and it covered on average 18–31% of the sub-basin areas. Finally, the examination CyaBI index against the FCA data by Kahru and Elmgren (2014) showed a significant relationship. These results make us confident that the CyaBI index gives a synoptic measure of cyanobacterial accumulations in the Baltic Sea.

4.2. The data sources used in the indicator development

The data sources and their limitations, when used for the purposes of an environmental indicator, should be investigated thoroughly (Samhouri et al., 2012). The algae bloom product used as the main data source in the indicator development, is an empirical product based on the remote sensed chlorophyll *a* and turbidity data (Appendix A). Here chlorophyll *a* is intended to indicate increased phytoplankton biomass in the subsurface areas and on the surface blooms with living cyanobacteria cells. Turbidity information is aimed especially to detect the surface scums of cyanobacteria that may contain high amount dead cyanobacteria cells that have lost their chlorophyll *a* pigments. Both of these are commonly used for giving information on cyabacteria blooms (Kahru et al., 2007; Klemas, 2012; Öberg, 2013; Kahru and Elmgren, 2014; Huang et al., 2015; Palmer et al., 2015; Woźniak et al., 2016), but

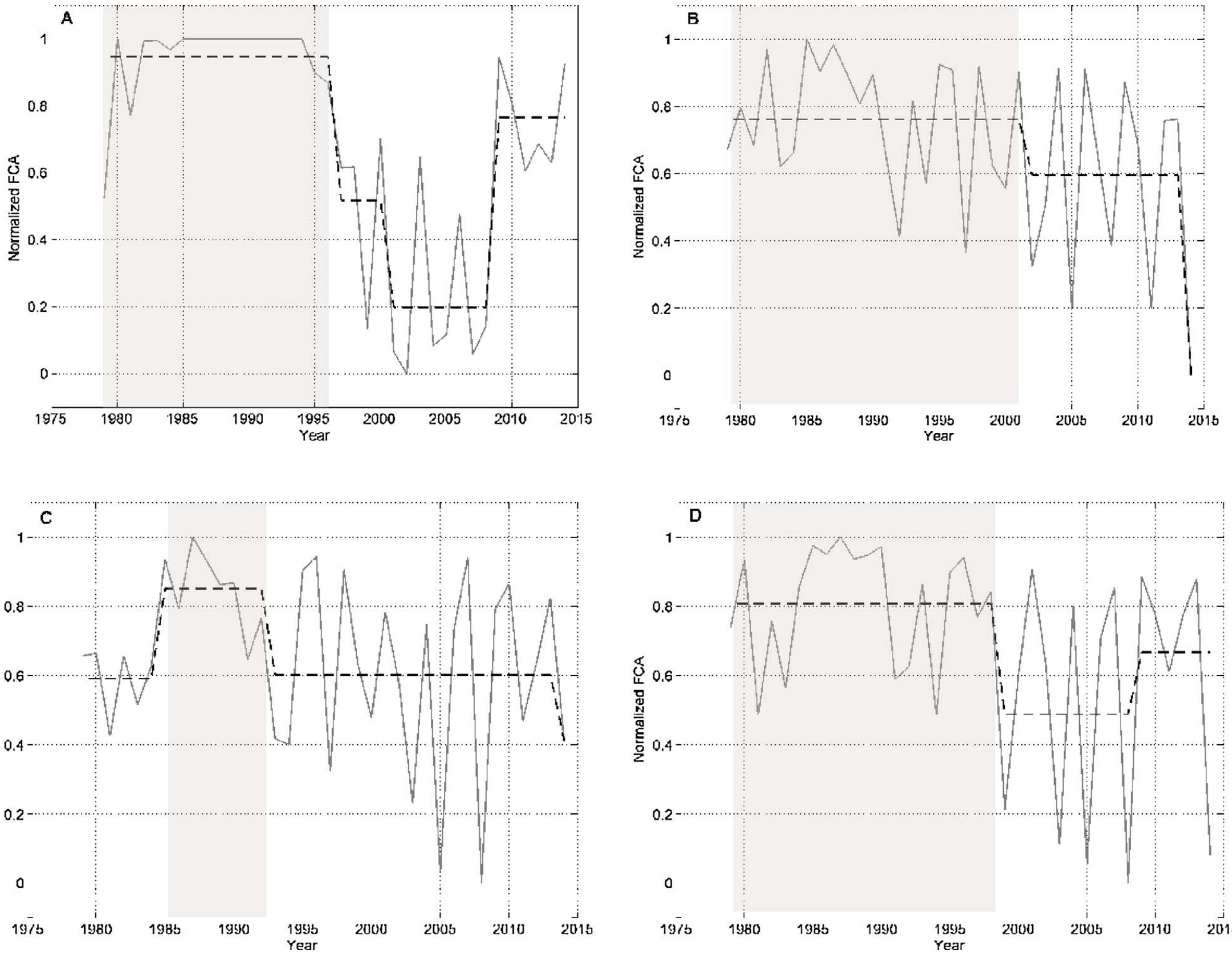

Fig. 5. Normalised FCA time series for (a) the Gulf of Finland, (b) the Northern Baltic Proper, (c) the Western Gotland Basin and (d) the Eastern Gotland Basin, with regimes without significant changes and identified break points (dashed line). The target periods, i.e. the regimes with the highest average FCA value and thus the lowest level of blooms, are highlighted in grey.

are not the best proxies for estimating cyanobacteria biomass. Main critic for methods using chlorophyll *a* in the estimation is that they neglect the phycocyanin pigment that cyanobacteria use also for their photosynthesis (Seppälä, 2009; Woźniak et al.,2016). However, Stumpf et al. (2010) and Ferreira et al. (2011) found that satellite based chlorophyll *a* can be used for estimating the characteristics of cyanobacterial surface accumulations.

The remotely sensed chlorophyll *a* and turbidity data behind the algae bloom products originated from two satellite instruments (MERIS data for 2003–2011 and MODIS data for 2012–2015). It has been shown that the spectral resolution and band widths of the MODIS instrument are generally less suitable for chlorophyll *a* estimation than those of the MERIS instrument were (Härmä et al., 2001; Kutser et al., 2006). Also the fine scale spatial and temporal variability of algae bloom events are likely to have an effect on the how satellite sensors with different measurement properties (e.g. spatial resolution and band settings) detect the phenomenon (e.g. Kutser et al., 2006; Reinart and Kutser, 2006). However, the reported accuracy assessments of chlorophyll *a* and turbidity estimations the MERIS and MODIS used here have both showed reasonable accuracy (Alasalmi et al., 2013; Attila et al., 2013; Simis et al., 2013). Therefore we considered the data set combined from two instruments feasible at least for the purpose of indicator development. We would like to also emphasize that the CyaBI method is not restricted to the data used in the development work, but can be applied by using various data sources providing information on cyanobacterial accumulations. Especially, the EO methods currently developing for estimating the phycocyaning concentration (c.f. Woźniak et al., 2016), would give significant additional information for the indicator. In general, the new instruments on board new Sentinel satellites by European Space agency, namely the MultiSpectral Instrument (MSI; on board the Sentinel 2; launched in 2015) and Ocean and Land Colour Instrument (OLCI; onboard Sentinel-3; launched in 2016

Table 1
The identified target periods for the sub-basins, the mean FCA and SE of the identified target periods, the CyaBI GES boundary values, confidence estimates for GES boundaries and current statuses estimated from CyaBI values of 2011–2015. GES is reached if the current status is higher than the GES boundary value.

Area	Target period	FCA GES value (SE of target period)	CyaBI GES boundary	CyaBI GES confidence (Δe)	CyaBI status 2011–2015
Gulf of Finland	1979–1996	0.96 (0.12)	0.90	0.11	0.72
Northern Baltic Proper	1979–2001	0.72 (0.18)	0.74	0.14	0.52
Western Gotland Basin	1985–1992	0.85 (0.11)	0.83	0.10	0.78
Eastern Gotland Basin	1979–1998	0.81 (0.17)	0.80	0.13	0.81

and 2017) are expected to increase the overall performance of satellite based information (Malenovský et al., 2012).

4.3. The methods used in aggregating bloom information

We applied two distinct methods for the spatial and temporal aggregation for deriving the seasonal bloom characteristics information. The algae barometer method (Rapala et al., 2012) was found to be very practical for the condensation of spatially extensive satellite derived data into a single statistical parameter describing the daily status in each sub-basin. In essence, the algae barometer method aggregates the weighted proportion of algal blooms observed in the three abundance classes and thus also takes into account the severity of blooms. Basic aggregation statistics, such as spatial mean or mode, do not have this property. The Empirical Cumulative Distribution Function (ECDF), on the other hand, is a visual tool for deriving the seasonal bloom characteristics information. The bloom characteristics used here, namely the duration, seasonal volume, and severity of cyanobacterial surface accumulations, all give different information on the bloom event; thus a combined index describes the bloom events more comprehensively than a single value is able to.

4.4. Setting the target levels for GES

GES represents a state where the marine environment is ecologically diverse and functioning, allowing its sustainable use (Anonymous, 2008). In setting the target levels for GES, we followed the common principles set for marine indicators (HELCOM, 2013). These include that 1) GES target levels should reflect a state where the highest average conditions are observed, 2) target levels should be a clearly connected to pressures, 3) methods applied should be science-based, 4) spatial variability needs to be taken into account and 5) the confidence of the identified target levels need to be evaluated. The target level setting used here can be argued to pass these principles. Firstly, in setting the GES boundary levels for the CyaBI indicator, we used the longest available and scientifically described time series on algal blooms from the studied area. Secondly, there is a clear connection with the pressures as discussed below. Thirdly, the method we used for identifying the target periods has been scientifically described by Rodionov (2004) and Rodionov and Overland (2005) and the data set used were spatially representative EO observations, and finally, we also estimated the confidence for the targets. The main concern in the target level setting is that the FCA data by Kahru and Elmgren (2014) use here do not reach far enough back in time to conditions with no or very little anthropogenic eutrophication. The time period starting from 1979 could not be used as a reference period for no or very little human impact. Instead, we considered the time periods with the lowest observed average bloom levels suitable to represent a sustainable level of blooms according to the best available knowledge. This approach seems particularly suitable for the Gulf of Finland, where the FCA values during the relatively long target period of 1979–1996 indicated good conditions and varied only a little. In the Western Gotland Basin, a similar confidence estimate was found, but the variability throughout the whole time series is evidently higher. In the other two sub-basins, however, the overall variability in the early years of the FCA time series and during the target periods were higher. The confidence of the target setting is also affected by the uncertainty related to the linear model used in transforming the FCA value to respective CyaBI values. The highest disagreements between the data sets were found on in Eastern Gotland Basin and Western Gotland Basin and in years 2008 and 2014. In 2008, the duration of algae blooms variable in the CyaBI index showed poor conditions while the two indicative variables showed relative good conditions (Fig. 4C and D). This might indicate that CyabBI considers the bloom event more pervasively by noting also the strength of the blooms that effect on the two other indicative variables, while FCA is based on the binomial classification o observations. The reasons for the high differences in 2014 remain unknown. The uncertainty related to the joint use of two data sets was notified by including the standard error of the slope coefficient to the combined confidence estimate. In the future, reduction of this uncertainty source is should be further studied in order to increase overall confidence of the target levels. Overall, the determined GES levels represent the best average conditions observed from the available data and follow the criteria set by HELCOM (2013). The method used in setting GES target levels can thus be considered suitable for the intended purpose. If further back in time reaching and more accurate information on cyanobacteria blooms from the Baltic Sea is generated in the future, the method used here, i.e. using the relationship between CyaBI index with data aimed for target setting, can be applied to update the GES boundaries.

4.5. Eutrophication assessment with the CyaBI and linkages to the ecosystem management

The evaluation of cyanobacterial bloom levels based on the CyaBI resulted in sub-GES conditions for all sub-basins except for the Eastern Gotland Basin. The results are in line with the HELCOM eutrophication assessment for 2007–2011, based on inorganic nitrogen, inorganic phosphorous, chlorophyll *a* concentrations, water clarity and oxygen depth (HELCOM, 2014; Fleming-Lehtinen et al., 2014), as well as in line with the assessment on inputs of nutrients (Svendsen et al., 2015). The aim of the CyaBI indicator is to reflect symptoms of Baltic Sea eutrophication driven by a surplus of the anthropogenic nutrients nitrogen and phosphorus and maintained through internal nutrient cycling processes. The connections between nutrient status and the concentrations, frequency and intensity of harmful algal blooms, including those formed by cyanobacteria, have previously been demonstrated in numerous studies (e.g. Anderson et al., 2002; O'neil et al., 2012).

In the Baltic Sea, in particular a phosphorus load into a dominantly nitrogen-limited environment is considered the main anthropogenic pressure promoting cyanobacterial blooms (Bianchi et al., 2000). Especially in offshore areas cyanobacterial blooms are strongly controlled by the internal processes and nutrient loading from anoxic bottom areas, and are largely unaffected by the short-term changes in external loads (Conley et al., 2002; Vahtera et al., 2007). Thus, reductions in external loadings of phosphorus and nitrogen potentially decrease cyanobacterial bloom formations only in the longer time scales (Vahtera et al., 2007).

5. Conclusions

We present a novel cyanobacterial bloom indicator that was tested in four Baltic Sea sub-basins. The CyaBI method is demonstrated with EO that gives the synoptic areal and temporal coverage required in algal bloom monitoring, but it can be complemented with various data which provide information on the bloom events. The CyaBI index was found to be sufficiently accurate in measuring the current status of cyanobacterial blooms, and the target level setting for GES followed the general scientific principles set for such work. In the discussion, we argued that the CyaBI indicator fulfils three critical factors set for marine indicator development (Samhouri et al., 2012), i.e. it is connected to Baltic Sea management goals, its target setting follows scientific principles, and its current status is measured accurately. Future tasks in the development include the inclusion and testing of additional data sources to the indicator and the definition of their appropriate weights in the CyaBI index, as well as the study of the usability of ecosystem modelling in deriving target conditions which represent periods with no or minor anthropogenic eutrophication impact on the marine ecosystem.

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Appendix A Derivation methods and validation of the algal bloom products from the satellite data

The methods used for deriving algal bloom potentiality information

General method

The algal bloom product of the Finnish Environment Institute (SYKE) detects potential areas of algal blooms. The general procedure for deriving the algal bloom product is as follows: first the remote sensed chlorophyll *a* and turbidity estimates are separately generalized and classified into four classes with empirically derived concentration value boundaries (no algal surface accumulations [0], potential algal surface accumulations [1], likely algal surface accumulations [2] and evident algal surface accumulations [3]; Fig. 2 of the main article). Finally, the algal bloom product combines the two classifications by using the highest surface accumulation class for each pixel. All available satellite raw data for the areas of interest were downloaded using the EOLI-SA service by ESA (https://earth.esa.int/web/guest/eoli) and from NASA's Ocean color near real time data service (see http://oceancolor.gsfc.nasa.gov/), for the MERIS and MODIS instruments, respectively.

Methods used for deriving chlorophyll a and turbidity estimations

Chlorophyll *a* concentrations were derived for the MERIS observations using BEAM plug-in processor MERIS Case-2 Water Properties Processor (FUB) according to Schroeder et al. (2007a, 2007b). The MERIS turbidity estimations applied the BEAM plug-in processor Case 2 Regional (C2R; version 1.6.2) according to Doerffer and Schiller (2007). The use of these processors for MERIS data is supported also by other studies conducted in the Baltic Sea by Kratzer et al. (2008), Beltrán-Abaunza et al. (2014) and Harvey et al. (2015). The MODIS chlorophyll *a* and turbidity were derived according to Maritorena et al. (2002, 2010) and O'Reilly et al. (1998, 2000). In the case of MODIS data, the algorithms for chlorophyll *a* and turbidity were adjusted to the best performance when compared to available *in situ* monitoring programme observations.

Methods used for deriving the algae bloom product

The calculation procedure for the algal bloom product consists of three consecutive spatial filtering procedures (e.g. Gonzalez and Woods, 1992) performed separately for the chlorophyll *a* and turbidity satellite products. The first one (a minimum spatial filtering with a window size of 3*3 pixels) is targeted to remove the outlier pixel values typically caused by small clouds or land areas. The following two filtering procedures (i.e. a median filter with an 8*8 window size and a maximum filter with a 10*10 window size) generalise the daily estimations, seeking to identify larger sea areas with elevated concentrations. Finally, the generalised chlorophyll *a* and turbidity products are separately classified by using specific limit values, namely 11, 27, and 46 μg/l for the chlorophyll *a* data and 2.5, 4.5 and 7 FNU for the turbidity. The limit values used between the algal abundance classes and the window sizes for the spatial filtering were derived by analysing histograms of satellite chlorophyll *a* and turbidity observations from blooms, together with a comparison against visual algal observations made by the Finnish Border Guard during their surveillance flights by aeroplane.

The validation method and results for the algal bloom product

In the summertime, the Finnish Border Guard patrols monitor the cyanobacterial bloom situation during their surveillance flights. The presence or absence of surface accumulations is noted with general areal markings on a map template according to the guidance for visual cyanobacterial observations described in Table A1.

The satellite data based algal bloom products by SYKE were validated qualitatively by comparing the satellite observations and the visual observations made by the Finnish Border Guard on the same dates. The correspondence between the two was estimated on a scale of evident, good, poor and none, together with general comments on observed similarities and dissimilarities. As a result, the validation of the algal bloom product from the years 2006–2008 and 2011–2015 against the visual observations from Finnish Border Guard flights resulted in good or excellent correspondence in 77% of comparison pairs (n = 93; Fig. A1). For the years 2009 and 2010, the Finnish Border Guard data were not available. In the years 2006–2008 and 2011, when MERIS data was used, the comparison resulted accuracies in evident or good classes of 80%. Respective results for the years with MODIS data of were 72%. Example of a validation pair is presented in Fig. 2 of the main article.

Table A1
The guidance for the algal abundance classification used by the Finnish Border Guard in the visual observation of algal blooms.

Class	Description
0 = No algae	No algae on the water surface or on the shoreline. The transparency of the water is not affected by algae
1 = Some algae	Greenish flakes or narrow stripes detectable in the water or along the shore. The water transparency is reduced by the algae
2 = Abundant	The water is distinctly discoloured by algae, small surface scums or cyanobacterial masses can be observed
3 = Very abundant	Widespread and heavy surface scums or thick aggregates of cyanobacteria are present

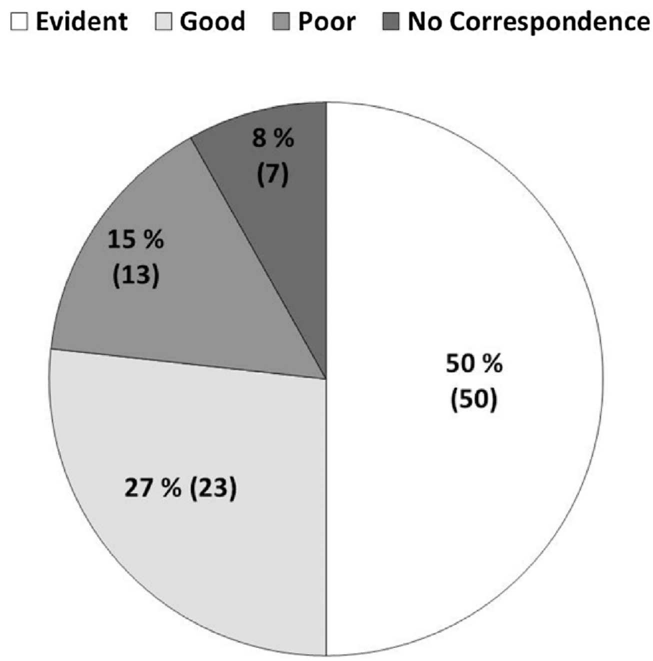

Fig. A1. The correspondence between the SYKE remote sensed algal bloom product and the Finnish Border Guard visual observations from 93 data pairs from the years 2006–2008 and 2011–2015. Chart shows the comparison pairs resulted in different correspondence classes and the number of observations in the parenthesis.

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