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Recognising cyanobacterial blooms based on their optical signature: a modelling study

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Mass populations of cyanobacteria are increasingly attracting the attention of environment agencies, water authorities, and human and animal health organizations, since they can present a range of water quality and treatment problems as well as hazards to human and animal health. The problem is especially severe in the Baltic Sea where cyanobacterial blooms occur every summer covering areas of more than 100 000 km^2. We studied optical properties of several phytoplankton species (including cyanobacteria) present in the Baltic Sea region. The measurements results were used in a bio-optical model together with optical properties of other phytoplankton species from literature. Our results show that cyanobacteria have a characteristic double feature (peak at 650 nm and phycocyanin absorption feature near 630 nm) in their reflectance spectra which can be detected by remote sensing instruments. Our estimation for the open Baltic Sea waters shows that concentration of chlorophyll has to be 8–10 mg m^{-3} before the double feature becomes detectable by remote sensing instruments which spectral resolution is 10 nm and signal-to-noise-ratio is 1000:1. Therefore, it is highly unlikely that remote sensing can be used for early warning of emerging potentially harmful blooms as chlorophyll concentrations higher than 4 mg m^{-3} qualify as blooms here.

Introduction

Cyanobacteria are common inhabitants of aquatic and terrestrial environments on a global scale and natural populations of these organisms can occur away from human influence. They respond positively to eutrophication by the development of massive populations (blooms, scums and mats) (Fogg *et al*. 1973, Sutcliffe and Jones 1992). Such mass populations are increasingly attracting the attention of environment agencies, water authorities, and human and animal health organizations, since cyanobacteria can present a range of water quality and treatment problems as well as hazards to human and animal health (NRA 1990, Ferguson *et al*. 1996). Summer blooms of nitrogen-fixing cyanobacteria: *Aphanizomenon flos-aquae*, *Nodularia spumigena* and *Anabaena* ssp., are regular phenomena in the Baltic Sea (Öström 1976, Niemistö *et al*. 1989). These bloom-forming species are toxic or potentially toxic (Sivonen *et al*. 1989).

There are various health issues associated with toxins of cyanobacteria including neurotoxins, hepatotoxins, cytototoxins, skin irritants and gastrointestinal toxins. Toxins enter the food chain through grazing zooplankton or when phytoplankton is filtered from the water by shellfish such as clams, mussels, oysters or scallops. The toxins gradually accumulate, eventually reaching levels that are potentially lethal to humans or animals (Codd 1998). Closing of beaches due to intensive cyanobacterial blooms during the peak of the summer holiday season has resulted in economic loss and considerable public interest in this phenomenon (Subramaniam *et al*. 2000).

It has been shown (Rantajärvi *et al*. 1998) that spatial and temporal frequency of conventional water-sampling programs are not adequate to report changes in phytoplankton biomass, especially during bloom conditions, when spatial and temporal variabilities in phytoplankton densities are particularly high. The use of unattended flow-through systems on ships-of-opportunity (Leppänen *et al*. 1995, Rantajärvi *et al*. 1998), and airborne (Dekker *et al*. 1992, Jupp *et al*. 1994) and satellite remote sensing (Kahru *et al*. 1993, 2000, Kahru 1997, Kutser 2004) have been recommended for gathering more reliable information about the extent of the cyanobacterial blooms than the conventional monitoring programs can provide.

The autonomous flow-through systems on ships-of-opportunity record chlorophyll-*a* concentration, salinity, temperature and turbidity but only along their routes. The ships take water from a fixed depth (usually about 5 m). It is assumed that the top water layer is well mixed and that the concentration of chlorophyll is constant in the upper mixed layer. This assumption is true in the case of "normal conditions", when algae that cannot control their vertical movement dominate in the waters. Some cyanobacteria, however, can regulate their buoyancy and in calm weather they tend to remain close to the water surface, quite often forming very dense accumulations just below the water surface and surface scum (Pearl and Ustach 1982, Sellner 1997). Taking water samples that represent the real amount of cyanobacteria in these bloom conditions is very difficult also from research vessels as vessels disturb the natural distribution of phytoplankton and water samplers cannot usually catch aggregations of cyanobacteria and surface scum unless special methods are used. Remote sensing is potentially the only way to get adequate estimates of spatial distribution and the amount of cyanobacteria during bloom conditions when the biomass is concentrated just below the water surface. On the other hand the subsurface accumulations may reach densities where the depth of penetration of remote sensing sensors is in the range of centimetres (Kutser 2004) but the layer where the majority of cyanobacteria are may be thicker. Surface scum is opaque and estimating chlorophyll-*a* concentration in or below it is practically impossible. Thus, there are extreme conditions where remote sensing can be used only for mapping location and extent of cyanobacterial bloom but not concentration of cyanobacteria in some parts of the bloom.

The concentration of chlorophyll *a* (C_{Chl}) as a general indicator of plankton biomass can be assessed in clear oceanic waters using imagery from a wide range of air- and space-born sensors (Vos *et al*. 2003). However, the standard chlorophyll-retrieval algorithms fail in coastal and inland waters even if the Case II water algorithms are used. For example, SeaWiFS and MODIS standard algorithms overestimate C_{Chl} in the Baltic Sea by 200% during non-bloom condition (Darecki and Stramski 2004) and underestimate by 3–4 times during blooms (Reinart and Kutser 2006). It has also been shown (Kutser 2004) that C_{Chl} may be underestimated by up to two orders of magnitude even with in situ methods when extensive cyanobacterial blooms occur.

Recent advances in space born remote sensing technology broaden the perspectives of monitoring toward the identification and quantification of plankton groups, and the use of remote sensing in coastal and inland waters. Algorithms for the retrieval of C_{Chl} from turbid water reflectance have been developed (Gons *et al*. 2002, Kutser 2004). Algorithms have been developed to retrieve pigments typical to cyanobacteria like cyanophycocyanin (CPC) and cyanophycoerythrin from hyperspectral reflectance (Dekker *et al*. 1991, Gons *et al*. 1992, Jupp *et al*. 1994). However, empirical relationships that have been devised to quantify cyanobacterial phycocyanin from the spectral reflectance of turbid waters

(Dekker 1993, Schalles and Yacobi 2000) require more spectral information than provided by most satellite sensors (Kutser *et al*. 2006). Hyperion and MERIS have sufficient spectral resolution to enable mapping of cyanophycocyanin from space (Simis *et al*. 2005) or to detect presence of CPC (Kutser 2004, Kutser *et al*. 2006) in the reflectance spectra. The problem is that the phycobilipigments CPC and cyanophycoerythrin are not routinely measured from water samples, and there is no information available on the CPC and cyanophycoerythrin concentrations in the Baltic Sea cyanobacteria. Moreover, Simis *et al*. (2005) found that the specific absorption coefficient of cyanophycocyanin is rather variable.

Capabilities and limitations of different satellite sensors for detecting presence of cyanobacteria in the water were studied by Kutser *et al*. (2006). The aim of the present paper is to study optical properties of algae present in the Baltic Sea and surrounding lakes and to estimate using model simulations whether or not cyanobacteria are separable from algae based on their reflectance spectra provided fully hyperspectral data (airborne, ship board or handheld sensors) is available. Kutser (2004) showed that it is possible to estimate C_{Chl} during cyanobacterial blooms provided hyperspectral remote sensing imagery with adequate spatial resolution is available. However, Kutser (2004) used rather crude classification with just 12 different classes (C_{Chl} used were 1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024 mg m^{-3}, surface scum). In the present study we attempt to estimate the threshold concentration of chlorophyll *a* for detection of cyanobacterial dominance with a theoretical hyperspectral remote sensing instrument. In addition we derive the accuracy of C_{Chl} estimations for different concentration ranges i.e. estimate the minimum changes in chlorophyll-*a* concentrations which can be detected by hyperspectral remote sensing sensors.

Methods

Laboratory measurements of optical properties of phytoplankton

Optical properties (absorption and backscattering coefficients) of five different phytoplankton species were measured in our laboratory. The studied species were the cyanobacteria *Aphanizomenon flos-aquae* var. "*baltica*", *Anabaena circinalis and Nodularia spumigena*, the diatom *Cyclotella cryptica* and the chlorophyte *Scenedesmus obliquus*. The species were chosen to match the dominating and bloom-forming groups of the three largest Swedish lakes and the Baltic Sea.

Cultures of the studied species were grown in laboratory at low light (ca. 25 μE cm^{-2} s^{-1}) in a 16/8 hour light/dark cycle at 25 °C. The absorption coefficient spectra were measured using a Perkin-Elmer Lambda 900 spectrophotometer with a Spectralon integrating sphere. Detailed description of the methodology used is described in Kutser *et al*. (2006). Chlorophyll *a* and phaeopigments were measured according to ISO10260 (1992). Backscattering coefficient of the five phytoplankton species was measured using the six-channel (440, 470, 510, 590, 620, 670 nm) HydroScat-6 (HS-6) backscattering sensor from HOBI Labs described in Maffione and Dana (1997). The HS-6 has originally been designed as a field instrument, and is supposed to be used in open waters. However, it is possible to use the instrument in the laboratory (Vaillancourt *et al*. 2004) or field (Lindfors *et al*. 2005) inside a tank, if proper precautions are taken. In this experiment a 30 l tank developed for the HS-6 was used. Detailed description of the experiment and methodology used is given in Kutser *et al*. (2006).

Bio-optical modelling

Reflectance spectra for optically deep water were calculated from a semi-empirical model described in detail by Kutser (2004). The model is based on the results of Monte Carlo studies by Gordon *et al*. (1975) and Kirk (1984) and is expressed as

$$R(0-,\lambda) = (-0.629\mu_0 + 0.975)\frac{b_b(\lambda)}{a(\lambda)+b_b(\lambda)}, \quad (1)$$

where $R(0-,\lambda)$ is irradiance reflectance of optically deep water just below the water surface, $a(\lambda)$ is the total absorption coefficient, $b_b(\lambda)$is the total backscattering coefficient, μ_0 is the cosine

of the zenith angle of the refracted photons, and λ is wavelength. The μ_0 was taken equal to 0.85 according to solar zenith angle in mid-summer at the latitude of the central Baltic Sea.

As the light passes upwards through the water-air interface it undergoes refraction that increases its angle to the vertical. Combining these effects with the effect of internal reflection, Austin (1980) proposed the factor of 0.544 for relating radiance just above the surface with radiance just below the surface. Thus we can calculate the diffuse component of just above the water surface reflectance as follows:

$$r(0+,\lambda) = (-0.629\mu_0 + 0.975)\frac{b_b(\lambda)}{a(\lambda)+b_b(\lambda)} \quad (2)$$

We assumed that there are three optically active components in the water: phytoplankton, coloured dissolved organic matter (CDOM), and non-algal particles. Under these conditions the total spectral absorption coefficient, $a(\lambda)$, is described by:

$$a(\lambda) = a_w(\lambda) + a^*_{Ph}(\lambda)C_{Chl} + a_{CDOM}(\lambda) + a^*_{SM}(\lambda)C_{SM}, \quad (3)$$

where a_w is the absorption coefficient of pure water, $a^*_{Ph}(\lambda)$ is the chlorophyll-specific spectral absorption coefficient of phytoplankton, $a_{CDOM}(\lambda)$ is the spectral absorption coefficient of CDOM, and $a^*_{SM}(\lambda)$ is the specific absorption coefficient of non-algal particles. C_{Chl} and C_{SM} are concentrations of chlorophyll *a* and total non-algal particles.

The total spectral backscattering coefficient $b_b(\lambda)$ can be described as:

$$b_b(\lambda) = 0.5b_w(\lambda) + b^*_{b,Ph}(\lambda)C_{Chl} + b^*_{b,SM}(\lambda)C_{SM}, \quad (4)$$

where b_w is the scattering coefficient of pure water and it is assumed that the backscattering probability is 50% in pure water. $b^*_{b,Ph}$ is the chlorophyll-specific backscattering coefficient of phytoplankton and $b^*_{b,SM}$ is the suspended sediment-specific spectral backscattering coefficient of non-algal particles.

In our model the values of absorption and scattering coefficients of pure water were taken from Smith and Baker (1981). The absorption by CDOM is expressed as a function of the absorption coefficient of filtered water sample at wavelength 380 nm, $a_{CDOM(380)}$, and slope factor, *S*, by the following equation:

$$a_{CDOM}(\lambda) = a_{CDOM(380)} \exp[-S(\lambda - 380)]. \quad (5)$$

According to estimations by Mäekivi and Arst (1996) $S = 0.017$ gives the best approximation in the Baltic Sea, and Estonian and Finnish lakes. The specific absorption coefficient of non-algal particles was taken from Kutser (1997), and specific scattering coefficients of non-algal particles, as well as backscattering to scattering ratio, were taken from Kutser *et al.* (2001). Values and spectral shapes of the parameters are given in Fig. 1.

The modelling was carried out for two distinctly different water types: (1) CDOM-rich coastal waters, and (2) open Baltic Sea waters. For the first water type the concentration of non-algal particles was taken as 6 mg l^{-1} and $a_{CDOM(380)}$ = 15 m^{-1} resembling the situation near a river inlet at the Estonian west coast. For the open Baltic Sea waters we took C_{SM} = 2 mg l^{-1} and $a_{CDOM(380)}$ = 1.5 m^{-1}. The selected concentrations are take from actual measurements in two distinctly different sites in Estonian coastal waters. Model simulations were computed with a large variety of chlorophyll-*a* concentrations from 1 mg m^{-3} to 300 mg m^{-3}. However, the increment used for different concentration ranges varied. An increment of 1 mg m^{-3} was used for C_{Chl} range 1–10 mg m^{-3}, an increment of 2 mg m^{-3} was used for the range 10–20 mg m^{-3}, an increment of 5 mg m^{-3} for the range 20–50 mg m^{-3}, an increment of 10 mg m^{-3} for the C_{Chl} range 50–300 mg m^{-3}.

The modelling was carried out with specific absorption and backscattering coefficients of 14 phytoplankton species. Optical properties of nine species (including three species of cyanobacteria) were taken from Ahn *et al.* (1992). Optical properties of five cultured species (including three species of cyanobacteria) were investigated as described above and Kutser *et al.* (2006).

Signal-to-noise ratio

Capabilities of remote sensing sensors are described by their capability of separating

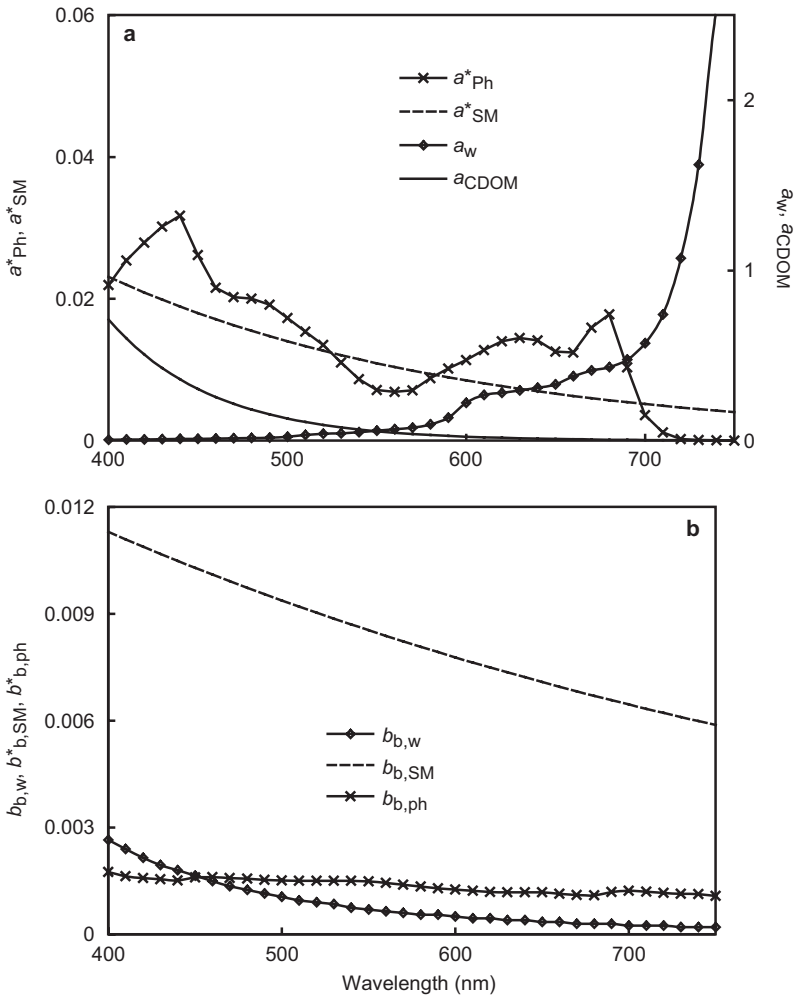

Fig. 1. Spectra of absorption (**a**) and backscattering coefficients (**b**) used in the model. a_w = absorption coefficient of pure water (m^{-1}, Smith and Baker 1981); a_{CDOM} = absorption coefficient of coloured dissolved organic matter (m^{-1}, Eq. 5); a^*_{SM} = specific absorption coefficient of suspended matter (m^2 mg^{-1}, Kutser, 1997); a^*_{Ph} = chlorophyll-*a*-specific absorption coefficient of cyanobacterium *Anabaena flos-aquae* (m^2 μg^{-1}, Kutser *et al.* 2006); b_{bw} = backscattering by pure water (m^{-1}, calculated from Smith and Baker 1981); $b^*_{b,SM}$ is the specific backscattering coefficient of suspended matter (m^2 mg^{-1}, Kutser *et al.* 2001); and $b^*_{b,Ph}$ = chlorophyll-specific backscattering coefficient of cyanobacterium *Anabaena flos-aquae* (m^2 μg^{-1}, Kutser *et al.* 2006)

desired radiance signal from noise i.e. signal to noise ratio (SNR). In actual remote sensing environments there are sources of noise in the image data such as atmospheric variability, the air-water interface with swell, wave and wavelet induced reflections and refraction of the diffuse skylight and direct sunlight (Dekker *at el.* 2005). The environmental SNR can be estimated from image data using method proposed by Dekker and Peters (1993) and further developed by Brando and Dekker (2003) and Wettle *et al.* (2004). Thus, the total SNR is a sum of instrument and environmental SNR. However, our aim was not to test suitability of the particular instruments (airborne or hand held) for detecting and quantitative mapping of cyanobacteria. Therefore we used SNR 1000:1 which is currently attainable by airborne remote sensing systems such as AVIRIS and CASI, flown under ideal circumstances (Dekker *et al.* 2001).

Results and discussion

Values of the specific absorption coefficient spectra of cyanobacteria measured by us (Figs. 2 and 3) were in the same range as values of algae species measured by by Ahn *et al.* (1992). Chlorophyll-*a*-specific absorption coefficients of cyanobacteria measured by Ahn *et al.* (1992) were 2–4 times higher in the shorter (400–550 nm) wavelength range than those of cyanobacteria measured by us. The CPC absorption feature (*in vivo* maximum at 627 nm, Dekker *et al.* 1992) was clearly visible in the specific absorption coefficient spectra of all cyanobac-

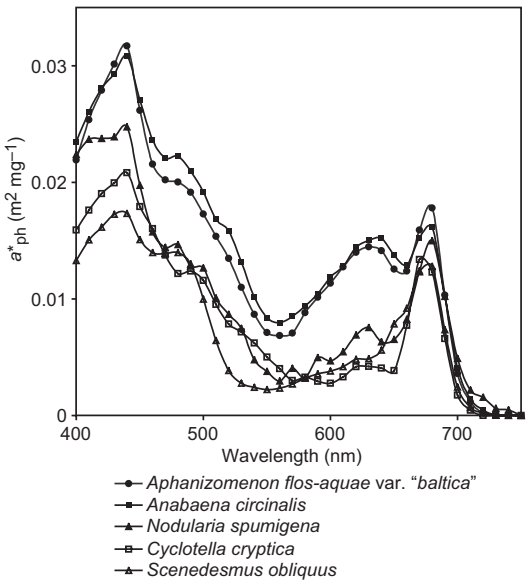

Fig. 2. Chlorophyll-*a*-specific absorption coefficient spectra of phytoplankton species measured in the present study.

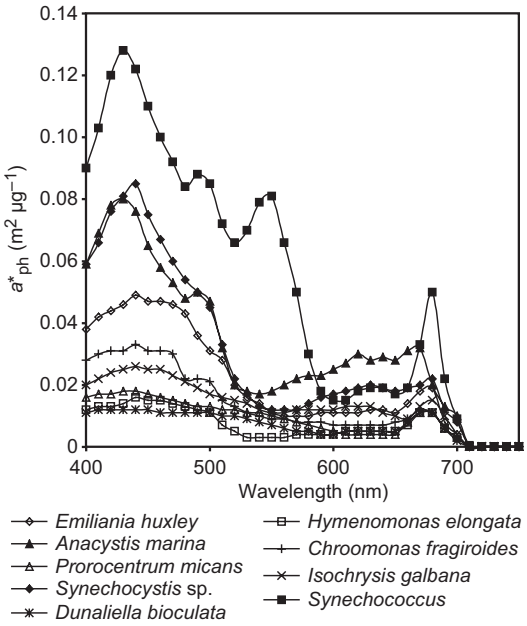

Fig. 3. Chlorophyll-*a*-specific absorption coefficient spectra reproduced from the study by Ahn *et al.* (1992).

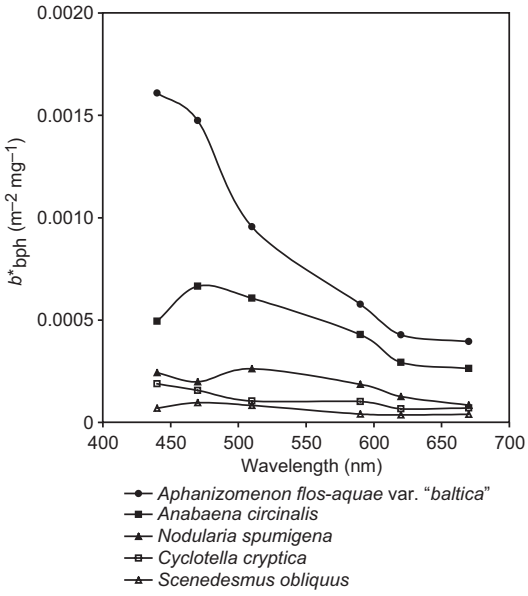

Fig. 4. Chlorophyll-*a*-specific backscattering coefficient spectra of phytoplankton species measured in the present study.

teria suggesting that it may also be detectable in reflectance spectra measured by remote sensing instruments.

The specific backscattering coefficient of cyanobacteria was higher than that of algae species (Fig. 4). Decreasing backscattering towards longer wavelengths was more significant in case of cyanobacteria. The same trends were also observed by Ahn *et al.* (1992). Backscattering coefficient values measured by Ahn *et al.* (1992) varied between 10^{-3} and 10^{-5} m^2 mg^{-1}. Backscattering coefficients of cyanobacteria measured by Ahn *et al.* (1992) were higher than those of other phytoplankton species and in the same order of range as our measurements.

In our work and results of Ahn *et al.* (1992) the specific absorption and backscattering coefficients were measured in pure algal cultures. Cyanobacteria respond to changing environmental conditions and this can also cause variability of CPC absorption values. It has been shown before that chlorophyll-*a* absorption coefficient varies with cell morphology and photo-adaptive responses (Sathyendranath *et al.* 1987, Staehr *et al.* 2002). CPC is an accessory pigment that can efficiently increase the light harvesting capacity in the "green gap" of chlorophyll *a* (Britton 1983). The cellular pigment concentration of

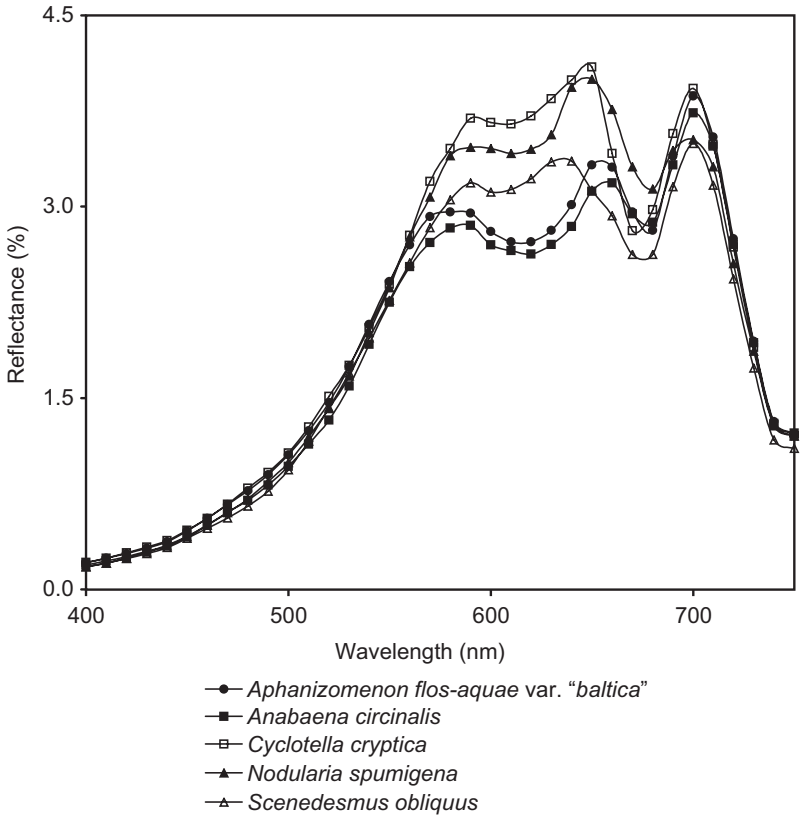

Fig. 5. Modelled reflectance spectra of different phytoplankton species in CDOM-rich coastal waters (Type I). The modelling was carried out using the following concentrations of optically active substances: C_{Chl} = 30 mg m^{-3}, C_{SM} = 6 mg l^{-1} and $a_{CDOM(380)}$ = 15 m^{-1}.

CPC can be expected to fluctuate more than chlorophyll *a* does in changing nutrient and light environments (Tandeau de Marsac 1977). It has been proposed that phycobiliproteins (including CPC) might be broken down during nitrogen shortage, to recycle amino acids (Bogorad 1975). Such mechanisms imply high variability in cellular CPC concentration and specific absorption coefficient of CPC (Simis *et al*. 2005).

Another problem related to the laboratory measurements is that optical properties of pure cultures differ from that of natural assemblages. In very dense natural cyanobacterial blooms the situation may be quite close to pure culture (cyanobacteria 72%–94% of biomass, Dekker *et al*. 1992). However, in the beginning of a cyanobacterial bloom, different algae species are dominating in the water column and their optical properties dominate in the water reflectance spectrum. It is practically not possible to measure reflectance spectra of all possible concentrations and species combinations of phytoplankton species which may be present in the Baltic Sea. Therefore, we rely on pure culture optical properties measurements in our model simulations. The effect of this simplification on the results of this study is discussed in the Modelling section.

Modelling

Figures 5 and 6 illustrate the difference between CDOM-rich coastal water and open Baltic Sea water. To improve readability of the figures we included reflectance spectra of the phytoplankton species studied in our lab only. C_{Chl} was 30 mg m^{-3} in both cases to increase the between-species difference in the reflectance spectra. It must be noted that the concentration of non-algal particles was three times higher in the Type I water (CDOM-rich coastal water) (Fig. 5) than in the Type II water (open Baltic type) (Fig. 6). There was a limited between-species difference in the reflectance spectra in Type I water (Fig. 5). However, the shape of the spectra was very similar. All the reflectance spectra contained a

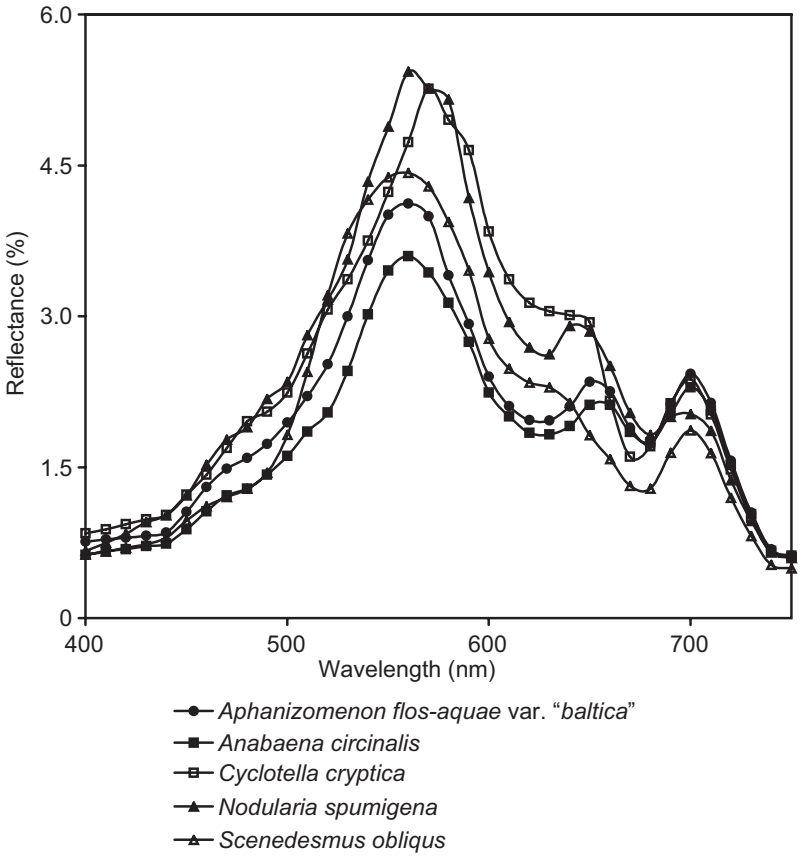

Fig. 6. Modelled reflectance spectra of different phytoplankton species in open Baltic Sea waters (Type II). The modelling was carried out using the following concentrations of optically active substances: C_{Chl} = 30 mg m^{-3}, C_{SM} = 2 mg l^{-1} and $a_{CDOM(380)}$ = 1.5 m^{-1}.

double peak (at 590 nm and 650 nm) and a minimum between them. This was caused by the absorption of light by CDOM as the concentration of phytoplankton used in the modelling was equal in both cases (Figs. 5 and 6), whereas the concentration of CDOM was 10 times higher in case of the reflectance spectra seen in Fig. 5 as compared with those seen in Fig. 6. Figure 7 illustrates the effect of CDOM on formation of the double peak (590 nm and 650 nm) which was seen in case of all studied species in CDOM-rich waters (Fig. 5). Reflectance spectra of *Cyclotella cryptica* (diatom) seen in Fig. 7 were simulated using the identical concentrations of chlorophyll *a* (30 mg m^{-3}) and non-algal particles (2 mg l^{-1}) but ten times different concentrations of CDOM. The effect of CDOM was clearly seen in wavelengths up to 730 nm in case of the brown waters. The peak near 590 nm in the brown coastal water spectra was there because this was the wavelength range where absorption by CDOM decreased to the level where backscattering due to phytoplankton and non-algal particles can be seen in the reflectance spectra. The concentration of non-algal particles used in modelling the reflectance spectra seen in Fig. 5 was three times higher than in case of Fig. 7. The backscattering coefficient of non-algal particles decreases monotonously with increasing wavelength. Therefore, the peak near 590 nm was higher in case of higher concentration of non-algal particles (Fig. 5). Thus, the minimum near 630 nm in reflectance spectra of all phytoplankton species in CDOM-rich coastal water was the result of very high absorption by CDOM and increased backscattering by higher concentration of non-algal particles and did not have anything to do with any phytoplankton pigments.

Detecting emerging cyanobacterial blooms as early as possible is important from public health point of view as many cyanobacteria are potentially toxic. Therefore we established the minimum concentrations of cyanobacteria needed to cause the spectral features that can be detected

by remote sensing sensors. If the C_{Chl} is 4 mg m^{-3} (bloom threshold in the Baltic Sea) then reflectance spectra of algae and cyanobacteria were very similar and there were no spectral features that differentiated cyanobacteria (Fig. 8). The spectral features typical to cyanobacteria became visible when the C_{Chl} increased to 8 mg m^{-3}.

The spectral feature typical to cyanobacteria is a peak near 650 nm and a CPC absorption feature near 630. Therefore, we calculated the difference in reflectance values at these two wavelengths as an indicator of presence of cyanobacteria. The results for C_{Chl} = 10 mg m^{-3} are plotted in Fig. 9. The difference was positive (reflectance at 650 nm higher than at 630 nm) in case of cyanobacteria and negative in case of other phytoplankton species. The difference had to be at least 0.1% to be detectable by remote sensing sensors with SNR 1000:1. We can assume that in case of such sensors and C_{Chl} higher than 10 mg m^{-3} it will be possible to separate water dominated by cyanobacteria from other waters having in mind that in case of algae the reflectance difference at these wavelengths is –0.1% or more and in case of cyanobacteria is higher than 0.05%.

An exception among all studied algae was *Isochrysis galbana* (Prymnesiophyceae) which optical properties were available from Ahn *et al*. (1992). The reflectance spectrum of this species in higher concentrations was similar to that of cyanobacteria, i.e. there was an absorption feature near 630 nm at chlorophyll-*a* concentrations in which it occurs in reflectance spectra of cyanobacteria. This was caused by chlorophylls c_1 and c_2, which are the major pigments (> 10% of total cellular chlorophylls as based on HPLC analyses) of the total chlorophylls in the algal class prymnesiophyceae. Chlorophylls c_1 and c_2 have absorption peaks near 628 and 630 nm, respectively (Jeffrey and Vesk 1996). Most prymnesiophyceae are planktonic marine unicells, either flagellate or with flagellate stages in the life history. Prymnesiophyceae are found mostly in tropical and subtropical oceans with only few species abundant in polar waters. Two phytoplankton species, *E. huxleyi* and *H. elongata*, studied by Ahn *et al*. (1992) belong to the prymnesiophyceae. However, there was no significant absorption feature near 630 nm neither in the measured absorption coefficient spectra nor modelled reflectance spectra of these species. Bricaud *et al*. (1988) studied optical properties of ten phytoplankton species including two species of cyanobacteria. Peaks in absorption coefficient spectra near 630 nm were observed only in case of cyanobacteria. Blooms of *Chrysochromulina* (prymnesiophyceae) have been reported in the Baltic Sea (Hajdu *et al*. 1996). Unfortunately, no information on optical properties of the *Chrysochromulina* species present in the Baltic Sea is available. Absorption coefficients of some Baltic Sea phytoplankton species — filamentous cyanobacteria (*Nodularia spumigena*, *Aphanizomenon* sp.), cryptomonad (*Rhodomonas* sp.), and diatoms (*Skeletonema* sp.) — were studied by Raateoja *et al*. (2004). For cryptomonads and diatoms, chlorophyll c_2 contributed 12%–20% of the total cellular chlorophylls based on the HPLC data. Nevertheless, there was no visible increase in specific absorption coefficient near 630 nm of these species. Therefore, it is possible that in the Baltic Sea only cyanobacteria have the characteristic feature in their absorption (and reflectance) spectra near 630 nm caused by CPC. However, optical properties of *Chrysochromulina* have to be studied before one can conclude that no other phytoplankton species in the Baltic Sea has optical signature which could be confused with cyanobacteria.

It must be noted that the CPC-to-chlorophyll absorption ratio was fixed for each species of

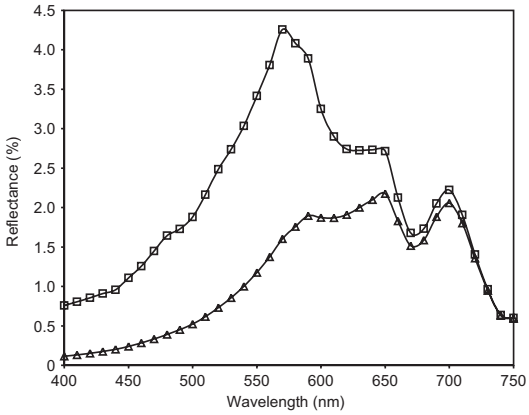

Fig. 7. Modelled reflectance spectra of a diatom *Cyclotella cryptica* for two different concentrations of CDOM: (**a**) squares: $a_{CDOM(380)}$ = 1.5 m^{-1} (**b**) triangles: $a_{CDOM(380)}$ = 15 m^{-1}. C_{Chl} = 30 mg m^{-3} and C_{SM} = 2 mg l^{-1} in both cases.

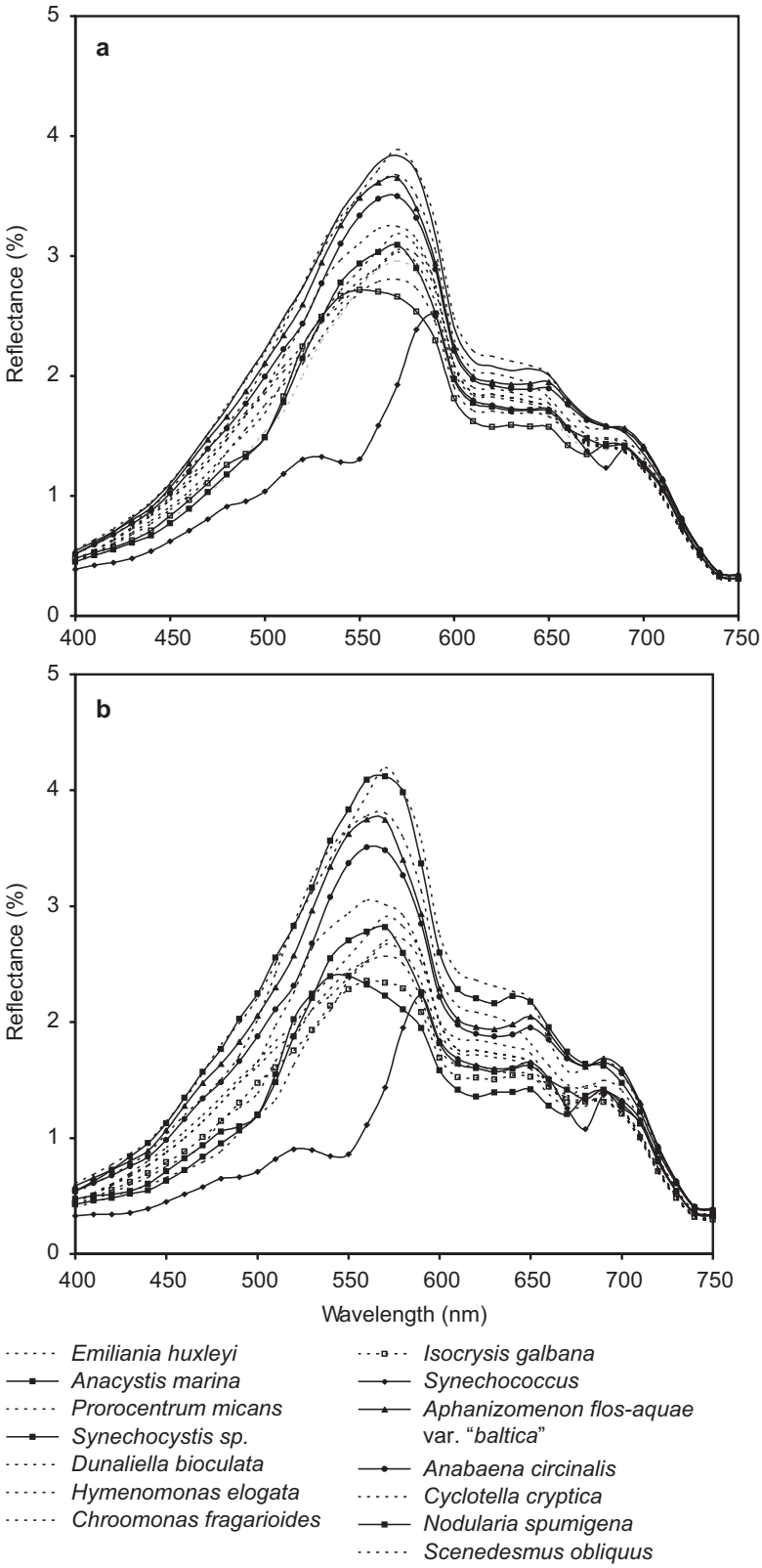

Fig. 8. Modelled reflectance spectra of different cyanobacteria (solid lines) and other species of phytoplankton (dashed line). Non-algal particles and CDOM concentrations were the same in both cases: C_{SM} = 2 mg l^{-1} and $a_{CDOM(380)}$ = 1.5 m^{-1} The chlorophyll concentrations used were (**a**) C_{Chl} = 4 mg m^{-3} and (**b**) C_{Chl} = 8 mg m^{-3}.

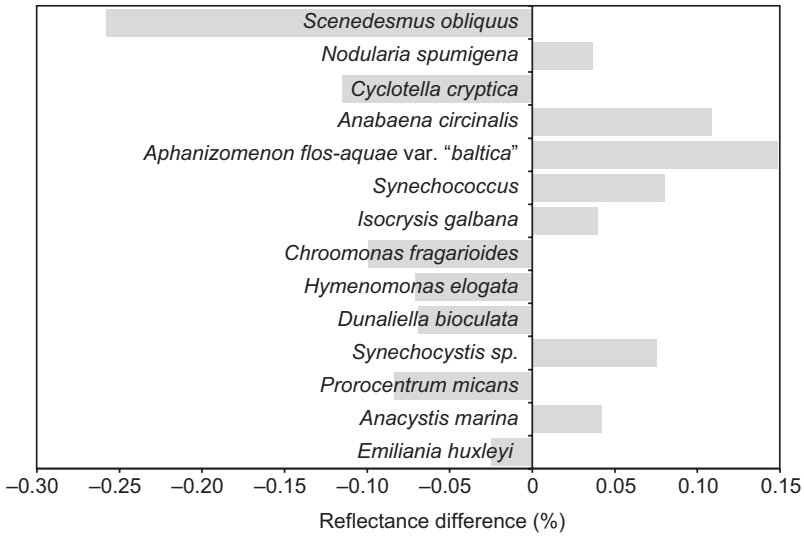

Fig. 9. Difference in reflectance values at 650 and 630 nm for all studied species. The modelling was carried out for the open Baltic Sea waters using the following concentrations of optically active substances: C_{Chl} = 10 mg m^{-3}, C_{SM} = 2 mg l^{-1} and $a_{CDOM(380)}$ = 1.5 m^{-1}.

cyanobacteria used in the modelling study as the absorption spectra were measured for one particular culture of each species. The actual concentration of CPC was not measured. Therefore, the CPC to chlorophyll ratio is unknown in terms of mass. The CPC absorption feature in remote sensing reflectance spectra may be detectable at chlorophyll values that differ from those determined in the present study if the CPC to chlorophyll ratio in actual water sample differs significantly from that used in our model simulations, where higher CPC-to-C_{Chl} ratios will facilitate the detection.

We calculated differences between reflectance spectra of *Aphanizomenon flos-aquae* in Type II water (open Baltic waters) to estimate what the minimum concentration differences are to be recognised by hyperspectral remote sensing instruments with SNR 1000:1. For C_{Chl} around 20 mg m^{-3}, the difference has to be at least 4 mg m^{-3} before the reflectance spectra are separable from each other. For C_{Chl} around 100 mg m^{-3} the difference has to be at least 10 mg m^{-3}. The wavelength range 700–720 nm is the most useful for recognising changes in phytoplankton concentration. The smallest concentration change where detectable differences occur in reflectance spectra may also be interpreted as the accuracy in chlorophyll-*a* estimation we may achieve with remote sensing instruments. Thus, for C_{Chl} smaller than 10 mg m^{-3}, the estimation accuracy is 3 mg m^{-3}, for C_{Chl} around 20 mg m^{-3} it is 4 mg m^{-3}, and for C_{Chl} from 100–200 mg m^{-3} it is 10 mg m^{-3}. Consequently, the relative error in mapping the chlorophyll-*a* concentration is higher (33%) in the case of low concentrations of phytoplankton and drops to 5% with increasing C_{Chl}.

All model simulations were performed for pure cultures. Natural assemblages, however, are mixtures of phytoplankton of different species. It means that the actual concentrations where presence of cyanobacteria becomes detectable are slightly higher than the values obtained from our model simulations. In the Baltic Sea, the spring bloom of diatoms is followed by the summer minimum when C_{Chl} is below 1–2 mg m^{-3}. Some of the registered chlorophyll *a* is due to small amount of cyanobacteria which may be already present in the water column before the actual bloom starts. Therefore, we may assume that the concentration error caused by using pure cultures instead of natural assemblages is smaller than 2 mg m^{-3}.

Our results and measurements of Ahn *et al.* (1992) both show that backscattering of cyanobacteria is higher than that of other phytoplankton species. It means that a relatively small portion of cyanobacteria in the phytoplankton assemblage can cause stronger remote sensing signal and occurrence of the peak near 650 nm. For example Dekker *et al.* (1991) measured

absorption and reflectance from samples taken from Dutch lakes. The CPC absorption feature was obvious in both reflectance and absorption spectra when the percentage of cyanobacteria was 49% of biomass (10% diatoms, 28% green algae, 13% others). The peak near 650 nm could be seen in reflectance spectra of a sample where the biomass of cyanobacteria was just 15% (60% diatoms, 15% green algae, 10% others). Thus, the presence of cyanobacteria may be seen in reflectance spectra before cyanobacteria dominate in the biomass. The peak near 650 nm in reflectance spectra was detected in shipborne (Kutser 1997), airborne (Jupp *et al*. 1994, Kallio *et al*. 2001) and satellite (Kutser 2004) measurements data. Thus, the optical signature of cyanobacteria is strong also in natural phytoplankton assemblages, not only in pure cultures.

Conclusions

Remote sensing instruments with sufficient spectral resolution (10 nm or better) and SNR better than 1000:1 can be used for identification and quantitative mapping of cyanobacteria. Modelling results showed that concentration of chlorophyll *a* has to be 8–10 mg m^{-3} before the peak near 650 nm and CPC absorption feature near 630 nm become detectable in reflectance spectra if the above mentioned sensors are used. Therefore, it is highly unlikely that remote sensing can be used for early warning of emerging cyanobacterial blooms in the Baltic Sea as C_{Chl} higher than 4 mg m^{-3} already indicates a bloom.

The potentially achievable accuracy of remote sensing estimates of the chlorophyll-*a* concentration is variable. In the open Baltic Sea waters it is around 3 mg m^{-3} for C_{Chl} below 10 mg m^{-3}, rises to 4 mg m^{-3} for C_{Chl} between 10 and 20 mg m^{-3}, and increases to 10 mg m^{-3} when C_{Chl} values are around 100–200 mg m^{-3}. Thus, we may say that the uncertainty in mapping of chlorophyll-*a* concentration in such CDOM-dominated waters like the Baltic Sea is high, whereas concentration changes of less than 3 mg m^{-3} are hardly detectable even in reflectance spectra of relatively clear open Baltic Sea waters. The relative error in chlorophyll-*a* estimates decreases towards higher concentrations.

Some algal species (Prymnesiophyceae, diatoms) may contain chlorophylls c_1, c_2 and c_3 which absorb light near 630 nm. Two of the three Prymnesiophyceae species studied by us did not have the chlorophyll-*c* absorption feature near 630 nm in their reflectance spectra and the third species is not present in the Baltic Sea. Recent studies on optical properties of different phytoplankton groups (Raateoja *et al*. 2004, J. Seppälä pers. comm.) also indicate that there is no absorption feature near 630 nm in absorption coefficient spectra of several Baltic Sea algal species despite relatively high percentage of chlorophyll *c* in total chlorophylls. However, knowledge about optical properties of *Chrysochromulina*, which can form blooms in the Baltic Sea, is needed before one can conclude that no other phytoplankton species in the Baltic Sea has optical signature which could be confused with cyanobacteria.

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