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Suitability of MODIS 250 m resolution band data for quantitative mapping of cyanobacterial blooms

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Abstract. Optical properties of three bloom-forming cyanobacteria – *Aphanizomenon flos-aquae* var. *baltica*, *Anabaena circinalis*, and *Nodularia spumigena* – were studied in laboratory experiments. Specific absorption and backscattering coefficients of these cyanobacteria were used in an optical model to simulate water reflectance in the case of different concentrations of cyanobacteria. MODIS band 1 (620–670 nm) response to changes in the concentration of cyanobacteria was simulated from the spectral reflectance data. The results show that MODIS band 1 response to changes in the concentration of cyanobacteria is nonlinear. Band 1 response is strongest in the case of *Nodularia spumigena*, indicating that quantitative mapping of this species in bloom conditions is easier than in the case of the other two species of cyanobacteria investigated.

Key words: cyanobacteria, optical properties, remote sensing, Baltic Sea.

INTRODUCTION

Mass populations of potentially harmful cyanobacteria are increasingly attracting the attention of environment agencies, water authorities, and human and animal health organizations, because cyanobacteria can present a range of amenity, water quality and treatment problems, as well as hazards to human and animal health (Ferguson et al., 1996). Reliable mapping of the amount of cyanobacteria is especially important in the case of the Baltic Sea where the cyanobacterial blooms occur every summer covering an area of more than 100 000 km^2 (Kahru, 1997).

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It was shown (Rantajärvi et al., 1998) that spatial and temporal frequencies of conventional water sampling programmes are not adequate to report changes in phytoplankton biomass, especially during bloom conditions when the spatial and the temporal variability in phytoplankton density are particularly high. The use of unattended flow-through systems on ships-of-opportunity (Leppänen et al., 1995; Rantajärvi et al., 1998), 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 to provide more reliable information about the extent of cyanobacterial blooms than the conventional monitoring programmes can provide. However, each of the methods has its shortcomings from operational monitoring point of view. The flow-through systems operate on fixed routes and do not provide any information about spatial distribution of the bloom outside the ship track. Moreover, Kutser (2004) showed that the concentration of cyanobacteria may be by one to two orders of magnitude higher than reported by the flow-through systems during cyanobacterial blooms as cyanobacteria can regulate their buoyancy and in calm weather tend to keep themselves in the top water layer not sampled by the flow-through systems. Airborne remote sensing could provide spectral and spatial resolution needed for quantitative mapping of cyanobacterial blooms. However, the cost per study area is limiting the use of airborne instruments in routine monitoring. The most cost-effective way for mapping cyanobacterial blooms is satellite remote sensing. However, one kilometre spatial resolution of ocean colour satellites (MERIS, MODIS, SeaWiFS) is not adequate in coastal waters with sophisticated shoreline and numerous islands and islets (like many coastal regions in the Baltic Sea). Moreover, standard algorithms developed for MODIS or SeaWiFS overestimate chlorophyll concentrations in the Baltic Sea by 150–200% even in non-bloom conditions (Darecki & Stramski, 2004).

The only data available regularly (up to 4 times per day) and with sufficient spatial resolution for coastal waters are MODIS band 1 (620–670 nm) and band 2 (841–876 nm) imagery with 250 m spatial resolution. Those bands were designed for mapping land, cloud, and aerosol boundaries and not water environments. Pure water is a medium whose absorbance increases exponentially with increasing wavelength at wavelengths beyond 580–590 nm. As a result the water leaving signal is very small already at wavelengths below 600 nm (Kirk, 1994) and almost negligible at wavelengths of MODIS band 1 in the case of clear natural waters (oceans, alpine lakes). However, the large amount of suspended sediment or phytoplankton in turbid water increases backscattering of light to the level where the water leaving signal in MODIS band 1 is not negligible any more. Hu et al. (2004) showed that MODIS band 1 can be used to map total suspended matter concentrations in coastal waters. Visual inspection of MODIS band 1 imagery indicates that it is straightforward to map the extent of dense cyanobacterial blooms as the signal in bloom areas is higher than in areas not affected by bloom.

The aim of the current study was to estimate by means of model simulations whether MODIS band 1 configuration is suitable for quantitative mapping of cyanobacteria to create concentration maps with 250 m spatial resolution.

METHODS

Laboratory measurements of optical properties of algae

Three dominating and bloom-forming groups of cyanobacteria in the Baltic Sea – *Aphanizomenon flos-aquae* var. *baltica*, *Anabaena circinalis*, and *Nodularia spumigena* – were grown in batch cultures at low light (ca 25 μE cm^{-2} s^{-1}) in a 16/8 hour light/dark cycle at 25 °C. About two weeks before the measurements of inherent optical properties (IOP), new batch cultures of a different phytoplankton were set up and their optical density was measured semi-daily in order to monitor their growth rate. When the growth rates were determined, a third set of new batches was set for the IOP-measurements. Finally, when all IOP-measurements were made, the chlorophyll *a* + phaeophytine *a* concentration of all batches was measured spectrophotometrically after extraction in ethanol (ISO 10 260). By backward interpolation using the measured growth rates, chlorophyll concentrations for each IOP-measurement and subsequently chlorophyll-specific IOPs could be estimated.

The optical density $OD(\lambda)$ was measured over the range 350–750 nm, using a Perkin-Elmer Lambda 900 spectrophotometer equipped with a Spectralon integrating sphere (150 mm in diameter) at the Department of Solid State Physics, Uppsala University, Sweden. A 1-cm quartz cell was placed right in front of the entrance of the integrating sphere, and the total optical density, $OD_{\mathrm{tot}}(\lambda)$, of the phytoplankton batch cultures was measured. Then the batch cultures were filtered through 0.22 μm Millipore membrane filters, and the optical density of their filtrates, $OD_{\mathrm{CDOM}}(\lambda)$, was measured. For all measurements, 0.22 μm Millipore membrane filtered, UV-treated Milli-Q water was used as reference.

To obtain the spectral absorption coefficients for the different phytoplankton species, $a_{\mathrm{Ph}}(\lambda)$, the following calculations were made:

$$a_{\mathrm{tot}}(\lambda) = \frac{2.303\, OD_{\mathrm{tot}}(\lambda)}{0.01\ \mathrm{m}}, \tag{1}$$

$$a_{\mathrm{CDOM}}(\lambda) = \frac{2.303\, OD_{\mathrm{CDOM}}(\lambda)}{0.01\ \mathrm{m}}, \tag{2}$$

$$a_{\mathrm{Ph}}(\lambda) = a_{\mathrm{tot}}(\lambda) - a_{\mathrm{CDOM}}(\lambda). \tag{3}$$

Beam attenuation was measured using the same equipment as above, but this time the 1-cm quarts cell was placed 25 cm away from the entrance of the sphere. Additionally, the entrance of the sphere was decreased to about 2 mm × 2 mm. In this way the acceptance half angle became about 0.11°. Measurements and calculations were then made analogously to those above, resulting in spectral beam attenuation coefficients for the different phytoplankton batch cultures, $c_{\mathrm{Ph}}(\lambda)$. No correction for scattering errors was made, as the low half angle should only allow an error of less than 3% (Ahn et al., 1992).

The spectral phytoplankton scattering coefficient was simply calculated as the difference between the beam attenuation and absorption coefficients of phytoplankton:

$$b_{\mathrm{Ph}}(\lambda) = c_{\mathrm{Ph}}(\lambda) - a_{\mathrm{Ph}}(\lambda). \quad (4)$$

Backscattering was measured using the six-channel HydroScat-6 (HS-6) backscattering sensor (Maffione & Dana, 1997) from HOBILabs. The HS-6 was originally designed as a field instrument to be used in open water. However, it is possible to use the instrument both in the laboratory (Vaillancourt et al., 2004) and in field (Lindfors et al., 2005) inside a tank, if proper precautions are taken. In this experiment a tank of approximately 30 L specially developed for the HS-6, was filled up with pure water (UV-treated Milli-Q water). The inner walls of the tank are black, and the bottom is convex in order to minimize any bottom effects. A small submergible pump was placed inside the tank, ensuring total mixing of the water. While the tank was filled with pure water, background backscattering possibly related to tank effects and particles in the water passing the purification system was measured. Then, at regular intervals (e.g. 2 min), a small amount of phytoplankton batch culture (10–100 mL depending on culture) of known chlorophyll concentration was added to the tank. The backscattered signal was measured as soon as it became stable. After proper care had been taken in correcting the backscattered signals using the total absorption and scattering coefficients (HOBILabs, 2000), spectra of the backscattering coefficient were obtained. However, by keeping chlorophyll concentrations relatively low in the tank during the measurements, the effects of the corrections were small, generally in the order of a few percent. By subtraction of background backscattering from the recorded backscattering after each addition of phytoplankton and then division by chlorophyll concentration, chlorophyll-specific phytoplankton backscattering could finally be calculated. The reported values were based on averages of 3–5 spectra.

Bio-optical modelling

Reflectance spectra of the optically deep water were calculated using 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 with the equation

$$R_{\infty}(0-,\lambda) = (-0.629\mu_0 + 0.975)\frac{b_{\mathrm{b}}(\lambda)}{a(\lambda) + b_{\mathrm{b}}(\lambda)}, \quad (5)$$

where $R_{\infty}(0-,\lambda)$ is irradiance reflectance just below the water surface, $a(\lambda)$ is the total absorption coefficient, $b_{\mathrm{b}}(\lambda)$ is the total backscattering coefficient, and λ is wavelength. The value of μ_0 was taken equal to 0.85 according to the solar zenith angle in mid-summer at the latitude of the central Baltic Sea.

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

$$a(\lambda) = a_{\mathrm{w}}(\lambda) + a^{*}_{\mathrm{Ph}}(\lambda) C_{\mathrm{Chl}} + a_{\mathrm{CDOM}}(\lambda) + a^{*}_{\mathrm{SM}}(\lambda) C_{\mathrm{SM}}, \quad (6)$$

where a_{w} is the absorption coefficient of pure water; $a^{*}_{\mathrm{Ph}}(\lambda)$ is the chlorophyll-specific spectral absorption coefficient of phytoplankton (cyanobacteria); $a_{\mathrm{CDOM}}(\lambda)$ is the spectral absorption coefficient of CDOM; $a^{*}_{\mathrm{SM}}(\lambda)$ is the specific absorption coefficient of suspended matter; and C_{Chl} and C_{SM} are concentrations of chlorophyll *a* and total suspended matter, respectively.

The total spectral backscattering coefficient, $b_{\mathrm{b}}(\lambda)$, can be described as:

$$b_{\mathrm{b}}(\lambda) = 0.5 b_{\mathrm{w}}(\lambda) + b^{*}_{\mathrm{b,Ph}}(\lambda) C_{\mathrm{Chl}} + b^{*}_{\mathrm{b,SM}}(\lambda) C_{\mathrm{SM}}, \quad (7)$$

where b_{w} is the scattering coefficient of pure water, and it is assumed that the backscattering probability is 50% in pure water; $b^{*}_{\mathrm{b,Ph}}$ is chlorophyll-specific backscattering coefficient of cyanobacteria; and $b^{*}_{\mathrm{b,SM}}$ is suspended sediment specific spectral backscattering coefficient of suspended matter.

In our model the values of absorption and scattering coefficients of pure water were taken from Smith & Baker (1981). The absorption by CDOM is expressed as a function of the absorption coefficient of filtered water sample at a wavelength of 400 nm, $a_{\mathrm{CDOM}}(400)$, and the slope factor, S, by the following formula:

$$a_{\mathrm{CDOM}}(\lambda) = a_{\mathrm{CDOM}}(400) \exp[-S(\lambda - 400)]. \quad (8)$$

According to estimations by Mäekivi & Arst (1996) $S = 0.017$ gives the best result in the case of the Baltic Sea and Estonian and Finnish lakes. The specific absorption coefficient of suspended matter was taken from Kutser (1997), and the specific scattering coefficients of suspended matter, as well as the backscattering probabilities (backscattering to scattering ratio), were taken from Kutser et al. (2001).

The modelling was carried out using characteristics of open Baltic Sea waters, where $C_{\mathrm{SM}} = 2$ mg L^{-1} and $a_{\mathrm{CDOM}}(400) = 1.5\ \mathrm{m}^{-1}$. These concentrations are taken from in situ measurements made during a cyanobacterial bloom, but slightly outside the dense bloom area. Model simulations were performed with a large variety of chlorophyll concentrations from 1 mg m^{-3} to 300 mg m^{-3}. However, the increment used for different concentration ranges varied. The increment of 1 mg m^{-3} was used for the chlorophyll range 1–10 mg m^{-3}, 2 mg m^{-3} for 10–20 mg m^{-3}, 5 mg m^{-3} for 20–50 mg m^{-3}, and 10 mg m^{-3} for 50–300 mg m^{-3}. MODIS band 1 results were simulated from the hyperspectral data calculating the average value for the band 1 wavelengths (620–670 nm).

RESULTS AND DISCUSSIONS

Spectral absorption of the three studied cyanobacteria species is shown in Fig. 1. Absorption by phycocyanin, a pigment present solely in cyanobacteria, is clearly seen near 630 nm. Backscattering coefficient values of the three species are quite variable as seen in Fig. 2. It must be noted that optical properties of these species have not been studied before. Despite the high need for information on inherent optical properties of different algae species such data are still rare. Spectral absorption and backscattering coefficients of some species were measured by Ahn et al. (1992). For cyanobacteria the values measured by Ahn et al. (1992) are slightly higher than the results presented in the present paper. Still, the results of the present study are within the range of values measured by Ahn et al. (1992).

Reflectance values are proportional to the ratio of absorption and backscattering coefficients. Thus, the reflectance value in MODIS band 1 may increase or decrease with increasing chlorophyll concentration if the amounts of suspended matter and CDOM remain the same. Cyanobacteria contain phycocyanin, which absorbs light at wavelengths of MODIS band 1. However, backscattering by the cyanobacteria exceeds the absorption and higher reflectance values near 650–660 nm (caused by absence of absorbing pigments there), resulting in an increase in band 1 reflectance values with increasing chlorophyll concentration in the case of all the three species studied. The backscattering coefficient of *Aphanizomenon flos-aquae* is the highest of all the species studied. Nevertheless, the band 1 reflectance values are highest

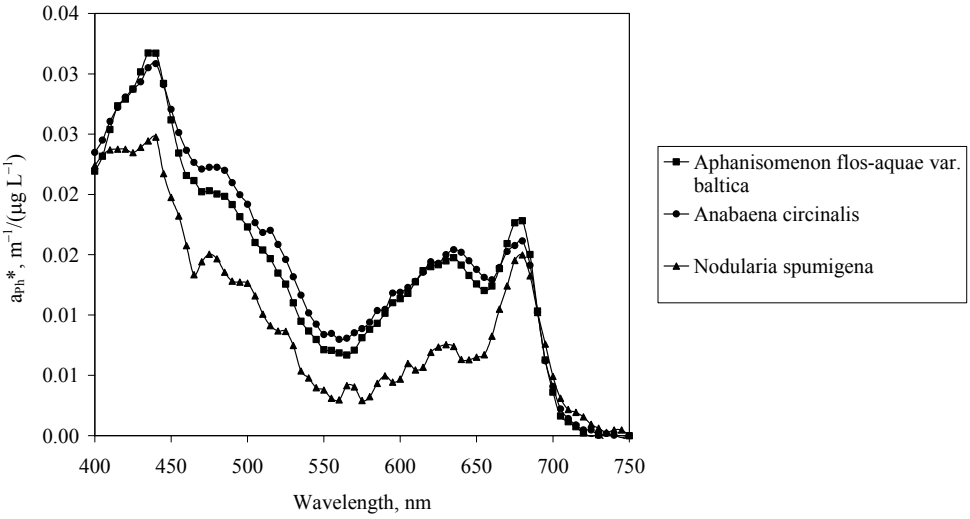

Fig. 1. Specific absorption coefficient of three species of cyanobacteria measured from laboratory cultures.

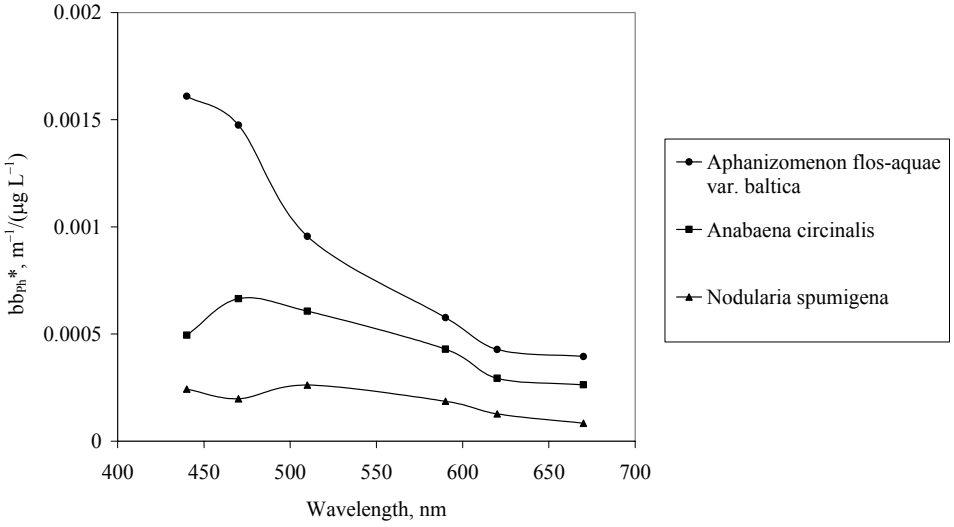

Fig. 2. Backscattering coefficients of three species of cyanobacteria measured with HydroScat-6.

in the case of *Nodularia spumigena* (see in Fig. 3) as *Nodularia*'s absorption coefficient is the lowest of the three species studied.

The modelling results indicate that quantitative mapping of *Nodularia* is easier with MODIS band 1 than in the case of the other two species. The band 1 value increases more rapidly in the case of *Nodularia* and does not reach the plateau value in the concentration range used in the present study. Laboratory (Quibell, 1992), in situ (Jupp et al., 1994), and modelling results (Kutser, 2004) indicate that chlorophyll concentrations above 300 mg m^{-3} are related to surface scum rather than dense accumulation of cyanobacteria below the surface. Detection of the surface scum is relatively straightforward with sensors with sufficient spectral and spatial resolution as cyanobacteria floating on the water surface have very high (up to 50%) reflectance in the infrared part of the spectrum. Results by Reinart & Kutser (2006) show that MODIS band 2 can be used to detect surface scum of cyanobacteria as there are no other reasons at these wavelengths (841–876 nm) that could cause an increase in the water-leaving signal in open sea waters. Thus, the cases of surface scum can be separated from dense bloom areas using MODIS band 2.

There is no information available on optical properties of water constituents beyond 750 nm. Therefore, we were not able to study whether MODIS band 2 is suitable for quantitative mapping of surface scum. It should be noted that this problem may be unsolvable as remote sensing sensors can see only the surface of scum but scum may be up to several centimetres thick. Another problem is that optical properties of the surface of scum may differ from those inside the scum as cyanobacteria are decaying more rapidly on the surface of the scum due to photo-

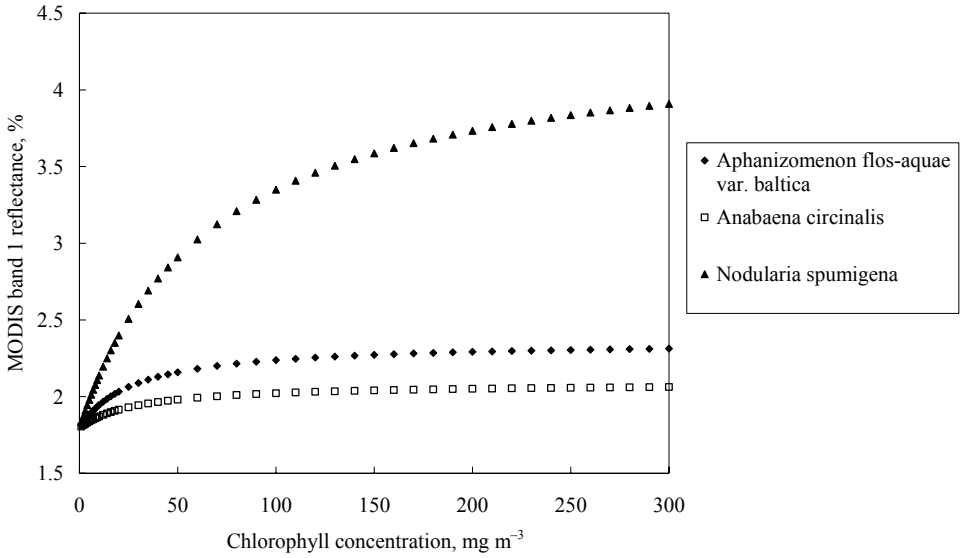

Fig. 3. Dependence of simulated reflectance values in MODIS band 1 on different concentrations of chlorophyll in the case of three cyanobacteria species investigated.

oxidation and other processes. Optical properties of cyanobacterial scums need further studies in order to detect whether live or dead cyanobacteria are dominating in the scum. However, quantitative mapping of cyanobacteria may be impossible by remote sensing sensors due to opaqueness of the scum and variability in the properties of cyanobacteria within the scum.

MODIS band 1 reaches an almost stable value at chlorophyll concentrations above 50 mg m^{-3} in the case of *Anabaena* and *Aphanizomenon*. This means that any further increase in the concentration of cyanobacteria may be undetectable or detected with large errors by MODIS band 1.

The model simulations were performed with the assumptions that there is one dominating species in the bloom and the concentration of the cyanobacteria is constant over one MODIS pixel. Cyanobacterial blooms are extremely patchy. Even 30 m spatial resolution was shown to be inadequate (Kutser, 2004), especially if surface scum occurs. Therefore, the concentration of any optically active material MODIS can detect is averaged over space. In our case the concentrations used in the model have to be understood as the mean values for one pixel. Natural assemblages of algae contain several species. In July–August cyanobacteria (mainly *Aphanizomenon flos-aquae* and *Nodularia spumigena*) usually dominate in the Baltic Sea algal assemblages (Elder et al., 1984; www.seiremonitor.ee). The signal detected by remote sensing sensors is much more strongly dominated by cyano-bacteria than by other algae species during bloom conditions whereas cyanobacteria are floating close to or on the water surface and other species are mixed in the water column. Thus, the presence of other algae species can be neglected from

remote sensing point of view in cyanobacterial bloom conditions. On the other hand, the cyanobacteria community may also consist of several dominating species. In such cases the reflectance signal detectable by MODIS band 1 should be between the graphs for pure cultures seen in Fig. 3.

Variabilities of chlorophyll, CDOM, and suspended matter are largely unknown for cyanobacterial blooms. Earlier we carried out model simulations with different concentrations of non-chlorophyllous suspended matter and CDOM (Kutser et al., 2006) than those used in the present paper. For example, modelling was carried out for a CDOM-rich estuary. However, the cyanobacterial blooms usually occur offshore. The concentrations of suspended matter and CDOM used in the present study were measured offshore during a cyanobacterial bloom, but slightly outside the dense bloom area. Thus, the concentrations used in the modelling can be considered as normal background values. However, decaying cyanobacteria in the later stages of bloom may cause local increases in CDOM, which may have some small influence at the MODIS band 1 wavelengths. A more serious problem may be related to the dead cyanobacterial cells and surface scum, whose optical properties are unknown. Backscattering by live cells is taken into account through a specific backscattering coefficient of cyanobacteria and concentration of chlorophyll. Backscattering by non-chlorophyllous particles is calculated based on the specific backscattering coefficient and their concentration, but in the later stages of bloom there may be a significant amount of dead cells, whose optical properties and amount are unknown and not taken into account in our model. Package effect and variable chlorophyll–phycocyanin ratios may cause variability in the specific absorption coefficient of cyanobacteria. Therefore, there is need to study in detail optical properties of dense cyanobacterial blooms and surface scum during different stages of scum to be able to get more accurate estimates of the concentration of cyanobacteria in the bloom.

CONCLUSIONS

Laboratory measurements of inherent optical properties of three cyanobacterial species dominating during summer months in the Baltic Sea showed that both absorption and backscattering coefficients of these three species are slightly lower than in the case of a few cyanobacterial species from other regions of the world published in scientific literature (Ahn et al., 1992). However, the IOP values are within the range measured by Ahn et al. (1992) for different algae species.

Model simulations show that MODIS band 1 is sensitive to changes in the concentration of cyanobacteria and can be used for quantitative mapping during cyanobacterial blooms. The relationship between MODIS band 1 and the amount of cyanobacteria is nonlinear. It is relatively easier to estimate the chlorophyll concentration in *Nodularia spumigena* bloom than in *Anabaena circinalis* or *Aphanizomenon flos-aquae* blooms as an increase in the concentration of *Nodularia* increases the reflectance the most strongly of the three bloom-forming cyanobacteria studied.

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Sinivetikate massõitsengute kvantitatiivne hindamine satelliidi MODIS 250 m ruumilise lahutusega piltidelt

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Kolme tsüanobakteri – *Aphanizomenon flos-aquae* var. *baltica*, *Anabaena circinalis* ning *Nodularia spumigena* – optilisi omadusi on uuritud laboris ja saadud erineeldumis- ning tagasihajumiskoefitsiente on kasutatud optilises mudelis, leidmaks vee heleduskoefitsiendi spektreid erinevate tsüanobakterite kontsentratsioonide korral. Vee heleduskoefitsiendi spektritest on hinnatud, kuidas reageeriks satelliidi MODIS esimene spektrikanal (lainepikkuste vahemik 620–670 nm) tsüanobakterite hulga muutusele vees. On olemas seos tsüanobakterite hulga ja MODISE esimese spektrikanali poolt mõõdetava signaali vahel, võimaldamaks tsüanobakterite kvantitatiivset hindamist MODIS-e abil. Ilmneb, et sõltuvus tsüanobakterite hulga ja MODIS-e esimese spektrikanali poolt mõõdetava signaali vahel ei ole lineaarne. Uuritud kolmest liigist kutsuks suurimaid muutusi vee heleduskoefitsiendis esile *Nodularia spumigena* kontsentratsiooni muutus. See tähendab, et selle liigi tsüanobakterite hulka saab massõitsengute korral hinnata suurema täpsusega ja suuremas kontsentratsioonide vahemikus. Ülejäänud kahe liigi korral suureneb MODIS-e esimeses spektrikanalis mõõdetav signaal suuremate klorofülli kontsentratsioonide kui 50 mg m^{-3} korral liialt vähe, hindamaks tsüanobakterite hulka vees rahuldava täpsusega.