Susanne Kratzer, Bertil Håkansson and Charlotte Sahlin

Assessing Secchi and Photic Zone Depth in the Baltic Sea from Satellite Data

Long-term trends in the Secchi depth of the Baltic Sea have been interpreted in terms of eutrophication (1, 2). The spectral attenuation coefficient K_d (490) can be estimated from remote sensing data (3). Given the empirical and theoretical relationships between diffuse attenuation and Secchi depth, it is therefore possible to estimate the trophic state from remote sensing data. This paper considers relationships among remotely sensed and in-water measured K_d (490), and Secchi depth data obtained during dedicated sea-truthing campaigns in the eastern Baltic Proper in 1999 (4) and in the western Baltic Proper/Himmerfjärden area during 2001 and 2002. In-water measurements are used to establish the relationship between the PAR and the spectral attenuation coefficient in the Baltic Sea *via* regression analysis. The analysis showed that in the area of investigation K_d (490) is about 1.48 times higher than K_d (*PAR*). This relationship is then used to define the link between the photic zone depth and the remote sensing optical depth, K_d (490)$^{-1}$. The results show that the depth of the euphotic zone is about 6.8 times K_d (490)$^{-1}$. The regression analysis between K_d (*PAR*) and Secchi depth confirmed previous work that K_d (*PAR*) is about 1.7 of the inverse Secchi depth. Furthermore, an in-water algorithm between Secchi depth and K_d (490) is used to simulate a Secchi depth map of the Baltic Sea from SeaWiFS K_d (490) data. This map is verified against sea-truthing data. K_d (490) data derived from satellite is compared to *in situ* K_d (490), and the sources of error are discussed.

INTRODUCTION

In order to solve prevailing environmental problems, such as eutrophication, pollution, and physical destruction in coastal zones, new approaches and techniques are required. Ocean color remote sensing is one of the methods that can improve our understanding of coastal processes. This paper is about how to relate water quality and different optical characteristics of the waterbody to remote sensing data. Once this information is calibrated and validated an effective method exists that can detect, monitor and assess processes in coastal waters on a large scale. However, before satellite remote sensing can be applied, the in-water characteristics of the waterbody must be known.

The advances in ocean color remote sensing over the last decades have made it possible to use remote sensing imagery to produce maps of chlorophyll *a* concentration and productivity in the world's oceans (5). The standard remote sensing algorithms work well in Case-1 waters (clear ocean waters), where the optical properties are influenced by water itself, as well as phytoplankton. However, coastal waters, so-called optical Case-2 waters (6) are more complex, as the optical properties are also influenced by suspended particulate matter (SPM), and by colored dissolved organic matter (CDOM), also referred to as yellow substance. From an optical point of view, the Baltic Sea is exceptional because of its brackish nature and its relatively high concentration of CDOM compared to other seas (7). Global algorithms tend to overestimate the concentration of chlorophyll *a* in the Baltic Sea because of the high CDOM concentrations (8).

This study is an analysis of how ocean color remote sensing can be used to determine the photic zone and the Secchi depth in the Baltic Sea. The optical parameters we chose for water quality are the Secchi depth, the spectral diffuse attenuation coefficient at 490 nm, K_d (490), and the diffuse attenuation coefficient, K_d (*PAR*), where *PAR* refers to Photosynthetically Active Radiation (300 – 700 nm). Although, the theoretical background of these parameters is well known (9) the relationship between K_d (490), K_d (*PAR*), and Secchi depth is somewhat dependent on the optical water type (10).

In 1953, Sverdrup introduced the term *critical depth* (11) as the depth at which the total photosynthetic production in the water column is just balanced by respiration. The illuminated surface layer of the sea is called the photic zone (12). It includes all mixed layers in which photosynthesis exceeds heterotrophic consumption.

Theoretically, K_d is inversely related to the depth of the photic zone, z_{eu}, which is the depth where 99% of the sunlight at the sea surface has disappeared. In many cases, the photic zone depth and the mixed layer depth determine the onset of phytoplankton blooms.

Both biotic and abiotic factors that scatter or absorb sunlight will influence K_d (*PAR*), and hence the depth of the photic zone. In coastal areas, CDOM, chlorophyll *a* and inorganic particles are optically active, whereas in the open Baltic Sea CDOM and biotic factors, such as cyanobacteria blooms, dominate (7). CDOM is of terrestrial origin, and is therefore inversely related to salinity (13, 14). Salinity is relatively low but stable in the open Baltic Proper (6, 7), which leads to a rather constant high background value in CDOM (15, 16). Note that K_d (*PAR*) is a measure of the gross changes in all optically active components.

The depth of the photic zone is also, by definition, the limit for vertical penetration of visible light, governing the distribution of heat content in the surface layer. Kahru et al. (17) used AVHRR imagery combined with ship measurements to demonstrate that surface accumulations of filamentous algal blooms cause an increase in the satellite-derived sea-surface temperature by up to 1.5°C. They attributed this phenomenon to increased absorption of sunlight due to increased phytoplankton pigment concentration. K_d (*PAR*) may therefore be seen as a link between biological and physical processes. Since K_d (*PAR*) influences the vertical heat distribution it also influences the sea-surface temperature. This parameter is important for determining the energy exchange between the atmosphere and the ocean. Hence, a reliable parameterization of K_d (*PAR*), taking into account spatial and temporal variability, is needed to reduce model errors of ocean, atmosphere and ecosystem models.

K_d (490) is a standard ocean color satellite product, for the first time tested by the Coastal Zone Color Scanner (CZCS) in the early 1980s (18) and in the late 1990s by SeaWiFS, the Sea-Viewing Wide Field of View Sensor (3). Satellite data is validated using empirical relationships between *in situ* and satellite derived K_d (490), in which case regional relationships (local algorithms), dependent on water type, are obtained. Hence, there is a strong need to test satellite derived K_d (490) in waters which have not been included in the regression scheme from the beginning, or have exceptional optical characteristics, such as the Baltic Sea due to its high content in CDOM. In this paper, an evaluation of satellite retrieved K_d (490) is presented using *in situ* measurements of K_d (490) in the Baltic.

The Secchi depth is a common standard parameter in experimental aquatic biology and ecosystem studies. It is a measure of the transparency of the water. It is an easy and inexpensive qualitative measure of biomass content. However, being qualitative in nature (19) there is a need for more quantitative measurements, such as K_d (*PAR*). Poole and Atkins (20) found empirically that the Secchi depth can be used to estimate K_d (*PAR*), since it is approximately inversely proportional to K_d (*PAR*), and therefore can also be used to predict the depth of the photic zone.

In Sandén and Håkansson (2), it was shown that the Secchi depth decreased in the Baltic Proper over time from before the 1940s and up to the 1990s. It was assumed that this was caused by increased primary production, leading to increased absorption of sunlight by phytoplankton, and therefore a reduction in Secchi depth. Kautsky et al. (1) showed that the maximum depth of *Fucus vesiculosus* (bladderwrack) decreased in the Baltic Sea during the same period of time as mentioned above, indicating that the depth penetration of sun radiation is a limiting factor for plant growth caused by increased pelagic primary production.

During the last 10 years, new *in situ* light meters have become available that can measure both K_d (490) and K_d (*PAR*) with high accuracy, such as the TACCS radiometer (Satlantic Inc., Canada), and the Underwater Quantum Sensor (LI-COR, USA). In this paper, the relationship between the attenuation coefficient and the Secchi depth for the open Baltic Sea is investigated. We also present analytical and empirical relationships between the Secchi depth and K_d (*PAR*), as well as satellite algorithms retrieving K_d (490) are presented. A description of sea-truthing as well as remote sensing methods are presented, as are results from sea-truthing campaigns, showing how K_d (490) is empirically dependent on K_d (*PAR*), and how K_d (*PAR*) in turn is related to the Secchi depth. Examples show how optical water quality parameters change when moving along a transect from inshore to offshore waters. An example of satellite retrieved K_d (*PAR*) for the Baltic Sea is also presented, and a Secchi depth map is simulated using an in-water algorithm.

THEORETICAL AND EMPIRICAL RELATIONSHIPS

In-water Optics

Light energy, which enters the water from above and is transmitted downwards is known as downwelling irradiance, E_d. It diminishes in an approximately exponential manner with depth (Beers law):

$$E_d(z) = E_d(0) * e^{-\int K_d(z)dz} \qquad \text{(Eq. 0)}$$

where E_d (0) and E_d (z) are the values of downward irradiance just below the surface and at depth z, respectively, and K_d (z), is the *PAR* diffuse attenuation coefficient (the rate of decrease in E_d).

Above the depth at which the irradiance has reached 1% of the surface value is the photic zone, Z_{eu}, where phytoplankton can assimilate light photons. Assuming K_d (z) to be approximately constant with depth, the euphotic zone can be derived from Kirk (9):

$$Z_{eu} = 4.6 * K_d(PAR)^{-1} \qquad \text{(Eq. 1)}$$

Holmes (21) found that K_d(*PAR*) can be derived from Secchi depth (*SD*) using the following equation:

$$K_d(PAR) = f * SD^{-1} \qquad \text{(Eq. 2)}$$

where f is 1.4 for turbid coastal waters (21).

In this paper, we first investigate the relationship between K_d (*PAR*) and K_d (490) for the area of investigation:

$$K_d(PAR) = m * K_d(490) \qquad \text{(Eq. 3)}$$

Then, we investigate the factor f in Eq. 2, and derive an algorithm valid for the Baltic Sea to estimate the photic zone depth from K_d (490). Note that the inverse of K_d(490) is also called the remote sensing optical depth.

Remote Sensing Algorithms

The diffusive attenuation coefficient at 490 nm is derived from remote sensing data using algorithms in the following structure (3):

$$K_d(490) = K_w(490) + A*[Lw(\lambda_1) / L_w(\lambda_2)]^B \qquad \text{(Eq. 4)}$$

where K_w(490) is the diffuse attenuation coefficient for pure water and $L_w(\lambda_1)$ and $L_w(\lambda_2)$ are the water-leaving radiance for 2 wavebands. In the case of CZCS, λ_1= 443 nm and λ_2= 550 nm. *A* and *B* are coefficients derived from linear regression analysis of *in situ* and satellite data.

Austin and Petzold (18) used K_w (490) = 0.022 m^{-1}, which was taken from Smith and Baker (22). After the launch of SeaWiFS, Mueller (3) suggested the use of K_w (490) = 0.016 m^{-1}, instead, and the following post-launch algorithm was recommended in order to derive K_d(490):

$$K_d(490) = 0.016 + 0.15645*[L_{w,n}(490) / L_{w,n}(555)]^{-1.5401} \qquad \text{(Eq. 5)}$$

where $L_{w,n}(\lambda_n)$is the normalized water-leaving radiance. The algorithm is used in SeaDAS, the standard data processing software for SeaWiFS data (SeaDAS v.4, 1999). Another algorithm was recently proposed by Mélin et al. (23) where *A* and *B* were modified to 0.205 and -1.754, respectively. The algorithm was empirically determined using data from the Adriatic Sea.

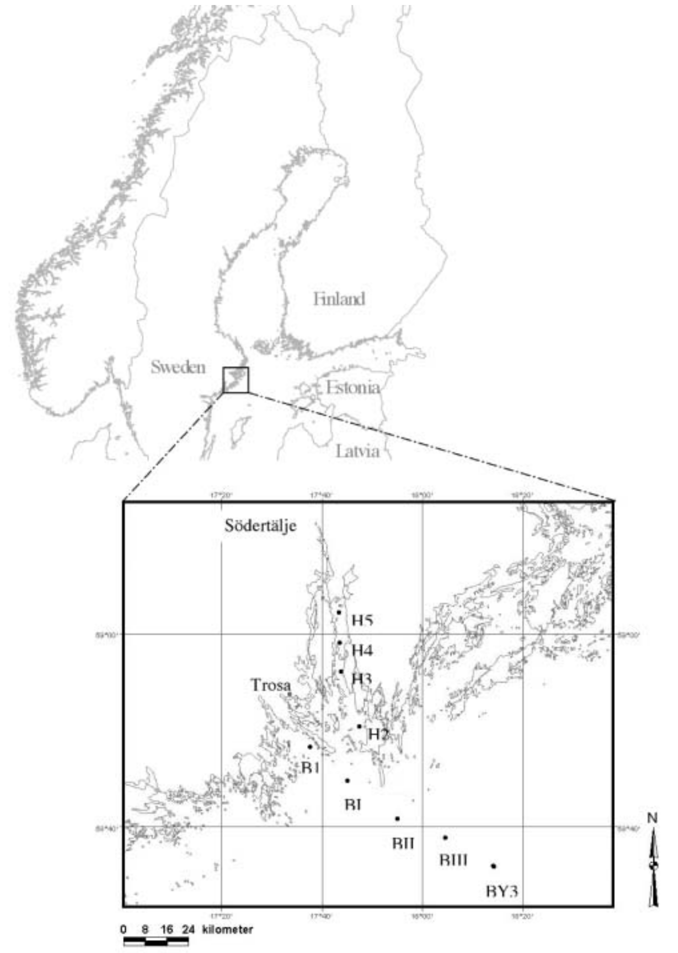


Figure 1. Locations of transects during the Askö field campaign 2001. Stations H2-H3 are standard monitoring stations in Himmerfjärden. Station B1 (just south of Askö) and station BY31 are standard Baltic Sea monitoring stations. Station BI-BII were placed between the 2 standard stations in order to form an open-sea transect for optical measurements. Table 1 lists the dates of each transect.

Instruments, Data and Methods

The satellite data covered the whole of the Baltic Sea, whereas the *in situ* data were sampled in the open Baltic Sea NW of Gotland and in Himmerfjärden. The data were gathered during sea-truthing campaigns from Askö field station in June 2001 and August 2002. Figure 1 shows the positions of the transect stations sampled. The transect data covered an inshore to offshore gradient to aim at a wide range of values for physical, biological, and optical variables. Secchi depth data from another field campaign in 1999 SW of Gotland (4) was used to verify the resulting Secchi depth map.

Instruments and *in situ* Sampling

The TACCS radiometer had a chain of 4 downwelling irradiance sensors, E_d (490), with a 10 nm bandwidth each. The sensors were fixed on a cable at 2, 4, 6 and 8 m depth. The radiometer was set to sample for 2 min at a sampling rate of 1 sample sec^{-1} (120 measurements at each station). The instrument was allowed to float 10-20 m away from the boat in order to avoid shading. The data was converted from binary to calibrated engineering units using the Satlantic SatCon software. The natural logarithm of the measured downwelling irradiance was plotted against depth and the slope of the line equalled K_d(490). The TACCS was used in both of the Askö field campaigns.

Another radiometer (LI-COR Biosensor Inc.), fitted with a cosine underwater quantum sensor, was used to measure the *PAR* downwelling irradiance during the Askö field campaign in 2002. The measurements were performed on the sunny side of the ship. Measurements were usually taken at 2, 4, and 6 meters. The natural logarithm of the downwelling *PAR* irradiance – E_d (*PAR*) – was plotted against depth, and the slope of the line equalled K_d (*PAR*).

The Secchi depth was measured using a standard 30 cm white Secchi Disk. A water telescope (collapsable bathyscope, Nuova Rade) was used additionally. Strictly speaking, the use of a bathyscope does not comply with the SeaWiFS protocols (24), but was required in order to be in line with historical site data (pers. comm. U. Larsson, Department of Systems Ecology, Stockholm University, 2000).

Table 1. Dates and location of transects during field measurements during the field campaign in 2001.

Date	Transect	Location
20 June 2001	Himmerfjärden	H5-H4-H3-H2-B1
28 June 2001	Open Baltic Sea	B1-BI-BII-BIII-BY31
2 July 2001	Himmerfjärden and Open Baltic Sea	H4-H3-H2-B1-BI
4 July 2001	Open Baltic Sea	B1-BII-BY31

Water samples

The concentration of SPM was measured in triplicates by gravimetric analysis using the method of Strickland and Parsons (25). For the determination of CDOM the water was filtered through 0.2 μm membrane filters and measured spectrophotometrically in a 10 cm optical cuvette using a Shimadzu UVPC 2401 spectrophotometer. G_{440}, the CDOM absorption coefficient at 440 nm, was derived according to Kirk (9). For the estimation of chlorophyll the spectrophotometric method was used (26-28), using GF/F filters and 90% acetone. Chlorophyll *a* was calculated according to the trichromatic method. All laboratory methods followed a standard protocol (7, 29).

Remote Sensing Data and Products

The measurements of optical properties of the water were timed with ocean color sensor satellite overpasses (AVHRR, SeaWiFS, and MERIS). The information for the overpasses was requested from NASA (for SeaWiFS) and in 2002 additionally from ESA (for MERIS sea-truthing), during the planning phase of each field campaign.

Furthermore, near real-time quick-looks were provided from the SeaWiFS project by the automated SeaWiFS Data Processing System (SDPS, NASA). The quick-looks were jpeg files of ”true color” images (from Level-1 bands 6,5,1) and Level-2 data (chlorophyll concentration), which were sent by e-mail on a daily basis. This information helped to decide on sampling strategies during field campaigns, as the MERIS protocols require a homogeneously mixed waterbody for calibration and validation of imagery.

The field campaign in 2001 was used for sea-truthing K_d (490) maps of the Baltic Sea as derived from SeaWiFS (30). The diffuse attenuation coefficient for the downwelling irradiance at 490 nm – K_d (490) – was retrieved as a SeaWiFS Level-2 product using the empirical relations of Mueller (3). NASA standard SeaWiFS Level-1a data were used as source data, and SeaDAS version 4.0 was used for data processing. The Level-2 processing included masking-out of clouds and sun-glint as well as the atmospheric correction of the remaining pixels. For this, the iterative method by Siegel et al. (31) was used. The spatial resolutions of Level-1a, and Level-2 data is 1.1 km in nadir. It was reduced to 4 km during the Level-3 processing. Daily Level-3 data was then compiled into monthly or weekly composite images with mean pixel values over the chosen time span.

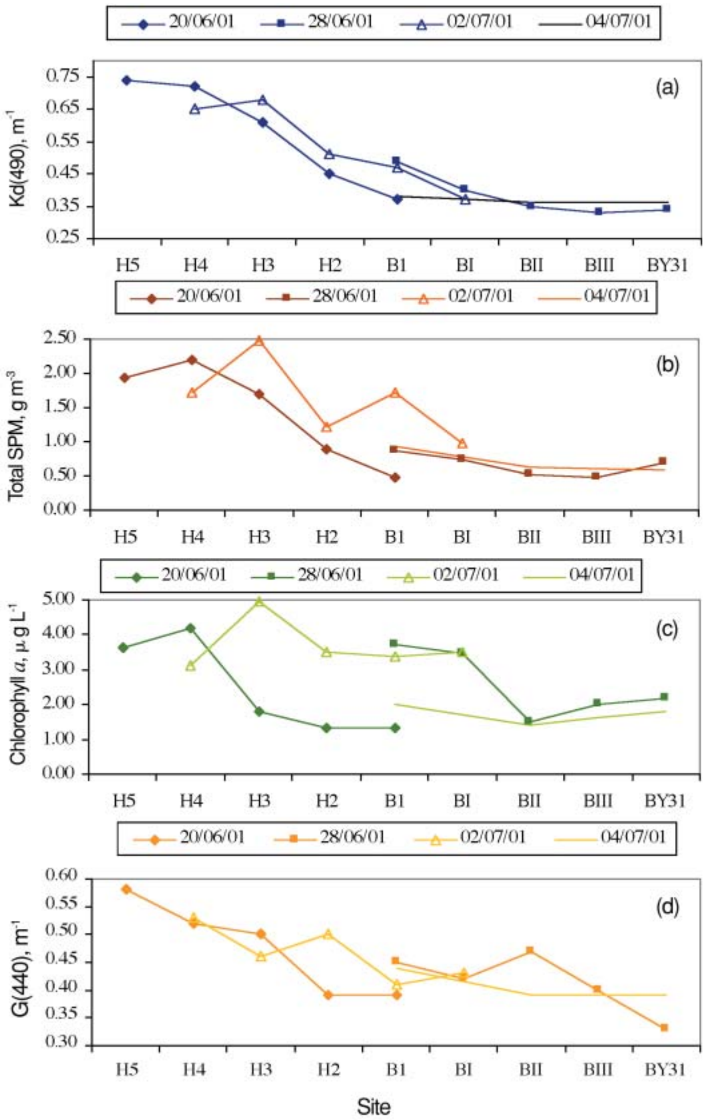


Figure 2a–d. K_d (490), total SPM concentration, chlorophyll *a* concentration and g_{440} measured during the transects during the Askö field campaign 2001. There is a clear trend of decreasing values for K_d (490) and total SPM from Himmerfjärden towards the open Baltic Sea stations (2a and 2b). For chlorophyll *a* and g_{440} this trend is not quite as pronounced (2c and 2d).

RESULTS

During the last 30 years, Himmerfjärden has been an area of intensive field and model studies related to biology, ecosystem analysis, and nutrient budgets (15, 32). Hence, Himmerfjärden is a suitable test area for high-resolution satellite data. Ekstrand (33) evaluated Landsat TM data for retrieval of chlorophyll *a* and SPM. However, this data set is not optimal for aquatic studies due to the low radiometric and spectral resolution and a low overpass frequency (approximately twice a month). Furthermore, the sea-truthing data did not include any measure of CDOM, which is optically dominant in the Baltic Sea. The simple use of band ratios, as suggested here, is likely to cause a bias in chlorophyll *a* concentrations due to the spectral influence of CDOM. Despite the vast amount of various biological, chemical and physical data available there are no historical optical data from this area. The aim of the field experiments during the summers of 2001 and 2002 was to obtain bio-optical data for modeling and sea-truthing in the Himmerfjärden and in the offshore region of the western Baltic (Fig. 1).

In Figure 2a–d, the results of 4 transects during summer 2001 are presented. The concentrations of total SPM, chlorophyll *a*, and the attenuation coefficient of CDOM at 440 nm, g_{440}, demonstrate that the water can be divided optically into a coastal and an offshore water mass. Station B1, situated south of Askö, is intermediate between coastal and offshore waters. This is also captured in the K_d (490) measurements (Fig. 2a). As this optical parameter is sensitive to all 3 constituents it allows for the classification of water masses, but it cannot be attributed to one single component.

The multiple regression analysis between K_d (490) and all 3 optical components from the whole data set from 2001, including both data from Himmerfjärden and the open Baltic Sea, yielded:

$$K_d(490) = -0.01 + 0.72 * g_{440} + 0.15 * [SPM] + 0.0003 * [chl\ a] \quad \text{(Eq. 6)}$$

with $r^2 = 0.91$, $p = 0.000$, and $n = 24$.

The coefficient in front of each variable indicates the strength of each variable. This means that CDOM (g_{440}) is the dominant optical component followed by total SPM.
For the open Baltic Sea stations the dominance of CDOM is not quite as strong, and the influence of SPM and chlorophyll

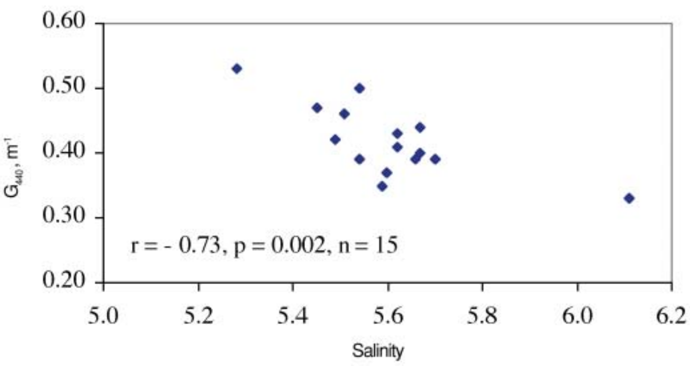


Figure 2e. Inverse correlation between salinity and colored dissolved organic matter (CDOM), here represented as g_{440}, the absorption coefficient of CDOM at 440 nm during the Askö field campaign 2001. The surface salinity was measured using a SAI/VAS STD instrument (Bergen, Norway).

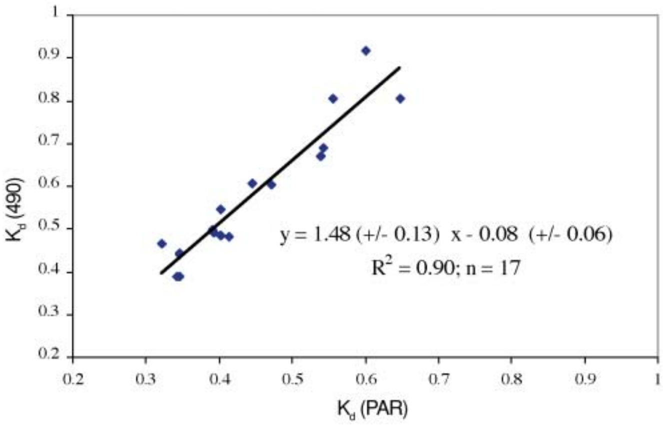
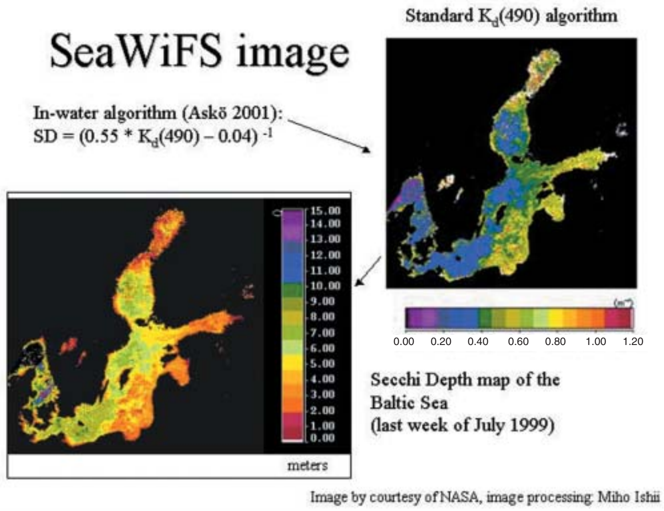


Figure 3. Regression between K_d (490) and K_d (*PAR*) for data measured during the field campaign in 2002.



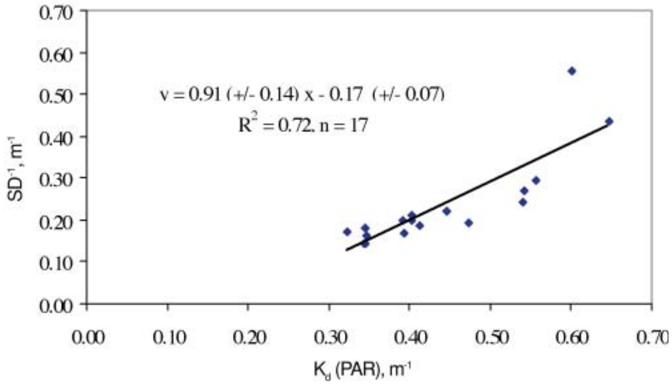


Figure 4. Regression between the inverse of the Secchi Depth, SD^{-1}, and K_d (*PAR*) for data measured during the field campaign in 2002.

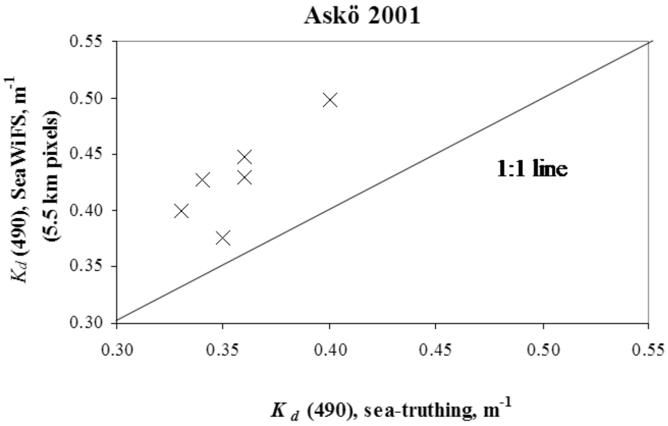


Figure 5a, b. Secchi depth map of the Baltic Sea (bottom left) simulated from a K_d (490) SeaWiFS composite from last week of July 1999 (top right), and the in-water algorithm derived from the field campaign in 2001. b) Comparison between K_d(490) as derived from SeaWiFS and K_d(490) *in situ* from the Askö field campaign in 2001. Note that the surface layer was well mixed. The correlation coefficient was 0.83 with p = 0.041.

is increasing:

$$K_d(490) = 0.23 + 0.12 * g_{440} + 0.07 * [SPM] + 0.03 * [chl\ a] \quad \text{(Eq. 7)}$$

with $r_2 = 0.64$, $p = 0.005$, and $n = 16$.

Note that the lower coefficient of determination is due to the lower range of concentrations in the open Baltic Sea. Also note that chlorophyll is highly correlated with SPM in the open Baltic Sea (7).

Table 2. Ranges, mean and standard deviation of the percentage of organic to total SPM for inside and outside Himmerfjärden, as well as at station B1 (data set from 2001). The Table shows that most of the suspended matter in the open Baltic Sea is of organic nature. It also shows that station B1 is different to the other open Baltic Sea stations, and has a higher terrestrial influence.

	Organic/total SPM		
	Range	Mean	STDEV
Inside Himmerfjärden	30-74%	50%	13%
B1	43-82%	67%	13%
Open Baltic Sea	84-100%	91%	6%

Figure 2e shows the inverse correlation between salinity and g_{440}, the absorption coefficient of CDOM at 440 nm, for the area of investigation. As the salinity increases as one proceeds from Himmerfjärden towards the open Baltic Sea, the concentration of CDOM decreases. The correlation coefficient was – 0.73 with p = 0.002 (n = 15).

Inorganic particles dominate the SPM in inshore waters, whereas organic particles (in this case filamentous cyanobacteria) are dominant in offshore SPM (Table 2). Since CDOM in the Baltic is of terrestrial origin it also increases in concentration when moving closer to the shore. The Baltic Sea as a whole is classified as a special type of Case-2 waters (24) as it is optically dominated by CDOM. However, the data presented here show that inshore waters are even more complex in optical characteristics as they are also highly influenced by SPM. In order to describe both inshore and offshore Baltic Sea water masses it is necessary to choose a parameter that can capture this optical variability. This is the main reason why we focus on the diffusive attenuation coefficient (K_d), since it represents all 3 optical components which determines the water quality.

The photic zone depth, is determined by the PAR diffusive attenuation coefficient, K_d(*PAR*), while the satellite can only

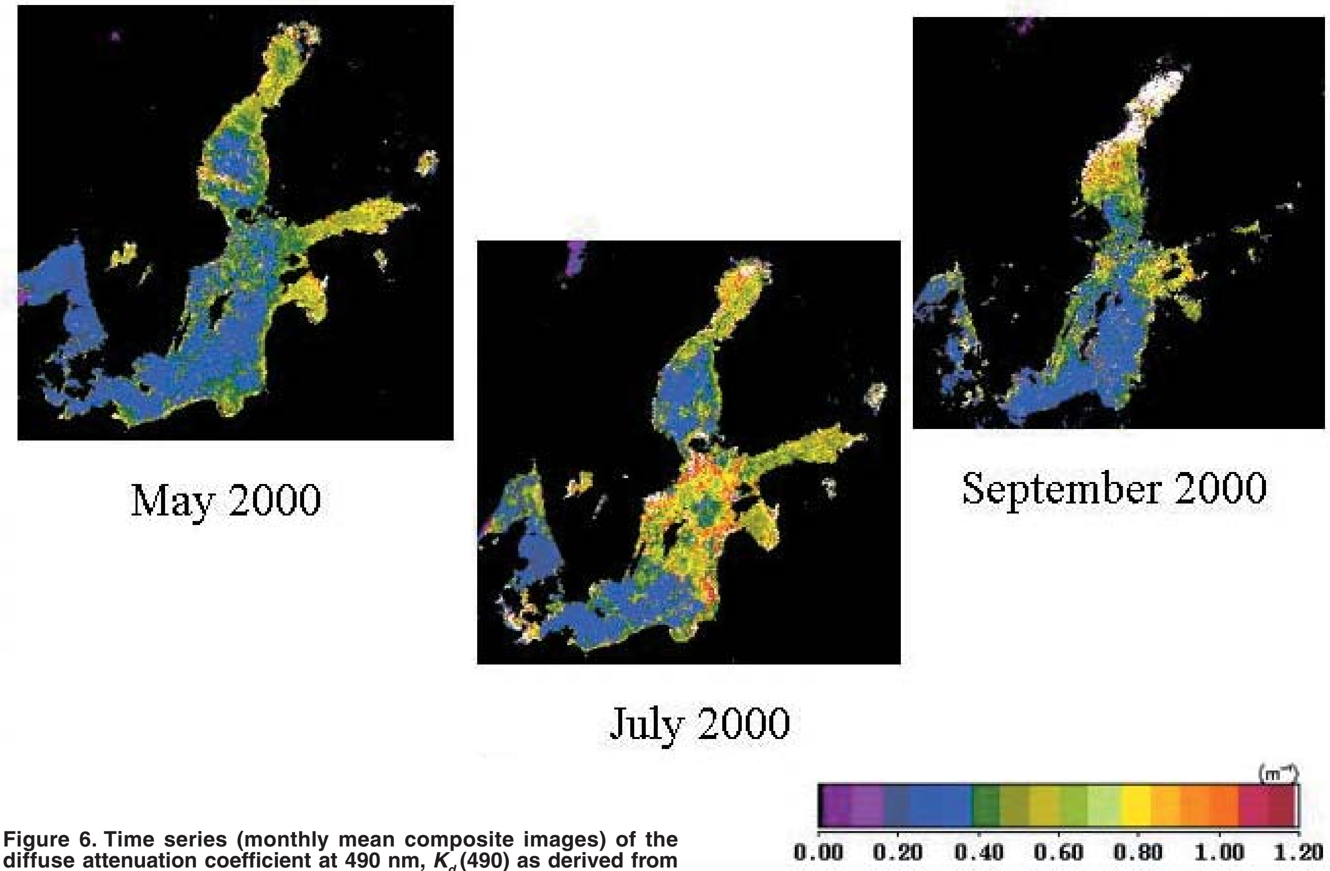


Figure 6. Time series (monthly mean composite images) of the diffuse attenuation coefficient at 490 nm, K_d(490) as derived from SeaWiFS (from: Ishii (30)).

measure the spectral attenuation coefficient at 490 nm empirically. It is possible to calculate the correlation between $K_d(PAR)$ and $K_d(490)$ for Baltic waters using optical models. More reliable, however, is to base the relationship on our measurements. In Figure 3, the empirical relationship is presented. The intercept of the regression is not significantly different from zero, yielding:

$$K_d\,(490) = 1.48 * K_d\,(PAR) \qquad \text{(Eq. 8)}$$

This means that the minimum spectral diffusive attenuation is located towards longer wavelengths, which is not surprising because of the high absorption of CDOM in the blue (7). According to Jerlov (10) the maximum depth of light penetration in the Baltic Sea, is at around 550 nm, while Lundgren (34) found that the minimum attenuation is at around 575 nm. Kratzer (7) found that the total absorption of all optical constituents has its minimum around 570 nm.
Using (Eq. 1) and (Eq. 8), we therefore derive the following relationship between the depth of the euphotic zone and the remote sensing optical depth:

$$Z_{eu} = 6.8 * K_d\,(490)^{-1} \qquad \text{(Eq. 9)}$$

Figure 4 shows the relationship between the inverse of the Secchi depth and $K_d(PAR)$ based on the sampling from 2002. Forcing the regression of $K_d\,(PAR)$ over the inverse of the Secchi depth, SD^{-1}, through zero (Eq. 2) yielded a value of f = 1.7 ± 0.1. This compares well with Raymont (35), Aertebjerg and Bresta (36) and Edler (37) who obtained f values of 1.7, 2.3, and 1.84, respectively, for Baltic Sea waters. According to HELCOM (38), these measurements indicate that f increases with decreasing salinity.

Measurements of optical properties are usually carried out during dedicated research expeditions, and therefore, are limited in number, while Secchi depth is a common and easily obtained parameter in monitoring, making it suitable for satellite data evaluation. Hence, it is of interest to compare the Secchi depth to $K_d(490)$, since the parameters are theoretically related (19). The data set from 2001 and 2002 yielded the following relationships, respectively:

$$SD^{-1} = (0.55 \pm 0.05) * K_d(490) - (0.04 \pm 0.02)$$
$$SD^{-1} = (0.54 \pm 0.06) * K_d(490) - (0.08 \pm 0.04) \qquad \text{(Eq. 10a,b)}$$

The slopes and intercepts of the 2 regressions are not significantly different.

Figure 5a shows an example of a composite SeaWiFS image from the last week in July 1999. The in-water algorithm (Eq. 10a from 2001) was applied to this $K_d(490)$ composite image, in order to simulate Secchi depth. The resulting map is shown in the same Figure. The range of values compares well with Secchi depth measurements sampled during a

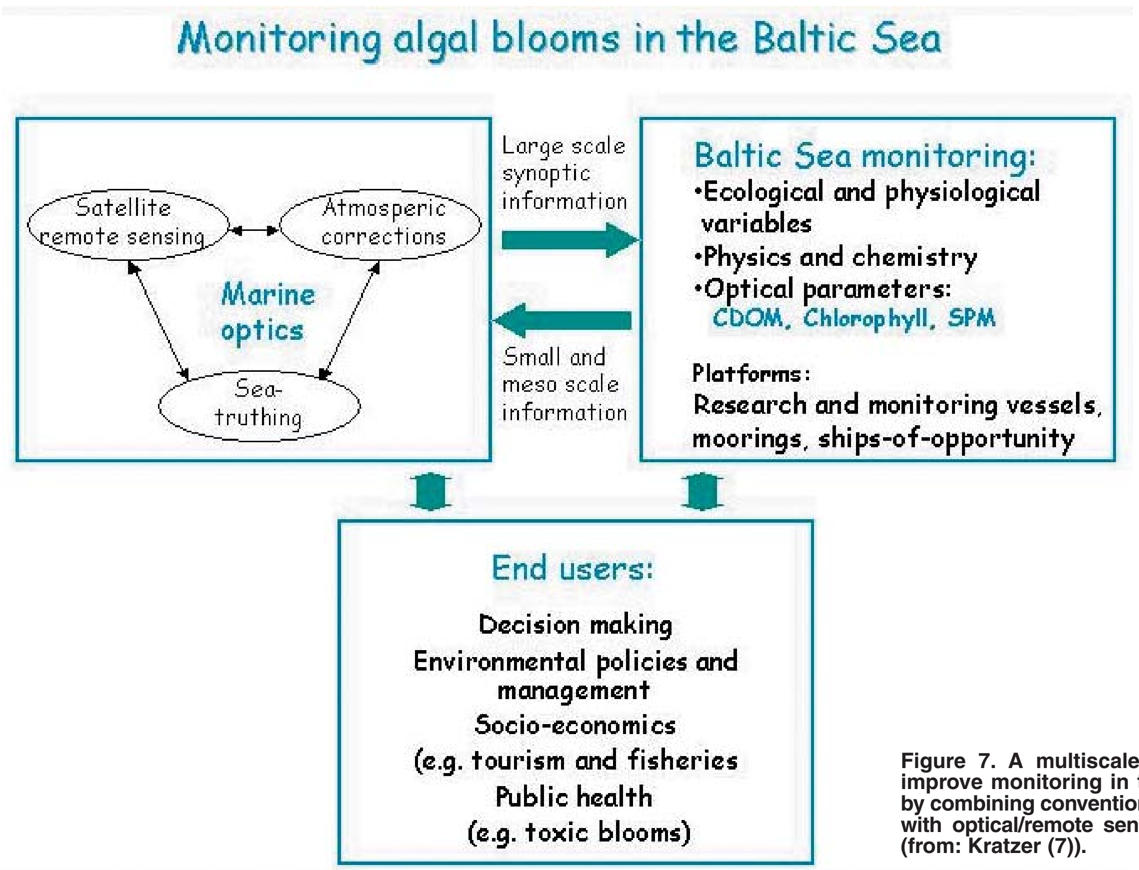


Figure 7. A multiscale approach to improve monitoring in the Baltic Sea by combining conventional monitoring with optical/remote sensing methods (from: Kratzer (7)).

sea-truthing campaign, which took place one week after the composite image in 1999 (4). The measured Secchi readings ranged from 0.3 to 5.1 m with a mean and standard deviation of 3.6 ± 1 m (n = 18). The 0.3 m reading was exceptional, and was found in an extremely dense bloom patch. The SeaWiFS Secchi map shows values of around 8 m for Landsort Deep, which was visited on 17 and 18 August 1999 with R.V. Baltica. The Secchi depth measured was 7 and 8 m, respectively. The satellite Secchi depth map also shows the right range of values when comparing to monitoring data from the Estonian Baltic coast (pers. comm. A. Jaanus, Estonian Marine Institute). The Secchi measurements from the Estonian Marine Institute during July 1999 ranged from 1.2 to 4.5 m with a mean and standard deviation of 3.0 ± 0.9 m (n = 16), which is mirrored in the Secchi depth map.

K_d(490) maps derived from SeaWiFS satellite data were also compared with K_d(490) derived from the TACCS radiometer. These data were sampled in 2001 along the 2 open sea transect listed in Table 1, excluding station B1, because of too close proximity to land (about 3 km off Askö).

The 2 transects provided a total of 6 data points for this comparison. The transect from 4 July 2001 had matching sea-truthing data (2 data points) within 1 hr of the overpass. The second transect from 27 July 2001 (4 data points) was compared to satellite data from 28 July 2001. This is justifiable as the prevailing high pressure system ensured extremely stable weather conditions. Furthermore the sea-truthing data from station B1 showed no significant change in the concentrations of optical components within the time span. As shown in Figure 5b the satellite-retrieved data points overestimate, to some extent, the *in situ* values. The latter are placed above the 1:1 line in a scatter plot, but are nevertheless in line with the observations (yielding a correlation coefficient of 0.83 with p = 0.041).

There are at least 2 possibilities for this bias. First, the atmospheric corrections have a tendency to overcorrect water-leaving radiances at short wavelengths (39) and, second the Mueller K_d(490) algorithm (3) has not been evaluated for this range of values. K_d(490) is relatively high in the Baltic Sea, ranging from 0.33 - 0.92 m^{-1} with a mean of 0.52 m^{-1} and a standard deviation of 0.15 m^{-1} (n = 47; data from summer 2001 and 2002). None of the empirically satellite-derived algorithms for K_d(490) cover such high values. According to Mélin et al. (23) the Mueller (3) algorithm underestimates K_d(490) in the range of values under investigation here.

DISCUSSION AND CONCLUSIONS

The Baltic Sea is an area characterized by a high content of terrestrial CDOM, and during summer cyanobacterial blooms occur frequently. The high latitude atmosphere is relatively clear compared to the atmosphere at low latitudes, but cloud cover is frequent. There is in general a lack of optical sea-truthing data from the Baltic, and very few available during satellite overpasses (40). Hence, satellite data and derived products are difficult to evaluate in this area. Dedicated bio-optical cruises were therefore carried out during summer 1999, 2001, and 2002 in order to obtain data for modeling and sea-truthing of satellite products. In this paper, we present results on one water-quality parameter, K_d(490), demonstrating that it is strongly correlated to K_d(PAR), and hence the depth of the photic zone. Phytoplankton growth may be expected, if the surface well-mixed layer is shallower than the photic zone (11, 12). During bloom events self-shading and light absorption of phytoplankton will reduce the photic zone and at the same time reduce the depth of short-wave radiation, leading to warmer surface waters, caused by a secondary thin density structure. Dynamic interactions can occur between biological and physical processes as demonstrated by Kahru et al. (17).

The data presented here showed that during summer K_d (*PAR*) can increase up to a value of 0.65 m^{-1}, which is 2-3 times higher than generally used in numerical models on the diffusive attenuation coefficient (15).

Cervantes-Duarte et al. (41) have investigated the relationship between the depth of the euphotic zone and the remote sensing optical depth, $K_d(490)^{-1}$, in different bio-optical provinces of the Gulf of California. They observed that the euphotic zone is typically about 2.5 to 3 times deeper than the remote sensing optical depth. The results presented here show that the relationship between the euphotic zone and the remote sensing optical depth in the Baltic Sea differs by more than a factor of 2 as compared to the range of values found in the Gulf of California. According to our results, the euphotic zone depth is about 6.8 times higher in the Baltic Sea than the remote sensing optical depth (Eq. 9). This may be due to the relatively high content of CDOM in the Baltic Sea which has a strong absorption in the blue to green part of the light spectrum. The relatively high content in CDOM leads to a lower remote sensing optical depth. Note that a factor of 6.8 will not be valid for the whole of the Baltic Sea because of the vast range in salinity, and therefore the change in CDOM concentration.

The spatial and temporal variability of $K_d(490)$ is presented in Figure 6. Monthly mean composites from 2000 show the variability of the depth of the photic zone across the whole of the Baltic Sea. There is a relatively high dynamic range of values over the geographic area considered. The changes over time are also considerable. The spring phytoplankton bloom can be observed mostly in coastal areas in May, and in July the filamentous cyanobacteria blooms are dominant in the open Baltic Sea.

The comparison of satellite derived products and *in situ* data is a difficult task in seawater, a medium with relatively fast changes in surface properties governed by dispersion, mixing and plankton growth or decay. It is also difficult to translate the concentration in a single bottled sample into a 1 km pixel coverage. One would have to take many samples within one pixel in order to get an idea about the variability in, e.g. chlorophyll concentrations within one single pixel. Furthermore, ship-based sea-truthing is expensive and time consuming, and can seldom cover such vast areas as achieved by satellite remote sensing. Hence, new techniques, including optical moorings and ships of opportunity, should be implemented in order to improve satellite data match-ups in the Baltic Sea. Figure 7 shows a conceptual model of how the different methods could be integrated.

Our results indicate that both the euphotic zone and the Secchi depth in the Baltic Sea can be derived from satellite ocean color imagery. Although the individual pixel values in the Secchi depth map may not be accurate, the map still gives the right range of values, and, more importantly, it pinpoints the areas in which photosynthesis may be light limited, or prone to eutrophication. This sort of information can, for example, be used by environmental agencies for the classification of Baltic Sea water masses.

However, in order to improve the accuracy of these methods, the atmospheric corrections first have to be solved. The vicarious calibration method used for SeaWiFS data in the Adriatic Sea appears to be a fruitful approach (23). The strength of this method is an improved atmospheric correction. It requires accurate *in situ* data for verification, once again underlining the importance of long-term field measurements of high quality. The method is currently validated for the Baltic Sea using data from the AERONET station in Gotland (pers. comm. B. Bulgarelli, Joint Research Centre, Ispra).

Secondly, a regional empirical $K_d(490)$ algorithm should be developed for the Baltic Sea. It is our intention to use the large amount of optical data we have accumulated to adapt the existing empirical models to the Baltic, taking into account the high $K_d(490)$ values that are characteristic for this semi-enclosed brackish sea.

References and Notes

1. Kautsky, N., Kautsky, H., Kautsky, U. and Waern, M. 1986. Decreased depth penetration of *Fucus vesiculosus* (L.) since the 1940's indicate eutrophication of the Baltic Sea. *Mar. Ecol. Prog. Ser. 28,* 1-8.
2. Sandén, P. and Håkansson, B. 1996. Long-term trends in the Secchi depth in the Baltic Sea. *Limnol. Oceanogr. 41,* 346-351.
3. Mueller, J.L. 2000. SeaWiFS algorithm for the diffuse attenuation coefficient, K (490), using water-leaving radiances at 490 and 555 nm. In: *SeaWiFS Postlaunch Calibration and Validation Analyses, Part 3,* Hooker, S.B. and Firestone, E.R. (eds). Greenbelt, Maryland: NASA GSFC, pp. 24-27.
4. Subramaniam, A., Kratzer, S., Carpenter, J.C. and Söderbäck, E. 2000. Remote sensing and optical in-water measurements of a cyanobacteria bloom in the Baltic Sea. *Sixth International Conference on Remote Sensing for Marine and Coastal Environments,* Charleston, SC, Veridian ERIM International, I-57-64.
5. Platt, T. and Sathyendranath, S. 1988. Ocean primary production. Estimation by remote sensing at local and regional scales. *Science 241*, 1613-1620.
6. Morel, A. and Prieur L.1977. Analysis of variations in ocean color. *Limnol.Oceanogr. 22,* 709-722.
7. Kratzer, S. 2000. *Bio-Optical Studies of Coastal Waters.* PhD Thesis, monograph, School of Ocean Sciences, University of Wales, Bangor, UK, 190 pp.
8. Jorgensen, P.V. 1999. Standard CZCS Case 1 algorithms in Danish coastal waters. *Int. J. Remote Sens. 20,* 1289-1301.
9. Kirk, J.T.O. 1994. *Light and Photosynthesis in Aquatic Acosystems.* 2nd ed., Cambridge University Press, Cambridge.
10. Jerlov, N.G. 1976. *Marine Optics.* Amsterdam, Elsevier Scientific Publishing Company.
11. Sverdrup, H.U., 1953, On conditions for vernal blooming of phytoplankton. *J. Cons. Int. Explor. Mer. 18,* 287-295.
12. Tett, P. 1990. The photic zone. In: *Light and Life in the Sea.* Herring, P.J., Campbell, A.K., Whitfield, M. and Maddock, L. (eds). Cambridge University Press, pp. 59-87.
13. Siddorn, J.R., Bowers, D.G. and Hoguane, A.M. 2001. Detecting the Zambezi River plume using observed optical properties. *Mar. Pollut. Bull. 42*, 942-950.
14. Bowers, D.G., Harker, G.E.L., Smith, P.S.D. and Tett, P. 2000. Optical properties of a region of freshwater influence (The Clyde Sea). *Estuar. Coastal Shelf Sci. 50*, 717-726.
15. Tett, P., Gilpin, L., Svendsen, H., Erlandsson, C.P., Larsson, U., Kratzer, S., Fouilland, E., Janzen, C., Lee, J.-Y., Grenz, C., Newton, A., Ferreira, J.G., Fernandes, T. and Scory, S., 2003. Eutrophication and some European waters of restricted exchange. *Nearshore Coastal Oceanogr.* (In press).
16. Larsson, U. and Kratzer, S. 2002. Himmerfjärden. In: *OAERRE Sites Description Report, 2.* Gilpin, L. and Tett, P. (eds). Napier University, Edinburgh, pp. 33-43.
17. Kahru, M., Leppaenen, J.-M. and Rud, O. 1993. Cyanobacterial blooms heating the sea surface. *Mar. Ecol. Prog. Ser. 101,* 1-7.
18. Austin, R.W. and Petzold, T. 1981. The determination of the diffuse attenuation coefficient of sea water using the Coastal Zone Color Scanner. In: *Oceanography from Space,* Gower J.F.R. (ed.) Plenum Press, pp. 239-256.
19. Preisendorfer, R.W. 1986. Secchi disk science; Visual optics of natural waters. *Limnol. Oceanogr. 31,* 906-926.
20. Poole, H.H. and Atkins, W.R.G. 1929. Photoelectric measures of submarine illumination throughout the year. *J. Mar. Biol. Ass. U K 16*, 297-324.
21. Holmes, R.W.1970. The Secchi disk in turbid coastal zones, *Limnol. Oceanogr. 15,* 688-694.
22. Smith, R.C. and Baker K.S. 1981. Optical properties of the clearest natural waters (200-800nm). *Appl. Optics 20,* 177-84.
23. Mélin, F., Zibordi G. and Berthon, J.F. 2003. Assessment of SeaWiFS atmospheric and marine products for the Adriatic Sea. *IEEE Trans. Geosci. Remote Sens. 41.* 584-558
24. Mueller, J.L. and Austin, R.W. 1995. *Ocean Optics Protocols for SeaWiFS Validation, Vol. 25, Revision 1,* SeaWiFS Technical Report Series, Hooker, S.B., Firestone, E.R. and Acker J.G. (eds). NASA Technical Memorandum 104566, Maryland 25, pp.
25. Strickland, J.H.D. and Parsons, T.R. 1972. A practical handbook of sea-water analysis, *Bull. J. Fish. Res. Bd Can. 167,* 185-203.
26. Jeffrey, S.W. and Humphrey, G.F.1975. New spectrophotometric equations for determining chlorophylls a, b, c1 and c2 in higher plants, algae and natural phytoplankton. *Biochem. Physiol. Pflanz. 167,* 191-194.
27. Parsons, T.R., Maita, Y. and Lalli, C.M.1984. *A Manual of Chemical and Biological Methods for Seawater Analysis.* Oxford, Pergamon Press.
28. Jeffrey, S.W., Mantoura, R.F.C. and Wright, S.W.1997. *Phytoplankton Pigments in Oceanography.* Monographs on Oceanographic Methodology. UNESCO Publishing, Paris.
29. Kratzer, S., Bowers, D.G. and Tett, P. 2000. Seasonal changes in color ratios and optically active constituents in the optical Case-2 waters of the Menai Strait, North Wales. *Int. J. Remote Sens. 21*, 2225-2246.
30. Ishii, M. 2001. *Diffuse Attenuation Maps of the Baltic Sea as Derived from SeaWiFS Data.* Examensarbete (BSc thesis), Department of Physical Geography and Quaternary Geology, Stockholm University, Sweden.
31. Siegel, D.A., Wang, M., Maritorena, S. and Robinson, W. 2000. Atmospheric correction of satellite ocean color imagery: the black pixel assumption. *Appl. Optics 39,* 3582-3591.

32. Elmgren, R. and Larsson, U. (eds).1997. Himmerfjärden. Stockholm, Naturvårdsverket Förlag. (In Swedish)
33. Ekstrand, S. 1992. Landsat TM based quantification of chlorophyll-a during algae blooms in coastal waters. *Int. J. Remote Sens. 13*, 1913-1926.
34. Lundgren, B. 1975. *Measurements in the Baltic with a Spectral Transmittance Meter.* University Copenhagen, Institute for Physics and Oceanography, Report 30, 28 pp.
35. Raymont, J.E.G., 1967. *Plankton and Productivity in the Oceans.* Pergamon Press, Oxford.
36. Aertebjerg, G. and Bresta, A.M. (eds) 1984. *Guidelines for the Measurement of Phytoplankton Primary Production.* Baltic Marine Biologists Publication,1. 2nd ed.
37. Edler, L. 1997. In: *Report of the ICES/HELCOM Workshop on Quality Assurance of Pelagic Biological Measurements in the Baltic Sea.* ICES CM 1997/E, 5.
38. HELCOM 2002. *Manual for the Marine Monitoring in the COMBINE Program of HELCOM, ANNEX C-5 Phytoplankton Primary Production,* http://www.helcom.fi/Monas/CombineManual2/PartC/anxc5.html
39. Carlund, T., Håkansson B. and P. Land. 2003. Aerosol optical depth over the Baltic derived from AERONET and SeaWiFS measurements. *Int. J. Remote Sens.* (In print).
40. HELCOM. 2003. *Report on the HELCOM Project 'Validation of Algorithms for Chlorophyll a Retrieval from Satellite Data of the Baltic Sea Area'.* Wolfram Schrimpf (Project Co-ordinator), European Commission – Joint Research Centre (JRC), Ispra.
41. Cervantes-Duarte, R, Mueller, JL, Trees, CC, Maske, H, Alvarez-Borrego, S, and Lara-Lara, R. 2000. Euphotic depth, irradiance attenuation and remote sensing K490 in bio-optical provinces of the Gulf of California. *Cienc. Mar. 26,* 533-560.
42. This work was funded by MISTRA under the Remote Sensing for the Environment Program, as well as by the Swedish National Space Board, and by the EU (contract number EVK3-CT1999-00002, ELOISE No. 444/34). We also thank the Wallenberg Foundation for generously supporting expensive instruments. Thanks a lot to NASA for providing real-time SeaWiFS imagery during fieldwork, and to Ove Rud for providing SeaWiFS imagery for the RESE project. Many thanks to Miho Ishii for contributing the mosaic imagery and for producing the Secchi depth map. Thanks to Stefanie Hirch, Roberta Mistretta and Antonia Sandman for technical help during cruises, and in the laboratory.

Susanne Kratzer is a researcher in the marine remote sensing group at the Department of Physical Geography and Quaternary Geology, Stockholm University. She studied biology in Germany (Philipps-Univeristät Marburg and Universität Bremen) and did her Master thesis (Diplomarbeit) in marine biology 1994 in the School of Ocean Sciences in Menai Bridge, North Wales. In autumn 2000, she defended her PhD in biological oceanography at the University of Wales, Bangor. She is specialized in the bio-optical properties of coastal waters and has been working at Stockholm University since January 1997. Her field of interest concerns ocean optics, optical modeling, and monitoring of algal blooms using optical and remote sensing methods. She has been managing a number of remote sensing projects. Her address: Department of Physical Geography and Quaternary Geology, Stockholm University, SE-106 91 Stockholm, Sweden. kratzer@natgeo.su.se

Bertil Håkansson is Head of the Oceanographic Unit at SMHI in Göteborg. His main interests are optical and radar remote sensing, and physical oceanography. During his associated professorship at the Department of Physical Geography and Quaternary Geology he was the leader of the marine project 'Remote Sensing for the Environment - Methods for detection of changes in aquatic ecosystems and monitoring of algal blooms (RESE 5)'. His address: Swedish Meteorological and Hydrological Institute, Nya Varvet 31, SE-426 71 Västra Frölunda, Sweden. bertil.hakansson@smhi.se

Charlotte Sahlin is an undergraduate student in biology and earth sciences at the Department of Physical Geography and Quaternary Geology, Stockholm University. She is currently writing her thesis for a BSc in physical geography with emphasis on marine optics. Her main interests are environmental as well as ecological applications. Her address: Department of Physical Geography and Quaternary Geology, Stockholm University, SE-106 91 Stockholm, Sweden. charlotte.sahlin@natgeo.su.se