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, $z_{ph}$, 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 inexpensive qualitative measure of biomass content.

In-water Optics

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 $K_w (PAR)$ 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):

$$E_d(z) = E_d(0) e^{-(K_d+K_w)z}$$  \[\text{(Eq. 0)}\]

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, $Z_{ph}$, where phytoplankton can assimilate light photons. Assuming $K_d (z)$ to be approximately inversely proportional to $Z_{ph}$ (Kirk (9)):

$$Z_{ph} = 4.6 * K_d (PAR)^{-1}$$  \[\text{(Eq. 1)}\]

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

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

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:

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

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):

$$K_d (490) = K_u (490) + A*[Lw \left( \lambda_1 \right) / L_u \left( \lambda_2 \right)]^B$$  \[\text{(Eq. 4)}\]

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

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

$$K_d (490) = 0.016 + 0.15645*[L_{uw} \left( 490 \right) / L_{uw} \left( 555 \right)]^{1.5401}$$  \[\text{(Eq. 5)}\]

where $L_{uw} \left( \lambda \right)$ 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.
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 (collapsible 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).

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 \( \mu \)m 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 jpg files of "true color" images (from Level-1 bands 6,5,1) and Level-2 data (chlorophyll concentration), which were

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

<table>
<thead>
<tr>
<th>Date</th>
<th>Transect</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>26 June 2001</td>
<td>Himmerfjärden</td>
<td>H5-H4-H3-H2-B1</td>
</tr>
<tr>
<td>27 June 2001</td>
<td>Open Baltic Sea</td>
<td>B1-BI-BII-BIII-BY31</td>
</tr>
<tr>
<td>2 July 2001</td>
<td>Himmerfjärden and Open Baltic Sea</td>
<td>H4-H3-H2-B1-BI</td>
</tr>
<tr>
<td>4 July 2001</td>
<td>Open Baltic Sea</td>
<td>B1-BI-BY31</td>
</tr>
</tbody>
</table>

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.
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.

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:

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

(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...
is increasing:

\[ K_d(490) = 0.23 + 0.12 \times g_{440} + 0.07 \times [SPM] + 0.03 \times [chl \ a] \]

(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).

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...
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:

\[
K_d(490) = 1.48 \times K_d(PAR) \quad \text{(Eq. 8)}
\]

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:

\[
Z_{eu} = 6.8 \times K_d(490)^{-1} \quad \text{(Eq. 9)}
\]

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 \( f = 1.7 \pm 0.1 \). 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:

\[
SD^{-1} = (0.55 \pm 0.05) \times K_d(490) - (0.04 \pm 0.02)
\]

\[
SD^{-1} = (0.54 \pm 0.06) \times K_d(490) - (0.08 \pm 0.04) \quad \text{(Eq. 10a,b)}
\]

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
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 $3.6 \pm 1$ 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 $3.0 \pm 0.9$ 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 Melin 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 \( K_d \) 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, \( K_d(490) \), 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 showed 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 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 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


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