Optical Teledetection of Chlorophyll *a* in Estuarine and Coastal Waters[†]

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A hand-held spectroradiometer was used for above-water determination of subsurface spectral irradiance reflectance in the Scheldt Estuary (Belgium/The Netherlands), the North Sea off the Belgian coast, and the Hudson/Raritan Estuary (New York/New Jersey). On the North Sea the measurement conditions were adverse, and elsewhere broken cloud caused considerable spectral variation. Despite this variation the retrieval of chlorophyll *a* (Chl-*a*) from three reflectance spectra at all sampling stations was stable. The algorithm calibrated for the freshwater IJssel Lagoon (The Netherlands) proved to be applicable to these estuarine and coastal waters ($N = 30$; standard error of estimate = 7 mg m^{-3} for corrected Chl-*a* ranging from 1 to 93 mg m^{-3}).

Introduction

Environmental perturbations may affect whole catchments together with adjacent seas and necessitate the assessment of water quality on a regional scale. Rapid and cost-effective monitoring with complementary use of satellites, aircraft and ships has increased the interest in using optical teledetection methods. Significant progress has been made in detecting the distribution of chlorophyll *a* (Chl-*a*) and particulate organic carbon (POC) in the oceans ([1], [2]). In oceanic waters (Case 1 waters) Chl-*a* and associated materials dominate, whereas inland and coastal waters (Case 2 waters) exhibit high concentrations of allochthonous particles and dissolved organic matter (DOM) ([3]−[5]). Optical heterogeneity of Case 2 waters is greater than within the Case 1 class ([4], [5]). For the oceans, [Chl-*a*] correlates to a blue-to-green ratio of reflectance or normalized water-leaving radiance ([6]). For Case 2 waters, this color ratio cannot be used because of interfer-

ences by varying concentrations of particles and DOM relative to the pigment ([3]−[5]). Bukata et al. ([7]) demonstrated the inadequacy of algorithms developed for the ocean in predicting [Chl-*a*] in lake water. For the coastal waters of the present study, satellite-derived [Chl-*a*] was calculated with the Seaviewing Wide Field-of-view Sensor (SeaWiFS) standard algorithm and was an order of magnitude greater than concentrations in situ. Moreover, the relative spatial distribution appeared to be false ([8]).

A far-red to red reflectance ratio can be used for retrieval of [Chl-*a*] in eutrophic lakes ([9]−[11]). Adequate prediction of [Chl-*a*] in various inland waters is achieved by incorporating backscattering as computed from the irradiance reflectance at null depth $R(0,\lambda)$ in the near-infrared waveband (NIR) ([12]). The pigment concentration can be equated to the reflectance ratio R for $\lambda = 704$ and 672 nm, the absorption coefficients of water $a_w(\lambda)$ for these wavelengths, and the NIR-derived backscattering coefficient b_b (assumed to be wavelength independent)

$$[\text{Chl-}a] = \{R(a_w(704)+b_b)-a_w(672)-b_b^p\}/a^*(672) \quad (1)$$

where the values of $a_w(672)$ and $a_w(704)$ are 0.415 and 0.630 m^{-1}, respectively ([13]); $a^*(672)$ is a mean Chl-*a*-specific absorption coefficient at $\lambda = 672$ nm; and p is an empirical constant. For the [Chl-*a*] range of 1−185 mg m^{-3}, the calibrated values of $a^*(672)$ and p were 0.018 m^2 (mg Chl-*a*)$^{-1}$ and 1.06, respectively ([12]).

If eq 1 were applicable to marine Case 2 waters, the optical teledetection method ([12]) could integrate the monitoring of lakes, rivers, estuaries and the sea in coastal regions. This paper reports the results of testing of [Chl-*a*] retrieval for the North Sea off the Belgian coast, the Scheldt Estuary in Belgium/The Netherlands, and the Hudson/Raritan Estuary of New York/New Jersey. Error in $R(0,\lambda)$ is important when the upwelling light signal is weak and changes in cloud cover cause significant fluctuations in the amount of reflected sky light in the water-leaving radiance ([12], [14]). An assessment was made of the impact of variability in $R(0,\lambda)$ on the prediction of [Chl-*a*].

Study Areas

North Sea, April 1998. The southern North Sea receives high nutrient input from Continental and English rivers. During the *Phaeocystis* spring bloom, a 3-d survey covering a monitoring network in the Belgian Economic Exclusion Zone was made by the naval RV *Belgica* ([8]). Distance to the coast and water depth varied from 4 to 38 km and from 10 to 28 m, respectively. Under up to near-gale westerly winds, rough seas prevailed. The cloud cover was variable. See Table 1 for physical and chemical conditions.

Scheldt Estuary, August 1996 and March 1999. The Scheldt Estuary exhibits steep gradients in organic and mineral particle content from the freshwater compartment to the North Sea ([17]). In 1996 the RV *Luctor* (Netherlands Institute of Ecology) cruised from Terneuzen to Antwerp ([12]). The survey in 1999 was made by the RV *Argus* (Netherlands Directorate-General for Public Works and Water Management) from five stations in the shipping lane from Terneuzen to Doel. The cruises were made under low to moderate wind speeds. The sky was clear in 1996, and cloudy weather prevailed in the other survey.

Hudson/Raritan Estuary, August 1999. This shallow and eutrophicated interface of the Hudson and Raritan Rivers and Atlantic Ocean ([18]) was cruised with the RV *Walford* (New Jersey Marine Sciences Consortium). Transects in-

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survey (month/year)	N	θ_0	μ_{ad}	R	b_b	salinity	Chl-*a*	TSM	Z_{SD}
Scheldt Estuary (8/96)	9	41−64	0.52−0.75	0.8−1.8	0.12−1.2	3−28	3−93	7−78	0.3−1.8
North Sea (4/98)	9	41−60	0.54−0.74	0.8−1.3	0.00−2.5	31−35	2−33	5−103	0.4−3.5
Scheldt Estuary (3/99)	5	55−71	0.61−0.73	0.8−1.0	0.15−1.1	1−16	1−3	15−58	0.2−0.6
Hudson/Raritan Estuary (8/99)	7	26−49	0.70−0.85	0.8−1.3	0.02−0.12	25−28	4−32	6−26	0.5−1.8

[a] Symbols: N = number of stations; θ_0 = sun zenith angle (degrees); μ_{ad} = average cosine of downwelling light above water; R = subsurface irradiance reflectance ratio $R(0,704){:}R(0,672)$; b_b = backscattering coefficient derived from the reflectance at 776 nm (m^{-1}).
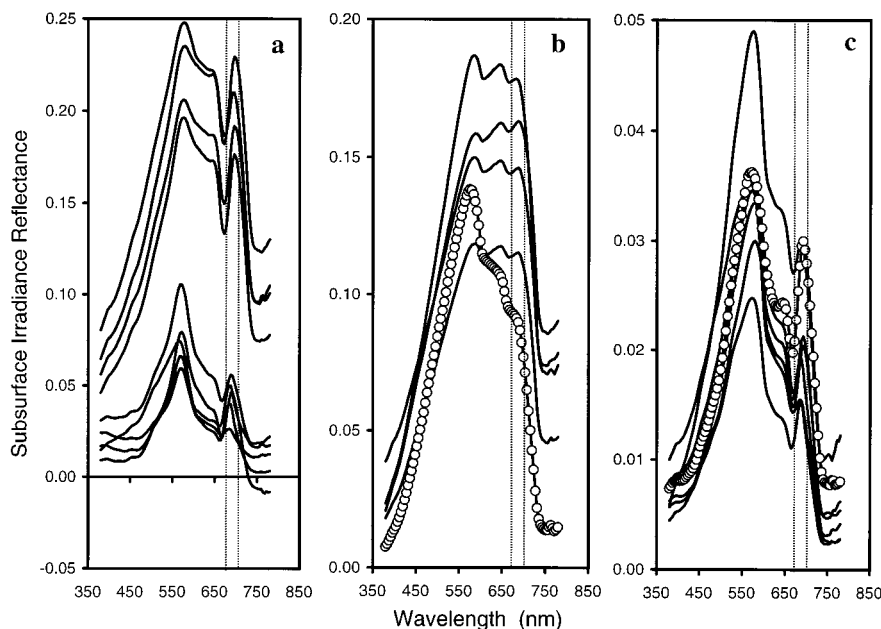

FIGURE 1. Subsurface spectral irradiance reflectance determined for North Sea (a; solid lines), Scheldt Estuary in March 1999 (b; solid lines; line with circles: station near Terneuzen), and Hudson/Raritan Estuary (c; solid lines; line with circles: station near Shrewsbury River). The vertical dotted lines indicate the wavelengths of 672 and 704 nm. Note the scale differences.

cluded three stations along the Sandy Hook Bay to the mouth of the Raritan River, two stations southeast of Staten Island and west of Coney Island, and another two near the tip of the Sandy Hook and Shrewsbury River on the New Jersey coast. The water depth varied from 2.2 to 8 m. In the shallowest water the Secchi-disk depth was 0.8 m. The water surface was nearly flat in the Sandy Hook Bay, and long waves were encountered elsewhere. Skies varied from fully overcast to mostly clear.

Determination of $R(0,\lambda)$

Method. To assess the impact of varying cloud and water surface roughness on the [Chl-*a*] retrieval, $R(0,\lambda)$ was derived three times for all stations. A model PR-650 Spectra-Colorimeter (Photo Research, Chatsworth, CA) which features 1°-measuring optics for acquiring spectra from 380 to 780 nm at full-width half-maximum bandwidth of 8 nm was used as described previously (*12*). The instrument was held 3−4 m above water. To assess $R(0,\lambda)$, successive measurements were made at a viewing direction φ of 90° from the plane of the sun for four radiance levels: (1) water-leaving radiance $L_w(\theta_a,\varphi,\lambda)$ at nadir angle $\theta_a \cong 42°$, (2) sky radiance $L_s(\theta_a,\varphi,\lambda)$ at zenith angle $\theta_a \cong 42°$, (3) radiance $L_p(\lambda)$ from a sunlight-exposed reference plaque and (4) radiance $L_d(\lambda)$ from the shaded plaque. In each measurement, the average of 10 spectra was recorded. The value of the subsurface upward radiance to irradiance conversion factor $Q(\theta_w,\varphi)$ was calculated from the average cosine of downwelling light above water (Table 1). For two stations within the Hudson/Raritan

Estuary the water was so still that the Fresnel reflectance $\rho(\theta_a) = 0.026$ was used for computing the sky light contribution to $L_w(\theta_a,\varphi,\lambda)$. Elsewhere the reflectance $\rho^* = 0.029$ was adopted (*12*).

Spectra of Estuarine and Coastal Waters. Of the 90 total $R(0,\lambda)$ spectra measured, 10 were negative in NIR. In one spectrum, the violet range was negative as well. For one station in the North Sea, each of the three spectra was negative in NIR. Excluding two stations exhibiting negative reflectance, the second of the three spectra is shown in Figure 1. Most peaks occurred between 560 and 590 nm. Valleys from 660 to 672 nm indicated the Chl-*a* red absorption peak. Variation in the wavelength of this minimum can be attributed mainly to the proportions of absorption by pigments. Valleys that were centered at $\lambda < 668$ nm occurred for relatively clear coastal water but not for inland waters (*12*). Many spectra of inland waters showed an additional valley near 630 nm, which indicates the cyanobacterial pigment phycocyanin. In the present data this feature was observed only near the Shrewsbury River.

The North Sea spectra represented two very different water compartments. Stations at distances < 15 km to the shore, i.e., within the coastal flow of water influenced by continental inputs, showed very high $R(0,\lambda)$ from 500 to 700 nm with local minima at 672 nm (Figure 1a). For these stations $R(0,\lambda)$ at every wavelength was higher than the spectral peaks for the Hudson/Raritan Estuary. Compared to the other North Sea stations the salinity was lower, [Chl-*a*] was higher, and the concentration of total suspended matter [TSM] was very
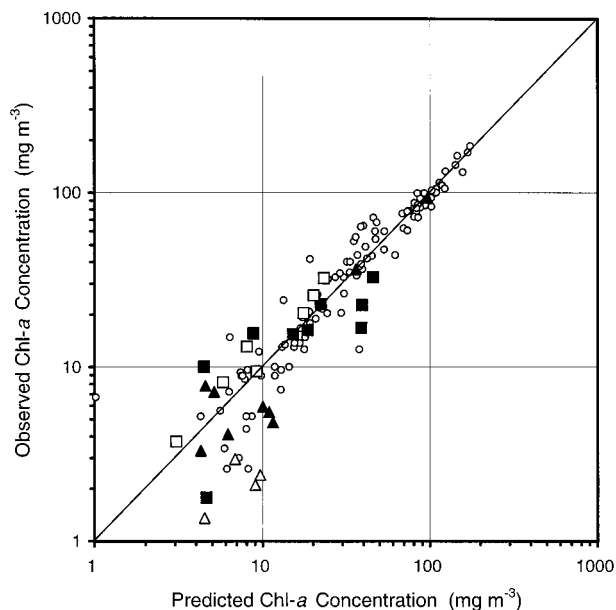
FIGURE 2. Concentrations of chlorophyll *a* in near-surface samples vs the values computed from subsurface spectral irradiance reflectance (eq 1) for North Sea (solid squares), Scheldt Estuary in August 1996 (solid triangles) and March 1999 (open triangles), and Hudson/Raritan Estuary (open squares). The open circles represent the calibration data for inland waters (*12*).

TABLE 2. Average Standard Deviations with Their Ranges (in Brackets) of the Ratio R, the Derived Backscattering Coefficient (b_b; m^{-1}), and the Predicted Concentration of Chlorophyll *a* (Chl-*a*; mg m^{-3}) from Three Spectra Per Sampling Station

survey (month/year)	standard deviation		
	R	b_b	Chl-*a*
Scheldt Estuary (8/96)	0.01 (0.00−0.02)	0.04 (0.00−0.11)	0.4 (0.1−1.8)
North Sea (4/98)	0.06 (0.01−0.32)	0.20 (0.02−0.31)	1.5 (0.7−2.9)
Scheldt Estuary (3/99)	0.01 (0.00−0.02)	0.15 (0.07−0.26)	0.6 (0.2−1.0)
Hudson/Raritan Estuary (8/99)	0.06 (0.01−0.17)	0.03 (0.00−0.08)	0.8 (0.5−1.5)

high. At the stations farthest off shore, the spectra were remarkably flat for $\lambda < 450$ nm. The lack of slope was attributed to low colored [DOM], i.e., absorption at 440 nm < 0.3 m^{-1} as opposed to typical values of 1.5 to 2 m^{-1} in Scheldt water.

Striking differences in $R(0,\lambda)$ also existed for the Scheldt Estuary between 1996 (*12*) and 1999. From sea to freshwater, the survey in 1996 showed spectral changes until the peak was in the far-red waveband, manifesting hypertrophy. In 1999 only the spectrum nearest to the sea at Terneuzen (Figure 1b) was similar to that of 1996. This spectrum was special because Chl-*a* absorption appeared as a mere shoulder. For water with a combination of low [Chl-*a*] and high [TSM], the spectra were similar to those for the freshwater IJssel Lagoon during resuspension from a gale (*12*). At the highest turbidity, the peak occurred near 690 nm instead of 580 nm.

The $R(0,\lambda)$ peaks for the Hudson/Raritan Estuary were lower than for the clearest North Seawater. Among inland waters similar low values have been observed for relatively deep lakes and the southern part of Lake IJsselmeer (*12*). Compared to these water bodies, most stations in the Hudson/Raritan Estuary showed stronger absorption by Chl-*a* as indicated by the $R(0,\lambda)$ peak in the far-red waveband.

Retrieval of [Chl-*a*]

Model Validation. The eq 1, originally developed and calibrated for inland waters, was used to predict [Chl-*a*] from the spectra shown in Figure 1 ($N = 21$) and from the Scheldt spectra of 1996 ($N = 9$; *12*). For the negative reflectance in NIR, the value at $\lambda = 776$ nm was subtracted so that b_b was set to zero and ratio R was lowered from 1.37 to 1.28. The relationship between observed and predicted [Chl-*a*] ($R^2 > 0.87$; $N = 30$; standard error of estimate = 7 mg m^{-3}) indicated that eq 1 with $p = 1.06$ and $a^*(672) = 0.018$ m^2 (mg Chl-*a*)$^{-1}$ could be used for estuarine and coastal waters as well as for lake and river water (Figure 2). The same is applicable for the use of $p = 1.06$ and $a^*(672) = 0.015$ m^2 mg^{-1} for Chl-*a* uncorrected for pheopigment (*12*). For both corrected and uncorrected Chl-*a* the greatest residual was 22 mg m^{-3}, which

was around 50% of the predicted concentration for a station in the Scheldt plume.

The [Chl-*a*] prediction was not improved much by fitting site-specific $a^*(672)$ and p to the observations of this study ($a^*(672) = 0.019 \pm 0.01$ and $p = 1.13 \pm 0.04$; $R^2 > 0.88$; $N = 30$). Thus, there was no reason to apply different algorithms for lakes and rivers as opposed to estuarine and coastal waters.

Effect of Variability in $R(0,\lambda)$. Except for the 1996 Scheldt survey performed under clear skies, triplicate determination of $R(0,\lambda)$ showed significant spread at several stations. The variation involved magnitude rather than spectral shape, as has been noted in both simulations and field data elsewhere (*14*). Computed values of b_b fluctuated considerably, while ratio R varied slightly. A number of spectra for the Hudson/Raritan Estuary and the relatively clear North Seawater were negative in NIR due to overestimated sky light contribution. The lowest value of −0.028 was computed for the North Sea. Also for [Chl-*a*] retrieval from these spectra the value at 776 nm was subtracted from $R(0,\lambda)$ at the relevant wavelengths. Ratio R changed $< 10\%$ in most cases but almost doubled for a spectrum acquired under variable clouds.

The impact of noise in $R(0,\lambda)$ on retrieval of [Chl-*a*] using eq 1 is summarized in Table 2. Standard deviation (sd) for R and b_b refers to the raw results, while the correction for negative reflectance in NIR had been made for prediction of [Chl-*a*]. The sd for triplicate determination of R was low for all Scheldt observations (cf. Table 1), but > 0.1 for one North Sea and two stations within the Hudson/Raritan Estuary. The derived b_b of the Scheldt Estuary was stable, but the sd was large for several stations at the other sites. Despite this variability, the effect on predicted [Chl-*a*] was small. Overall, the sd of prediction in triplicate remained < 3 mg m^{-3}, and the average sd for all surveys was < 1 mg m^{-3}.

Discussion

Depending on sky and water surface conditions, above-water determined $R(0,\lambda)$ can be significantly in error (*12*, *14*). The NIR range is highly sensitive because absorption by water is strong, giving low emergent light and consequently large relative error in $R(0,\lambda)$, particularly for relatively clear water. For highly turbid water ($b_b > 0.3$ m^{-1}), a sensitivity analysis of the model showed a minor impact of such error on [Chl-*a*] retrieval, except at concentrations < 3 mg m^{-3} where incorrect estimation of b_b from $R(0,\lambda)$ at 776 nm becomes a significant factor in eq 1. For water that scatters less strongly ($b_b < 0.1$ m^{-1}), the simulations showed that a noise level of 0.01 in $R(0,\lambda)$ has a considerable influence at high [Chl-*a*] (> 100 mg m^{-3}) via the ratio R. However, [Chl-*a*] and b_b will not be totally uncorrelated as was implicit in these simulations. For both present and previous work (*12*), derived $b_b < 0.1$ m^{-1} did not exist for measured [Chl-*a*] > 30 mg m^{-3}.

Residuals of [Chl-*a*] retrieval may be caused by other factors. The calibration had been performed for water with very different phytoplankton (*12*). Contrary to the lake water,

cyanobacteria were not abundant in the estuarine and coastal waters. The colony forming prymnesiophyte *Phaeocystis* spec. was dominant in the North Sea. Small centric diatoms were most abundant in Scheldt water except for the least saline compartments, when in 1996 they were outnumbered by chlorococcal green algae. Most abundant in the Hudson/ Raritan Estuary were the diatoms *Leptocylindrus minimus* and *Skeletonema costatum* beside the dinoflagellates *Gyrodinium* spec. and *Katodinium colundatum*. By diminishing the value of $a^*(672)$ the so-called package effect alone might cause significant discrepancies, while accessory pigments and chlorophyll break-down products may also influence the [Chl-*a*] prediction (*19*). Coinciding with very high pheopigment relative to [Chl-*a*], all concentrations in the Scheldt Estuary in 1999 were overestimated.

The retrieval of vertical light attenuation (*20*) and [POC] (*2*) involve b_b, and reliable determination of $R(0,\lambda)$ is needed for inverse modeling methods (*21*) as well. Clearly, insensitivity of [Chl-*a*] retrieval to statistical noise in $R(0,\lambda)$ does not detract from the need to define the protocol and determine $R(0,\lambda)$ as precisely as possible. Theoretical and empirical work give consistent results for dependence of the factor Q on incident light (*12, 22*) and of surface reflectance on cloud cover and wave field (*12, 14*). According to numerical simulations (*14*), the optimal viewing angle of water from a ship is about 40° from nadir and 135° from the sun. Almost the same nadir direction was used here, but the azimuthal angle was lower. The latter angle may be suboptimal on anchor stations but avoids the wake when sailing toward the sun. Although the shipboard operation may still be improved, more progress might be achieved by using instrumentation for synchronous recording of the radiances needed to compute $R(0,\lambda)$. A prototype instrument for shipboard use, though not hand-held and covering broad spectral bands, was developed in the 1980s (*23*).

The present optical teledetection of [Chl-*a*] performed quite well under the widely diverging physical conditions encountered. These shipboard studies provide a basis for the construction of chlorophyll-retrieval algorithms for aircraft and satellite systems. Using the red and NIR spectral range, instead of exploiting the blue Chl-*a* absorption maximum, has considerable advantages since the effect of DOM is small at these wavebands. Although inappropriate for SeaWiFS, which lacks information between the 670-nm and 765-nm bands, application to sensors such as the Medium Resolution Imaging Spectrometer (MERIS) with more red and NIR bands is probably the most promising approach to chlorophyll mapping for many Case 2 waters.

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