JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 89, NO. D4, PAGES 4977–4985, JUNE 30, 1984

CZCS Data Analysis in Turbid Coastal Water

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Different spectral signatures of coastal waters are presented and analysed with respect to possible improvements of the CZCS algorithms. When adjusted to the prevailing oceanographic conditions, algorithms can be improved in different ways: by adjustment of the coefficients in the ratio algorithms, by use of the amplitude of reflectance, or by adjustment of the method for the aerosol correction. It is shown that the combined use of ratio and amplitude of reflectance in a sediment algorithm can be used to distinguish between offshore upwellings and turbid near shore coastal water. The processing of CZCS scenes illustrates the importance of ocean color imagery in various aspects of oceanography: fundamental biology and transport of coastal pollutants.

1. INTRODUCTION

By measuring the visible spectral signature of the sea, the Coastal Zone Color Scanner (CZCS) on board satellite NIMBUS 7, is designed for the quantitative remote sensing of the biooptical properties of marine waters [*Hovis et al.*, 1980]. Positive results have already been obtained for the American coastal and pelagic waters [*Gordon et al.*, 1980; *Smith and Baker*, 1982; *Gower*, 1981; *Gordon et al.*, 1982]. Attractive results can also be expected in Europe, but cautious studies are required because the European coastal waters cover a large variety of conditions in biological oceanography, and the algorithms have to be tested in each case.

For example, the Mediterranean Sea consists of oceanlike waters, as well as shallow waters receiving important river outflows, as in the case of the north Adriatic Sea [*Artengiani and Azzolini*, 1981; *Franco et al.*, 1982; *Rizzoli*, 1981; *Sturm et al.*, 1981]. The near Atlantic and the English Channel offer other various oceanographic phenomena: coastal upwelling along the Iberian Peninsula [*Fuaza et al.*, 1982], mixing processes at the Celtic Sea shelf break [*Pingree et al.*, 1982], and an estival tidal front at the entrance of English Channel [*Holligan*, 1981; *Le Fevre et al.*, 1982; *Holligan et al.*, 1983; *Dupouy*, 1982]. There, extremely high chlorophyll concentrations (30 mg/m^3) are frequently observed. Beyond the English Channel the remote sensing data from the shallow waters of the North Sea become difficult to analyze, due to the natural and/or anthropogenic terrestrial discharges and to the resuspension of sediments by tidal currents. All these areas have often their own dominant plankton species and different composition of suspended and/or dissolved matter, which leads to a great variability in their optical properties and makes most of them belong to case 2 waters in the sense of Morel's classification [*Morel*, 1980]. This point is emphasized in this paper by the presentation and the discussion of different water spectral signatures.

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Paper number 3D1691.
0148-0227/84/003D-1691$05.00

2. SPECTRAL SIGNATURES OF COASTAL WATERS

In situ diffuse reflectances $R(\lambda)$ at the CZCS wavelength have been registered by means of an underwater radiometer (manufactured by Electro Optics Suarez) measuring simultaneously the upwelling and the downwelling irradiances. (Note that in all the sections the notation $R(\lambda)$ refers to the diffuse spectral reflectance of water just below the surface.) They are presented in Figures 1*a*–1*c*. Figure 1*a* corresponds to a *Gyrodinium aureolum* bloom at a thermal front in the Western English Channel. Figures 1*b* and 1*c* correspond to turbid coastal waters in the east English Channel (Dover Straits) and in the Adriatic Sea, respectively. The experimental conditions, the comparisons with CZCS, and the use of these data for marine environmental studies have been described by *Dupouy* [1982], *Holligan et al.* [1983], *Dupont* [1983], and *Sturm et al.* [1981], respectively.

Another kind of spectral signature (Figure 1*d*) is characterized by a very high level of reflectance (10% to 20%) and corresponds to a coccolithophorid (*Emiliana huxleyi*) bloom at the shelf break off Brittany during May 1982 (Groupe de Recherche Pelagique Manche Atlantique, personal communication, 1983; hereinafter GREPMA, 1982) [*Holligan et al.*, 1983]. In this case the spectral signatures have been derived from the CZCS data themselves by atmospherically correcting pixels from Figure 2. Such procedure is valid here because the water leaving radiation has been determined to be much greater than the aerosol component. Figures 1*b* to 1*d* are drawn with the same scale in order to outline the differences in the amplitudes of reflectance. The scale of Figure 1*a* is however twice that of the other figures to emphysize the more subtle spectral structure associated with that set of $R(\lambda)$ data.

There is a general agreement between numerous authors about modeling the diffuse water reflectance $R(\lambda)$ at wavelength (λ) by a simple formula [*Morel and Prieur*, 1977]

$$R(\lambda) = 0.33 \frac{\Sigma_i r_i b_i(\lambda)}{\Sigma_i a_i(\lambda)} \tag{1}$$

where a_i and b_i are the absorption and the scattering coefficients, respectively (per meter), of the ith water constituant (including the water itself) and r_i are the corresponding

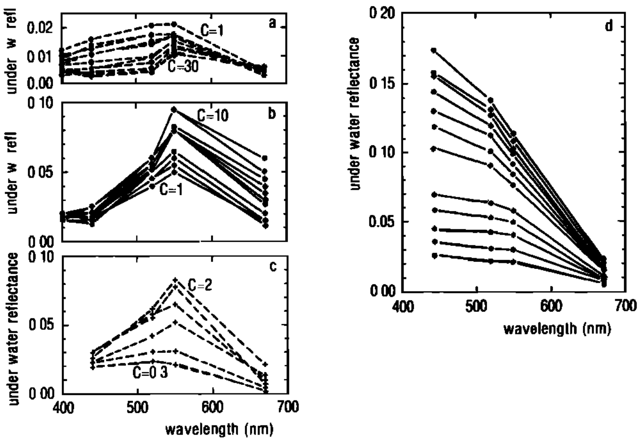

Fig. 1. Spectral reflectance of water at different European coastal zones. (*a*) Measured just below the surface in the Western English Channel, on July 16th, 1981, across a *Gyrodinium aureolum* bloom [*Dupouy*, 1982; *Holligan et al.*, 1983]. The chlorophyll concentration C ranged from 1 to 30 mg/m^3. The sediment content was negligible. (*b*) Measured across turbid coastal waters in the Eastern English Channel, on May 13th, 1982 [*Dupont*, 1983]. The chlorophyll concentration ranged from 1 to 10 mg/m^3 and was found covarying with the total suspended matter. (*c*) Measured across turbid coastal waters in the Northern Adriatic Sea, for September 1980 [*Sturm et al.*, 1981]. The chlorophyll concentration ranged from 0.3 to 2 mg/m^3. (*d*) Derived from CZCS data (May 29, orbit 13149) across a coccolithophorid bloom, at the continental shelf break, off Brittany [*Holligan*, 1982]. The chlorophyll concentration ranged from 0.5 to 3 mg/m^3. The number of coccolithophorid cells ranged from 0 to 80,000 cells/ml. The CZCS data have been corrected from atmospheric effects by deriving the aerosol correction at pixels contiguous to the bloom. See also Figure 2.

backward scattered fractions (typically, between 0.005 and 0.02 and independent of λ). From (1) it can be seen why a ratio of reflectances in the blue and in the green provides an index of chlorophyll: the effect of chlorophyll is to increase a, then to decrease R in the blue, whereas the reflectance in the green is unchanged or even slightly increased due to variations of b. This ratio index has been successfully tested using a great deal of experimental data [*Clark*, 1981]. However, a full analysis of the spectral signature with respect to the variations of a, b, and r under various oceanographic conditions requires further research, as discussed in the following, for specific cases.

2.1. *Case of the Gyrodinium aureolum Bloom*

For this bloom the sea is perceived as almost black, i.e. the reflectances (Figure 1*a*) are very low ($R < 0.02$). Furthermore, even the reflectance at 550 nm decreases as the chlorophyll concentration increases. With regard to (1), these observations are explained by low values of r and high values of a. According to *Morel and Bricaud* [1981], r should be less than 0.005, since the *Gyrodinium aureolum* cell is naked (soft wall without scale) and has large chromatophores. As high absorption coefficient values as 0.6 m^{-1} and 0.24 m^{-1} at 443 and 550 nm, respectively, were measured at the maximum of the chlorophyll content [*Dupouy*, 1982].

2.2. *Case of the Coccolithophorid Bloom*

The reflectances at 550 nm have typical values of 0.10 (Figure 1*d*), i.e., a factor 10 higher than in the preceding example. To explain this difference, one should assume that low values of a (<0.1) are here associated with high values of r (>0.02). According to the sea truth measurements [GREPMA, 1982; *Holligan*, 1981], such properties are plausible: relatively low chlorophyll concentrations (<1.5 mg/m^3), together with a great number of coccolithophorids *Emiliana huxleyi* were recorded by them. The cells of coccolithophorids are covered by scales (called coccoliths) of calcium carbonate in the form of calcite crystal. Furthermore, large numbers of coccoliths have been observed, in suspension, which are detached from the cells, with typical concentration of 80,000 coccoliths for 8000 cells/ml. It is assumed that the high value of the optical refractive index of calcium carbonate (1.6 relative to air) yields the observed high value of the backward scattered fraction r. However, since low values of r have been measured for batch cultures of coccolithophorids [*Morel and Bricaud*, 1981], we may infer that the individual detached coccoliths are the major contribution to the high values of r observed.

2.3. *Case of turbid coastal waters*

In this case, suspended sediments and dissolved detritic matter control the backward scattered fraction r and absorption. High values of r (between 0.01 and 0.02) are usual and dominate observed reflectances at 550 nm (between 0.05 and 0.10; Figures 1*b* and 1*c*). By contrast with the coccolithophorid bloom, however, the dissolved detritic matter (yellow substance) strongly absorbs the light at the shortest wavelengths, lowering the reflectance at 443 nm to around 0.02.

Another characteristic of the $R(\lambda)$ data shown in Figures 1*b* and 1*c* is that the reflectance at 550 nm has a tendency to follow the variations of the chlorophyll content. As a matter of fact, it is found even in class 2 waters that variations of chlorophyll and total suspended matter are correlated, but the correlation changes with location and time, as shown by *Sturm et al.* [1981]. This might be explained by the fact that mixing processes and terrestrial deposits have convergent effects both for increasing biological activity (nutrient input) and suspension of sediment.

3. ALGORITHM FOR THE CHLOROPHYLL CONTENT

Various algorithms have been proposed for the retrieval of chlorophyll content (C in mg/m^3) [*Arvesen et al.*, 1973; *Jain and Miller*, 1976; *Viollier et al.*, 1978; *Kim et al.*, 1980; *Bukata et al.*, 1981; *Tassan*, 1981; *Spitzer et al.*, 1982]. Note that chlorophyll content means here the concentration of chlorophyll-*a* plus phaeophytin-*a* [see *Morel*, 1980]. Now there is a general agreement for using an algorithm involving a ratio of reflectances [*Gordon et al.*, 1980; *Smith and Baker*, 1982]:

$$\log C = \alpha + \beta \log \frac{R(\lambda_1)}{R(\lambda_2)} \tag{2}$$

where two wavelengths (λ_1, λ_2) are alternatively used: (443, 550 nm) and (520, 550 nm).

For the three cases presented in Figures 1*a*, 1*b*, and 1*c*, this algorithm is tested by means of log-log plots of C versus $R(443)/R(550)$ and of C versus $R(520)/R(550)$, shown in Figure 3. From it (and the associated regression equations) one can conclude that the ratio method is generally suitable; however, the coefficients α and β seem to be dependent on phytoplankton type.

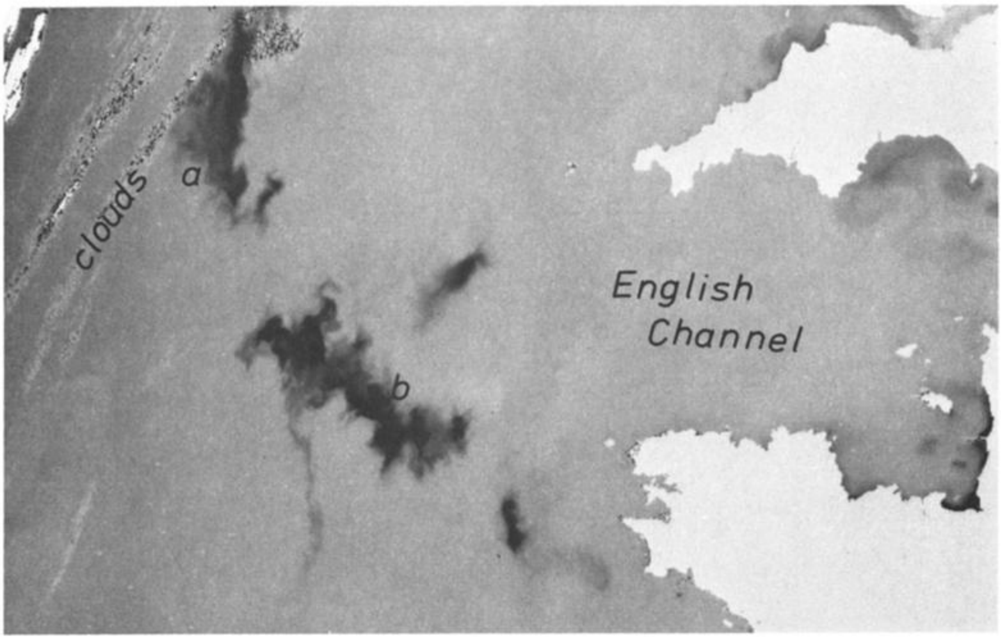

Fig. 2. CZCS observations of coccolithophorid blooms, on May 29, 1982 (orbit 18149). This figure represents the reflectances at 550 nm, after atmospheric correction (reflectance increases from white to black). The major patterns *a* and *b* are characterized by reflectances higher than 0.10 (see also Figure 1*d*) and are approximately located along the continental shelf break where the bottom depth changes from 200 to 4000 meters. There, mixing due to internal waves and upwelling yield an intense biological activity. At area *b*, sea truth campaigns for two periods, May 9–21 [*Grepma*, 1982] and May 24–June 3 [*Holligan*, 1982] have observed numerous cells of coccolithophorid *Emiliana huxleyi*. The image has been processed by M. Champagne at CMS Lannion, using codes developed by *Marsouin and Leglas* [1982].

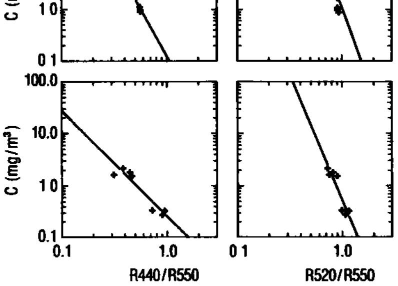

Fig. 3. Test of the ratio algorithm: chlorophyll concentration at the surface layer versus the ratio of reflectances at 443 and 550 nm (left) and at 520 and 550 nm (right). (Ratios are calculated from the $R(\lambda)$ data of Figure 1). (top) Case of a *Gyrodinium aureolum* bloom at the English Channel [*Dupouy*, 1982; *Holligan et al.*, 1983]. (middle) Case of coastal turbid waters (Dover Straits) on September 10, 1981 [*Dupont*, 1983]. (bottom) Case of turbid coastal waters in the Northern Adriatic. Regression lines, respectively: $\log C = -0.33 - 3.2 \log [R(443)/R(550)]$, $r^2 = 0.88$; $\log C = -0.91 - 3.68 \log [R(443)/R(550)]$, $r^2 = 0.76$; $\log C = -0.54 - 1.96 \log [R(443)/R(550)]$, $r^2 = 0.89$; and $\log C = 0.07 - 3.6 \log [R(520)/R(550)]$, $r^2 = 0.76$; $\log C = -0.02 - 5.65 \log [R(520)/R(550)]$, $r^2 = 0.52$; $\log C = -0.25 - 4.57 \log [R(520)/R(550)]$, $r^2 = 0.81$.

It must also be taken into account that in turbid coastal waters, the empirical relationship between C and the ratios of reflectance may be strongly influenced by yellow substances and suspended sediments.

4. ALGORITHM FOR THE CONTENT OF TOTAL SUSPENDED MATTER

In open ocean and off-shore upwellings (case 1 in Morel's classification) it is found that total suspended matter S (measured by filtration and weighing), expressed in milligrams per liter, is strongly correlated with chlorophyll concentration [*Clark et al.*, 1980; *Sturm et al.*, 1981]. Typically, a relation of the following form is found:

$$S = a\, C^b \tag{3}$$

a and b are empirical constants (not to be confused with absorption and scattering coefficients a and b of (1)), with $a \approx 0.5$ and $b \approx 0.7$, and correlation coefficient $r^2 > 0.8$. This strong correlation of S and C is due to the fact that in case 1 waters the total suspended matter results predominantly from biological activity (primary productivity, grazing).

A different situation is found in near coastal turbid waters where river discharge and/or resuspension of sediments also serve to increase the total suspended matter content. In these cases the correlation coefficient of a regression of type (3) is found to be much smaller than 0.8 [*Sturm et al.*, 1981], and the coefficient a is nearly 10 times greater, while b is of the order of 1.

The quantitative determination of total suspended matter in near coastal zones may be of interest for example in pollution studies in river estuaries and lagoons [*Donazzolo et*

Fig. 4. Map of sediment content in the Northern Adriatic Sea, obtained from atmospheric correction of CZCS data (orbit 3831, July 28, 1979) and from (7). Light tones correspond to high sediment content. The double-eddy circulation, assumed to be prevailing in summer, is clearly visible: one plume "spreading towards Istria and northward," the other "spreading in a southward direction and closing upon itself to form a smaller, anticyclonic gyre" [from *Franco et al.*, 1982]. Other drifts of coastal waters are suggested by the turbid patches observed around the lower center of the map.

al., 1982] where the value of S (in milligrams per liter) can give information about where and how much pollution is transported (see Figure 4).

The algorithm proposed by *Clark* [1980] for calculating suspended matter as a function of the blue-green ratio is not the most appropriate in class 2 waters. For instance, *Zbinden* [1981] finds that the best relationship between S and the spectral signature is not from a ratio of reflectances but from the absolute value of reflectances (at 520 or 550 nm). This conclusion however is valid for a specific case: the Bay of Mont St. Michel (central English Channel) during summer.

To derive a more general algorithm for determining total suspended matter we selected 82 measurements of $R(\lambda)$ and total suspended matter S: 9 from the Adriatic [*Sturm et al.*, 1981], 33 from Dover Straits [*Dupont*, 1983] and 40 from the Bay of St. Michel [*Zbinden*, 1981]. The S measurements ranged from S = 0.6 mg/l to about 30 mg/l. The data were

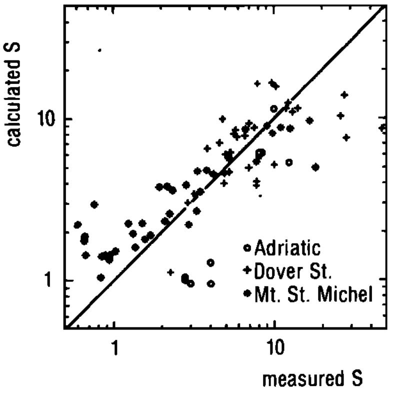

Fig. 5. Scatter plot of log S_{calc} versus log S_{meas}. $S_{calc} = 18.02\, \xi^{-1.566}\, \bar{R}^{-0.733}$; $\xi = 0.642\, [R(443)/R(550)] + 0.891\, [R(520)/R(550)] - 0.537$; $\bar{R} = [1/(670 - 443)] \int_{443}^{670} R(\lambda) d \cong 0.169R(443) + 0.2357R(520) + 0.3304R(550) + 0.2643R(670)$.

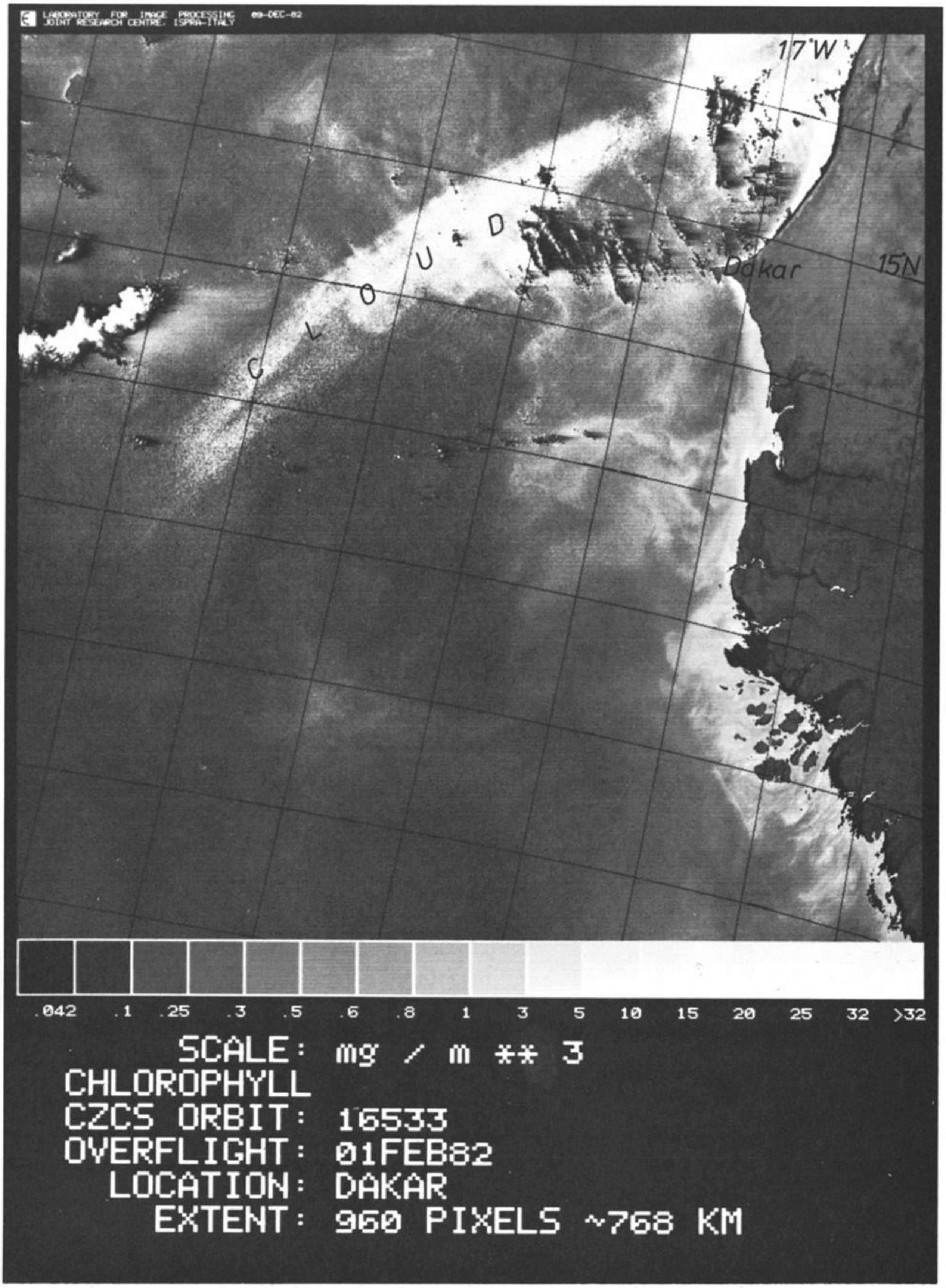

Fig 6. Map of chlorophyll content over West African coastal and offshore waters. The chlorophyll concentration was obtained from $C = 0.87\ \xi^{-1.833}$ (B. Sturm et al., unpublished manuscript, 1984).

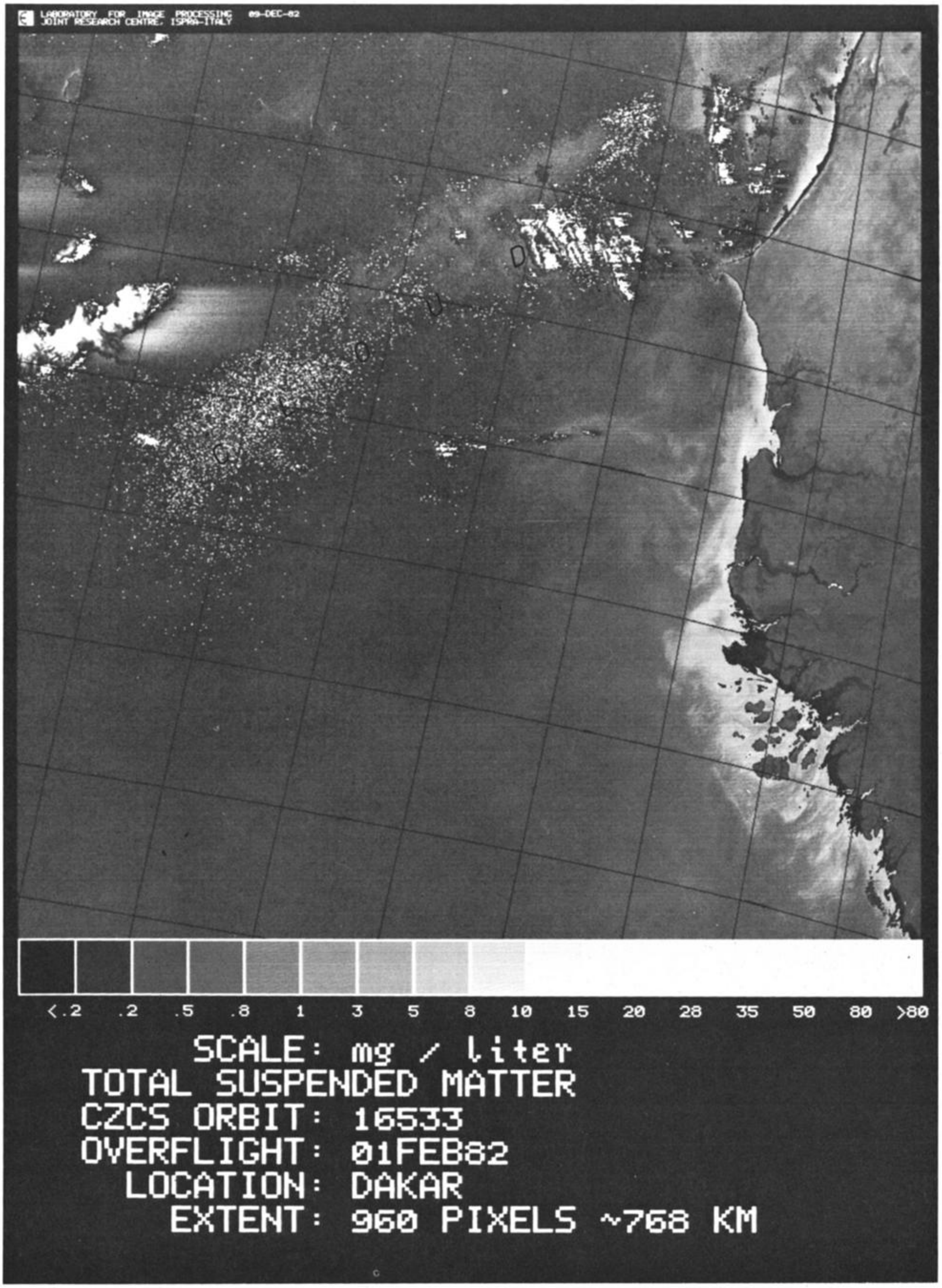

Fig. 7. Map of total suspended matter content over West African coastal and offshore waters.

fitted by multiple linear regression to the equation

$$\log S = A + B \log \xi + C \log \bar{R} \quad (4)$$

where ξ is an average blue-green ratio defined by [*Sturm et al.*, 1981]

$$\xi = 0.642 \frac{R(443)}{R(550)} + 0.891 \frac{R(520)}{R(550)} - 0.533 \quad (5)$$

and $\bar{R}$ is an average reflectance defined and estimated as

$$\bar{R} = \frac{1}{670 - 443} \int_{443}^{670} R(\lambda)\, d\lambda \approx 0.1696R(443)$$
$$+ 0.2357R(510) + 0.3304R(550) + 0.2643R(670) \quad (6)$$

The result was

$$A = 1.2558 \qquad B = -1.5655 \qquad C = 0.7332$$

with multiple correlation $r^2 = 0.6189$ and a F ratio of 64.1574 ($F(2, 79, 0.95) < 3.15$), using the method and nomenclature of *Draper and Smith* [1966]. Figure 5 shows the scatter plot comparing calculated with measured S values. The overall trend of the data in Figure 5 is strong, but clearly the data from the Adriatic would be better fit by a separate regional model.

The derived algorithm, which can also be written in the form

$$S = 18.02\ \xi^{-1.566}\bar{R}^{0.733} \quad (7)$$

takes advantage of the fact that total suspended matter acts on the optical properties of water in two ways: (1) via absorption, which influences mainly the blue-green ratio, i.e., ξ, and (2) via scattering, which influences mainly the backscattering coefficient and hence the average reflectance $\bar{R}$.

The results of applying such a combined absorption-scattering sediment algorithm can be seen in Figures 6 and 7 where the maps of chlorophyll and total suspended matter are shown for CZCS orbit 16533 (February 1, 1982) over West Africa. One notes in Figure 6 a relatively strong chlorophyll concentration front in the north-south direction near 19°W (the geographical coordinate grid is 1° × 1°). On Figure 7 the total suspended matter map does not show this front because the average reflectance there is decreased, while near the coast, high $\bar{R}$ values give rather high total suspended matter values. In this case, at least, the algorithm (7) clearly distinguishes near-coastal waters with high chlorophyll and high total suspended matter content from upwelled offshore waters with high chlorophyll and low total suspended matter content.

5. The Use of Channel 670 nm for the Aerosol Correction

In the CZCS atmospheric correction scheme, the aerosol component is computed from channel 670 nm [*Gordon*, 1978; *Viollier et al.*, 1980; *Sturm*, 1980; *Sorensen*, 1981]. If the water reflectance at 670 nm is not negligible, this method fails. The examination of Figures 1*a* to 1*d* shows that only $R(670)$ for the *Gyrodinium aureolum* bloom (Figure 1*a*) can be considered as negligible (in the CZCS analysis of this bloom described by *Holligan et al.* [1983], a constant value of 0.006 was introduced). In the other cases, values of $R(670)$ as high as 0.03 (Figure 1*c*) to 0.06 (Figure 1*b*) are observed, which are greater than the concurrent values of aerosol radiance. A means of estimating $R(670)$ from the other channels is needed for a more accurate aerosol correction.

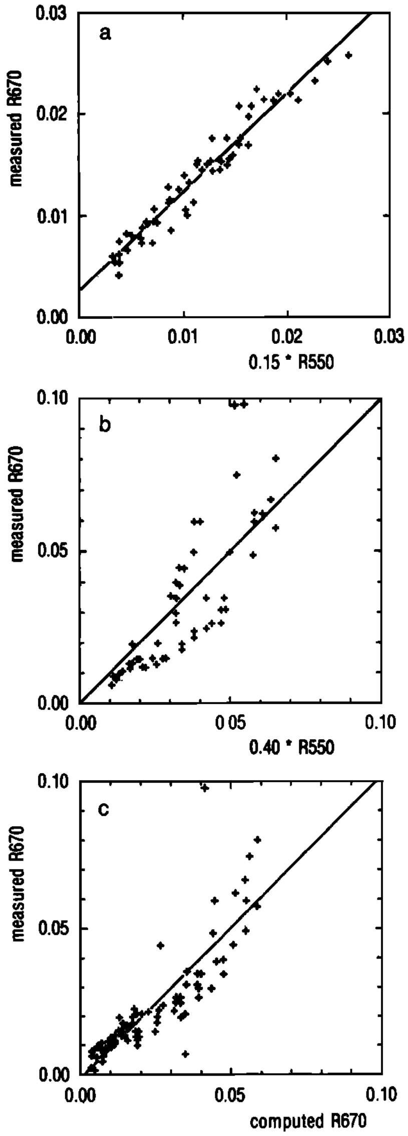

Fig. 8. Test for the retrieval of R_{670}: measured values versus values computed from the following. (*a*) A linear relationship: $R_{670} = 0.15\ R_{550}$ (case of the coccolithophorid bloom from CZCS orbits 3293 and 18149). (*b*) A linear relationship: $R_{670} = 0.40\ R_{550}$ (case of turbid coastal waters in the eastern English Channel). (*c*) Equation (9): $R_{670} = 0.23\ R_{550}\ (R_{520}/R_{550})^{-2}$ (of both types of water mentioned).

To solve this problem, the following equation was originally proposed by *Smith and Wilson* [1981]:

$$R(670) = aR(550) \left[\frac{R(440)}{R(550)}\right]^b \quad (8)$$

where $a = 0.083$ and $b = -1.66$ are empirical constants derived from $R(\lambda)$ measurements (the equation was given in terms of radiance, instead of reflectance; the modification for a and b should not exceed some percent). For class 2 waters, *Sturm* [1981, 1983] has proposed similar formulae with changed a and b and using both ratios 443/550 and 520/550.

The simple proportional relationship (i.e., (8) with $b = 0$) between $R(670)$ and $R(550)$ gives also significant correlation (Figures 8*a* and 8*b*). However, the constant a is different from one case to the other: 0.15 for the CZCS-derived $R(\lambda)$ data of coccolithophorid bloom and 0.40 for the in situ measured $R(\lambda)$ data of turbid coastal waters in the English Channel. An equation similar to (8), but involving channel 520 nm instead of channel 443 nm,

$$R(670) = a'R(550)\left[\frac{R(520)}{R(550)}\right]^{b'} \qquad (9)$$

with $a' = 0.23$ and $b' = -2$, yields satisfactory results for both kinds of waters (Figure 8*c*).

6. CONCLUSION

A documented catalogue of water spectral signatures is an important key to CZCS data analysis. However, such a catalogue is not readily available for European coastal waters and was nonexistent before recent studies were undertaken. Some of these recent examples are presented in this paper.

These examples illustrate the large variety of marine optical properties associated with different hydrobiological conditions. It is interesting to note that in one case (a coccolithophorid bloom), original observations were done using CZCS itself. The present analysis shows that the CZCS algorithms can be improved when adjusted to account for the prevailing oceanographic conditions. Methods for doing this include adjustment of the coefficients in the ratio algorithms, use of the amplitude of reflectance, and modification of the method for the aerosol correction. It has been shown that the combined use of reflectance ratio and amplitude of reflectance in a sediment algorithm can be used to distinguish between offshore upwelling fronts and turbid frontal structure in near shore coastal waters.

Acknowledgments. This paper uses some of the work and observations done in Europe in the field of the CZCS analysis. The authors would like to emphasize the basic work done at sea by many talented people for the cruise organizations, optical measurements, and seston and plankton studies. Crucial contributions were rendered by G. Ferrari, J. C. Maracci, P. Schlittenhardt (Joint Research Center at Ispra), L. Alberotanza (Consiglio Nazionale della Richerche Venice), J. Y. Balois and P. Lecomte (University of Lille), J. Dupont and C. Dupouy (Station Marine de Wimereux), Y. Thomas and R. Zbinden (Ecole Nationale Supérieure, Paris), participants of GREPMA (Brest, Nantes, Roscoff, Lannion), P. Holligan (Marine Biological Association, Plymouth, U.K.), and J. Aiken and M. Jordan (Institute for Marine Environmental Research, Plymouth, U.K.). The CZCS data processing software of the JRC Ispra was written by A. Stein and W. Mehl.

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(Received March 21, 1983;
revised October 17, 1983;
accepted October 18, 1983.)