

Retrievals of a size parameter for phytoplankton and spectral light absorption by colored detrital matter from water-leaving radiances at SeaWiFS channels in a continental shelf region off Brazil

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Abstract

Many efforts are currently oriented toward extracting more information from ocean color than the chlorophyll *a* concentration. Among biological parameters potentially accessible from space, estimates of phytoplankton cell size and light absorption by colored detrital matter (CDM) would lead to an indirect assessment of major components of the organic carbon pool in the ocean, which would benefit oceanic carbon budget models. We present here 2 procedures to retrieve simultaneously from ocean color measurements in a limited number of bands, magnitudes, and spectral shapes for both light absorption by CDM and phytoplankton, along with a size parameter for phytoplankton. The performance of the 2 procedures was evaluated using different data sets that correspond to increasing uncertainties: (1) measured absorption coefficients of phytoplankton, particulate detritus, and colored dissolved organic matter (CDOM) and measured chlorophyll *a* concentrations and (2) SeaWiFS upwelling radiance measurements and chlorophyll *a* concentrations estimated from global algorithms. In situ data were acquired during 3 cruises, differing by their relative proportions in CDM and phytoplankton, over a continental shelf off Brazil. No local information was introduced in either procedure, to make them more generally applicable. Over the study area, the absorption coefficient of CDM at 443 nm was retrieved from SeaWiFS radiances with a relative root mean square error (RMSE) of 33%, and phytoplankton light absorption coefficients in SeaWiFS bands (from 412 to 510 nm) were retrieved with RMSEs between 28% and 33%. These results are comparable to or better than those obtained by 3 published models. In addition, a size parameter of phytoplankton and the spectral slope of CDM absorption were retrieved with RMSEs of 17% and 22%, respectively. If these methods are applied at a regional scale, the performances could be substantially improved by locally tuning some empirical relationships.

Introduction

The effective use of ocean color to estimate biological parameters depends on understanding the relative importance of phytoplankton to the fate of incident irradiance. Previous

works have shown that a change in phytoplankton cell size, when compared to the effects of taxonomy (Ciotti et al., 2002) and pigment composition (Bricaud et al. 2004), in many situations is the dominant factor ruling the relationship between light absorption by phytoplankton and chlorophyll concentration. In turn, light absorption can, under some assumptions, be derived from reflectance (Roesler and Perry 1995, Carder et al. 1999, Loisel and Stramski 2000, Maritorena et al. 2002, Lee and Carder 2003). Therefore, it should be possible, at least in regions where phytoplankton absorption is significant, to develop methods to retrieve changes in cell size from ocean color measurements. In the recent past many efforts have been oriented toward extracting pigment or taxonomic information from such measurements (e.g., Subramaniam et al. 2002, Sathyendranath et al. 2004, Alvain et al. 2005), but very few attempts have been made to obtain information on the dominant size of populations from space (but see Uitz et al., in press). This parameter has obvious ecological importance, as it

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can provide information on the phytoplankton community structure and insights on energy transference through the trophic web.

Significant variations in water optical properties can also result from the presence of different amounts and types of dissolved substances, as well as organic and inorganic detrital particles (Gordon et al. 1988, Morel 1988). Therefore, changes in the detrital material content can potentially be retrieved from ocean color. Owing to the similar spectral behavior of these other components, their retrieval in bio-optical models is often combined into a single term, named colored detrital matter (CDM) (e.g., Carder et al. 1991, Nelson et al. 1998). Recent studies, using various methods, focused on extracting information about CDM (Maritorena et al. 2002) or only colored dissolved organic matter (CDOM) (Johannesen et al. 2003, Fichot and Miller 2004) content from satellite measurements. An estimate of the CDM content from space also has ecological relevance, as it would allow a synoptic view and near real-time observation of the corresponding carbon pool in the ocean. These components are usually more abundant over coastal areas with significant contribution of continental outflows. It is important to note that, because CDM is the combination of 2 distinct carbon pools in the ocean (i.e., colored dissolved organic matter and particulate detritus), the interpretation of the retrievals must take into account the relative contributions of both. It has been shown that CDOM is the main component of CDM at the global scale (Siegel et al. 2002), but at a regional scale particulate detritus can be important. The concurrent retrieval of the spectral slope of CDM, in addition to its magnitude, can be a useful tool in such cases, as values tend to be smaller when particulate detritus is more abundant than CDOM.

Because both CDM and phytoplankton absorption features influence ocean color, their retrieval from in situ or satellite ocean color measurements should be carried on simultaneously. Indeed, at a global scale, retrievals of chlorophyll concentration from remote sensing data seem dependent on the chosen model's ability to take CDM absorption into account (Siegel et al. 2005). Most of the available methods that retrieve information on phytoplankton or CDM absorption, however, are based on somewhat constraining assumptions. The method proposed by Maritorena et al. (2002), and applied to SeaWiFS data by Siegel et al. (2002), is a global minimization technique applied to the semi-analytical model developed by Garver and Siegel (1997). A basic assumption of this model is that the spectral shapes of absorption by phytoplankton and CDM are known. Johannesen et al. (2003) estimated the absorption coefficient of CDOM at several wavelengths (323, 338, 380 nm) from the diffuse attenuation coefficient, K_d , at the same wavelengths, using empirical relationships derived from in situ measurements (K_d values were, in turn, estimated from diffuse reflectance, also using empirical relationships). Fichot and Miller (2004) used a similar method to compute the CDOM absorption coefficient at 320 nm from $K_d(320)$ (K_d was derived from a principal component analysis of spectral reflectance)

and extrapolated CDOM absorption coefficients at other wavelengths by assuming that their spectral slope was constant.

Some inversion methods were also proposed to partition total absorption spectra, as measured in situ, into those of phytoplankton, detritus, and CDOM, or CDM (Chang and Dickey 1999, Gallegos and Neale 2002, Oubelkheir and Bricaud 2003, Schofield et al. 2004). These methods have generally been applied with some success to in situ measurements performed with absorption meters such as the WET Labs ac-9. Nonetheless, to our knowledge, none of these methods was tested with ocean color data from current sensors. The limited number of wavelengths in sensors such as SeaWiFS and MODIS results in a reduced number of degrees of freedom for extracting information. However, approaches for retrieving a second-order effect, such as changes in cell size, from ocean color data, can be employed only if the absorption coefficients can be derived from these data with sufficient accuracy.

In this article, we first used a previously published model (Loisel and Stramski 2000) to retrieve total absorption from remote sensing reflectances derived from SeaWiFS data in 5 bands of the visible range. Then we report the results of 2 inversion methods aimed at retrieving simultaneously, from total absorption coefficients, the amplitude and spectral shape of light absorption by CDM and a cell size parameter for phytoplankton. The first approach is based on the work by Oubelkheir and Bricaud (2003) and K. Oubelkheir, H. Claustre, A. Bricaud, and M. Babin (unpublished data), who adapted the method proposed by Bricaud and Stramski (1990) for the decomposition of particulate absorption, to make it applicable to total absorption measured with an in situ absorption meter. In the present work, the method was modified again for retrieving CDM and phytoplankton contributions from total absorption at SeaWiFS wavelengths. Once phytoplankton absorption is retrieved, a size parameter S_f is estimated using the mixed spectral model from Ciotti et al. (2002). Although S_f is not a commonly used bio-optical property, it can be shown for large in situ data sets (A. Bricaud et al., unpublished data) that S_f is inversely correlated to the dominant cell size. The mixed spectral model from Ciotti et al. (2002) establishes that S_f varies from 0, where phytoplankton is dominated by large cells ($> 20 \mu\text{m}$), to 1, where it is dominated by small cells ($< 2 \mu\text{m}$). Intermediate values represent the possible situations between these two extremes.

The second approach used here is an inversion technique, similar to that used by Roesler and Perry (1995) for diffuse reflectance. Observed and modeled values are adjusted and yield simultaneously the magnitude and spectral shape of CDM, and the S_f value. Both methods were tested using successively 2 data sets for input parameters: (1) both measured spectral absorption coefficients and measured chlorophyll *a* concentrations, and (2) SeaWiFS upwelling radiance data and chlorophyll *a* concentrations estimated from global algorithms. Our goal is to evaluate the performances of the proposed methods, in these two sit-

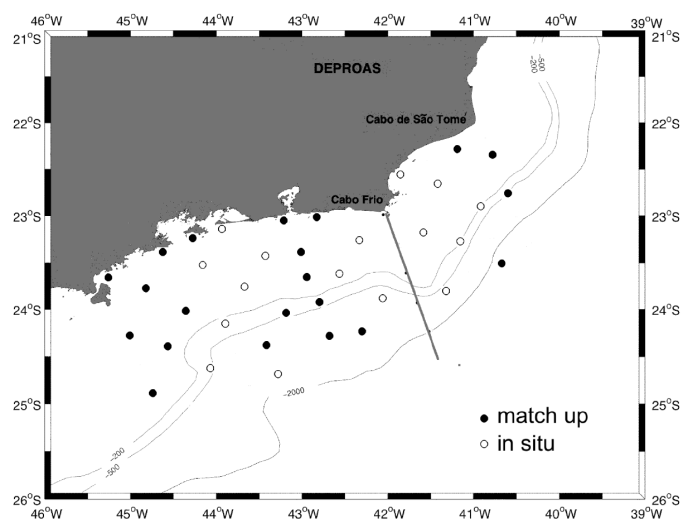


Fig. 1. Sampled area for the periods of the DEPROAS-3 and -4 cruises (January and August 2002). Only the stations with available absorption measurements are shown with circles. The filled circles indicate stations where simultaneous satellite data was available during DEPROAS-4. DEPROAS-2 was a series of stations over a single profile (indicated by the line) repeated 3 times.

uations corresponding to increasing uncertainties, and therefore the possibilities to retrieve both a size parameter for phytoplankton and CDM absorption coefficients from ocean color measurements.

Materials and procedures

Sampling—The inversion methods presented in this study were tested on field data collected during 3 cruises, performed on shelf waters between Cabo de São Tomé and São Sebastião Island (Brazil), and following a series of transects perpendicular to the coast (Figure 1 and Table 1). Samples were collected in the surface layer (0 to 20 m), and measurements of chlorophyll *a* concentration, particulate absorption, and CDOM absorption were performed. During the first cruise (DEPROAS 2), in situ measurements of upwelling radiances and downwelling irradiance were also acquired at 10 stations. Details on the cruises are presented elsewhere (A.M. Ciotti and S.A. Gaeta, unpublished data).

Table 1. Summary of cruises and measurements

Cruise	Design	Dates	Data	No. samples
Deproas 2	One transect perpendicular to the coast repeated 4 times plus a coastal transect	July 12-19, 2001	Chl, CDOM absorption, particulate absorption	27
Deproas 3	See Figure 1	January 4-24, 2002	Chl, CDOM absorption, particulate absorption	58
Deproas 4	See Figure 1	August 3-21, 2002	Chl, CDOM absorption, particulate absorption	57

Pigments—Chlorophyll *a* (chl, mg m^{-3}) concentrations were determined using a calibrated Turner Designs 10-005R fluorometer, equipped with the nonacidification filter set (Welschmeyer 1994). Samples of 500 mL were concentrated on GF/F filters that were stored in liquid nitrogen immediately after filtration. GF/F filters were extracted at -10°C or below, for at least 24 h, in precooled 90% acetone:DMSO solution (6:4 by volume; Shoaf and Lium 1976). Reported values are averages from triplicates.

CDOM absorption—Filtrates from the chlorophyll samples were collected in clean T-flasks. Although 0.2- μm membrane filters are generally used for the preparation of CDOM samples, the use of GF/F filters was preferred in the present study to ensure the consistency with the procedure used for particulate absorption measurements (see below) and the estimate of total absorption. An initial sample volume of 150 mL was discarded for rinsing the GF/F filter and the filtration apparatus. Care was taken not to dry the filter (i.e., pressure was interrupted when around 25 mL of sample was still unfiltered) to avoid disruption of cells. Samples were stored in amber Qorpak bottles that were previously cleaned as follows: (1) a 24-h 10% HCl bath; (2) 5 rinses with freshly produced Milli-Q water; (3) a sterilization using a microwave (10 min on high power for 12 bottles containing around 50 mL of Milli-Q water; the bottles were capped and the Milli-Q water was discarded just before sample collection); and (4) a final rinse with the sample. Samples were kept at 4°C until analysis and were taken in triplicates that were analyzed in sequence. Average storage time was 2 weeks for the first replicate and 1 month for the third replicate, except for Deproas 2 (more than 3 months, due to problems with the available spectrophotometer). Several Milli-Q blanks were produced in the laboratory before to the cruises and stored with the samples until the analyses using Hitachi U2010 (Deproas 2) and a Hitachi U3010 (Deproas 3 and 4) dual-beam spectrophotometers and a 10-cm quartz cuvette. Freshly produced Milli-Q water was used to zero the instrument, and samples were scanned against air from 800 to 250 nm, but only the data from 350 to 600 nm were used to derive the spectral slope of CDOM absorption, following Babin et al. (2003). Reported values are averages from triplicates. Details on storage effects can be found in Ciotti and Gaeta (2002) and A.M. Ciotti and S.A. Gaeta, unpublished data. Briefly, there was no significant change in the CDOM

absorption parameters (i.e., slope, magnitude, and infrared background) among the 3 groups of replicates, which suggested a very low or absent bacterial consumption, as well as low chemical loss or transformation of CDM within the samples. It should be noted here that any errors on CDM absorption coefficients due to storage effects, if existing, do not affect the performance of the methods when input parameters are total absorption coefficients, as these are “reconstructed” from measured values of CDM and particulate absorption. When SeaWiFS radiances are used, conversely, any errors on CDM absorption would lead to a degradation of performance (i.e., the actual performance would be better than that mentioned).

Particulate absorption—Samples of 1000 to 4000 mL were concentrated onto GF/F filters that were preserved in liquid nitrogen immediately after filtration. Absorption of particulate material was determined following the methods described by Tassan and Ferrari (1995) (“transmittance-reflectance method”), with a few modifications. A Hitachi U3010 dual-beam spectrophotometer equipped with an integrating sphere was used. The pathlength amplification corrections used were those described in Tassan et al. (2000), which were previously checked with monospecific cultures. Sample and blank filters were first scanned against air from 750 to 350 nm at the entrance of the sphere. A second scanning against air from 750 to 350 nm was performed with the sample placed directly against the exit of the sphere backed by a light trap. Blank and sample filters were treated with few drops of 0.5% NaHCl for 10 to 15 min and then carefully washed with the 0.2- μm filtered seawater. Absorption measurements were repeated as above, and spectral absorption by phytoplankton was computed as the difference between scans before (total particulate) and after (“detritus”) extraction. Reported values are averages from duplicates or triplicates.

Satellite data—SeaWiFS Level 1A (nadir resolution of 1.1 km) and daily meteorological data were obtained from the NASA GSFC’s Distributed Active Archive Center (DAAC). Remote sensing reflectances (R_{rs}) at 412, 443, 490, 510, 555, and 670 nm, as well as chlorophyll a (mg m^{-3}) estimates (using the OC4v4 algorithm), were produced using SEADAS 4.2 standard algorithms and masks. Note that the R_{rs} values obtained with this procedure are not corrected for directional effects. The images were mapped to a cylindrical projection. For comparison with in situ data in each available image, median values for all products for a window of 3 by 3 pixels centered on the locations of the oceanographic stations were computed, to minimize georeference errors. In other words, we assume a precision of ± 1 pixel. In general, the median R_{rs} value of the 3-by-3-pixel window was close to the mean value. Average standard deviations over means for the 3-by-3-pixel window were 17.7% for DEPROAS-2 and 15.9% for DEPROAS-4, with no evident dependence on wavelength. A very small number of SeaWiFS images were available during the DEPROAS-3 cruise, each having large portions covered by clouds. As a consequence, the (possibly contaminated) satellite data collected during this cruise were not included in the retrieval proce-

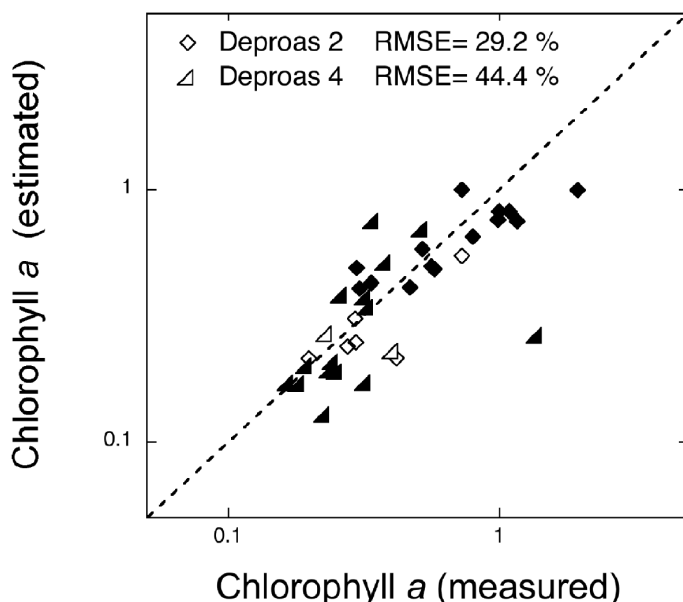


Fig. 2. Comparison between the chlorophyll a concentrations (mg m^{-3}) derived from SeaWiFS data using the OC4v4 algorithm and the values measured at sea by fluorometry during the 3 cruises. The time difference between satellite and in situ data is less than 24 h. Open symbols correspond to a 3-hour window. The relative RMSE for each cruise (DEPROAS-2 and -4) is indicated (see legend).

dures, and DEPROAS-3 data were used only for comparisons using in situ absorption measurements.

We considered satellite and in situ data as “simultaneous” when the time difference between the sample collection and the SeaWiFS passage over the study area was equal to or less than 24 h. This criterion, less constraining than NASA’s 3-h window used for comparing satellite and in situ data for algorithm development, has been adopted here to increase the number of match-ups. When appropriate, the results were graphically discriminated to illustrate the results observed outside the 3-h window.

Although some results exist comparing in situ and satellite reflectances measured during the DEPROAS 2 cruise (Ciotti and Gaeta 2002), the reduced number of data points and the limited spatial and temporal range covered by the data do not allow a proper evaluation of the atmospheric correction performances for our study region. Recently, Garcia et al. (2005) compiled in situ versus SeaWiFS matchup data for the Southwestern Atlantic and Southern Oceans, and concluded that the normalized water-leaving radiances for the 412 nm channel were underestimated by about 30%. Therefore, it is important to note that any underestimation in the retrievals found here could be a consequence of a possible overestimation of the atmospheric correction. The comparison between the chl a concentrations measured in situ and those derived from global algorithms was possible for 39 DEPROAS 2 and 4 stations. The comparison was performed for OC2V4 (not shown) and OC4V4 algorithms (Figure 2). Although the sample

number remained reduced, these results suggest that the global bio-optical algorithms for chlorophyll concentrations are well adapted to the studied area.

Retrieval of total absorption coefficients from reflectances—In this step, we retrieved total absorption coefficients from reflectances at 5 SeaWiFS wavelengths (412, 443, 490, 510, 555 nm) following the method proposed by Loisel and Stramski (2000). This method was chosen among others (e.g., Lee and Carder 2003) because it does not make any assumptions on the spectral variation of absorption or backscattering coefficients. The Loisel and Stramski method (hereafter called “LS method”), based on radiative transfer simulations, provides total absorption (a), scattering (b), and backscattering (b_b) coefficients in the upper oceanic layer, knowing irradiance reflectance just beneath the surface ($R(0^-)$) and the average attenuation coefficient for downwelling irradiance ($\langle K_d \rangle$) between the surface and the first attenuation depth. The absorption coefficients ($a(\lambda)$) at each wavelength were computed from $R(0^-, \lambda)$, $\langle K_d \rangle(\lambda)$, and the solar zenith angle in water (Eqs. 10 and 11 in Loisel and Stramski 2000). The $K_d(\lambda)$ values were derived from the chlorophyll concentration using the empirical formulas of Morel and Maritorena (2001). The computations of $a(\lambda)$ were made without consideration of Raman scattering, as its influence on the retrieval of absorption coefficients was found to be negligible for chlorophyll values as low as 0.02 mg m⁻³ and for wavelengths up to 660 nm (see Figure 5 in Loisel and Stramski 2000). We excluded the wavelength 670 nm, as the satellite radiance at this wavelength originates essentially from the atmosphere and the marine radiance cannot be retrieved with a sufficient accuracy. For comparisons with SeaWiFS-retrieved values, the measured absorption coefficients (sampled at 1 nm resolution) were degraded into 5 bands, 20 nm wide, centered on the SeaWiFS nominal wavebands. Each band represents a simple average of the 20 nm range.

Retrieval of the size parameter—As shown by Ciotti et al. (2002), a size parameter can be extracted from high-resolution (1 nm) absorption spectra of phytoplankton. It is therefore necessary to determine whether this parameter can be extracted with a sufficient accuracy when absorption coefficients of phytoplankton are available only at the SeaWiFS wavelengths. The decomposition method proposed by Ciotti et al. (2002) is based on a spectral mixing model:

$$a_\phi(\lambda) = a_{<\phi>}(\lambda) \cdot \{ [S_f \cdot \bar{a}_{<pico>}(\lambda)] + [(1 - S_f) \cdot \bar{a}_{<micro>}(\lambda)] \} \quad (1)$$

where $\bar{a}_{<pico>}(\lambda)$ and $\bar{a}_{<micro>}(\lambda)$ are the “basis vectors” (or absorption spectra normalized by their own average over the visible spectrum) corresponding to picoplankton and microplankton, respectively, and $a_{<\phi>}(\lambda)$ is the scaling factor to be applied to the normalized absorption spectrum. The size parameter S_f is a parameter constrained to vary between 0 and 1 and specifying the relative contributions of picoplankton and microplankton to absorption. Here we used a picoplankton vector different

from that used in Ciotti et al. (2002) (see justification and additional details in Ciotti et al. 2004), which is presented in Appendix I. The comparison of the S_f values derived from measured high-resolution spectra, and from absorption spectra degraded into 5 SeaWiFS bands of 20-nm width, shows that the S_f retrieval is very little affected when using 5 bands only, and no bias is introduced on the retrieved values (see Figure 2 in Ciotti et al. 2004).

Retrieval of phytoplanktonic absorption, size parameter, and CDM absorption from total absorption—Two different approaches were tested for retrieving CDM and phytoplankton absorption coefficients from total absorption, based on (1) a decomposition of total absorption spectra and (2) a nonlinear optimization technique, as described below.

Method 1: decomposition of total absorption spectra. Absorption coefficients can be expressed as the sum of absorption coefficients for the major absorbing components of seawater in the visible, that is, water molecules, phytoplankton cells, particulate detritus, and CDM:

$$a(\lambda) = a_w(\lambda) + a_\phi(\lambda) + a_{NAP}(\lambda) + a_{CDOM}(\lambda) \quad (2)$$

where the subscripts w , ϕ , NAP , and $CDOM$ represent water, phytoplankton, nonalgal particles, and colored dissolved organic matter, respectively. CDOM and NAP, which have similar absorption spectra, are often merged into a single term, named colored detrital matter (CDM).

The non-water absorption coefficients, $a(\lambda)$ and $a_w(\lambda)$, were partitioned into phytoplankton and CDM contributions, using a method derived from that proposed by Bricaud and Stramski (1990) for partitioning particulate absorption coefficients into their algal and nonalgal components. A modified method was already developed to partition total (i.e., dissolved and particulate) absorption coefficients, as measured with an ac-9 (Wetlabs) absorption meter, into their algal and nonalgal contributions (Oubelkheir and Bricaud 2003; K. Oubelkheir, H. Claustre, A. Bricaud, and M. Babin, unpublished data). Briefly, the method is based on 2 assumptions: (1) colored dissolved organic matter, CDOM, and nonalgal particles (NAP) can be merged into a single term (CDM), with absorption coefficients varying according to an exponential function of the form:

$$a_{CDM}(\lambda) = a_{CDM}(\lambda_0) e^{-S_{CDM}(\lambda - \lambda_0)} \quad (3)$$

where the slope S_{CDM} is variable; and (2) considering the available wavelengths, some absorption ratios of phytoplankton can be found, which are stable in a variety of oceanic environments. Here, this method was adapted again to be applied to the SeaWiFS wavelengths. The absorption ratios $a_\phi(490) / a_\phi(412)$ and $a_\phi(510) / a_\phi(412)$ were determined from a database of absorption spectra collected in surface waters, in various areas of the world ocean (Atlantic, Pacific, Mediterranean) and various seasons (see Bricaud et al. 2004). These ratios were found to vary slightly with the chlorophyll a concentration (Chl), according to the following equations:

Table 2. RMSE values, in % (see Eq. 12), obtained for the individual cruises and for all data pooled together, when the various coefficients were retrieved from measured total absorption using Method 1 (decomposition of absorption spectra) and Method 2 (nonlinear optimization technique).

Retrieved coefficient	Method 1				Method 2			
	DEPROAS-2	DEPROAS-3	DEPROAS-4	All data	DEPROAS-2	DEPROAS-3	DEPROAS-4	All data
<i>n</i>	27	58	57	142	27	58	57	142
$a_{\text{CDM}}(443)$	16.3	19.6	10.4	15.8	6.6	21.8	12.4	16.3
S_{CDM}	11.8	13.5	7.5	11.1	7.0	26.8	10.7	18.7
$a_{\phi}(412)$	29.9	32.2	38.3	34.4	15.9	37.3	38.0	34.6
$a_{\phi}(443)$	20.9	24.4	30.9	26.7	11.7	32.4	31.2	29.1
$a_{\phi}(490)$	19.3	24.4	31.4	26.6	13.6	37.0	40.5	35.4
$a_{\phi}(510)$	22.6	29.0	35.6	30.8	20.7	50.9	58.6	50.2
$a_{\phi}(555)$	27.1	42.2	43.9	40.5	37.3	91.1	92.8	84.3
S_f	74.7	80.2	107.0	91.1	22.8	32.8	48.9	38.7

n indicates the number of samples. The symbols for the various coefficients are the same as in Figure 6 (see legend). Note that the performances of Method 1 are slightly improved when using the regional values of phytoplankton absorption ratios ($r_1 = 0.80$, $r_2 = 0.51$; see text) instead of standard ratios: e.g., the RMSE decreases from 34.4 to 29.0% for $a_{\phi}(412)$, from 26.7 to 23.1% for $a_{\phi}(443)$, and from 26.6 to 25.2% for $a_{\phi}(490)$.

$$r_1 = a_{\phi}(490)/a_{\phi}(412) = 0.919\text{Chl}^{0.012} \quad (4a)$$

$$r_2 = a_{\phi}(510)/a_{\phi}(412) = 0.581\text{Chl}^{0.047} \quad (4b)$$

Although the exponents in these relationships are very close to 0, the corresponding variations in r_1 and r_2 are not negligible (for a Chl range of 0.05 to 2 mg m⁻³, r_1 and r_2 vary from 0.89 to 0.93 and from 0.50 to 0.60, respectively).

The nonwater absorption coefficients, $a(\lambda)$ and $a_w(\lambda)$, hereafter denoted $a_t(\lambda)$, were then partitioned into the $a_{\phi}(\lambda)$ and $a_{\text{CDM}}(\lambda)$ coefficients, by first solving the following system of equations for A and S_{CDM} (see Bricaud and Stramski 1990):

$$r_1 A e^{-412 S_{\text{CDM}}} - A e^{-490 S_{\text{CDM}}} = r_1 a_t(412) - a_t(490) \quad (5a)$$

$$r_2 A e^{-412 S_{\text{CDM}}} - A e^{-510 S_{\text{CDM}}} = r_2 a_t(412) - a_t(510) \quad (5b)$$

and then computing

$$a_{\text{CDM}}(\lambda) = A e^{-S_{\text{CDM}} \lambda} \quad (6)$$

$$a_{\phi}(\lambda) = a_t(\lambda) - a_{\text{CDM}}(\lambda) \quad (7)$$

Note that the spectral ratios, as derived locally from measurements during the DEPROAS cruises, differed significantly from those provided by Eqs. 4a and 4b ($a_{\phi}(490)/a_{\phi}(412) = 0.80$ (SD = 0.08) and $a_{\phi}(510)/a_{\phi}(412) = 0.51$ (SD 0.05), $N = 89$). The use of these local ratios was tested and found to improve the performances of the method (see legend of Table 2). We made the choice, however, not to “tune” the procedure with local information, and to use the standard ratios provided by Eqs. 4a and 4b, to keep the method as general as possible.

Method 2: nonlinear optimization technique. This method is based on the inversion technique presented by Roesler and Perry (1995) for diffuse reflectances, applied here to the total absorption coefficients. The output parameters are $a_{\text{CDM}}(443)$, the slope of the CDM absorption spectrum S_{CDM} , and the size parameter S_f . As in the previous method, the non-

water absorption coefficients are expressed as the sum of phytoplankton and CDM contributions:

$$a_t(\lambda) = a_{\phi}(\lambda) + a_{\text{CDM}}(\lambda) \quad (8)$$

Light absorption by CDM was parameterized using Eq. 3, with 443 nm as a reference wavelength. Phytoplankton light absorption was parameterized according to a spectral mixing model modified from Ciotti et al. (2002):

$$a_{\phi}(\lambda) = a_{\phi}(505) \cdot [S_f \cdot \bar{a}_{<\text{pico}>}(\lambda)] + [(1 - S_f) \cdot \bar{a}_{<\text{micro}>}(\lambda)] \quad (9)$$

where $a_{\phi}(505)$ rules the amplitude of the spectrum, and S_f (still constrained to vary between 0 and 1) rules its spectral shape. Note that the differences between equation 1 and equation 9 result from distinct normalizations chosen for the phytoplankton absorption. In Ciotti et al. (2002), the a_{ϕ} spectrum, as well as the $a_{<\text{pico}>}$ and $a_{<\text{micro}>}$ spectra, were normalized by their respective average values over the visible. Here, they were normalized by their values at 505 nm, which can be estimated using an empirical relationship (from Bricaud et al. 1998):

$$a_{\phi}(505) = 0.0185[\text{Chl}]^{0.684} \quad (10)$$

This empirical relationship was compared with measurements from the DEPROAS cruises. Whereas a good agreement was observed during the DEPROAS 2 cruise (Figure 3), measured a_{ϕ} values during the DEPROAS-3 and -4 cruises tended to be smaller than predicted by the empirical model. As previously, however, we made the choice to introduce no local information in the procedure.

For determining the optimal values of each parameter, we used a generalized reduced gradient nonlinear optimization code. The first step in the method is to attribute initial guesses to $a_{\text{CDM}}(443)$, S_f , and S_{CDM} . Here we used 0.02 m⁻¹, 0.5 nm⁻¹, and 0.015 nm⁻¹, respectively. Initial values of total absorption are

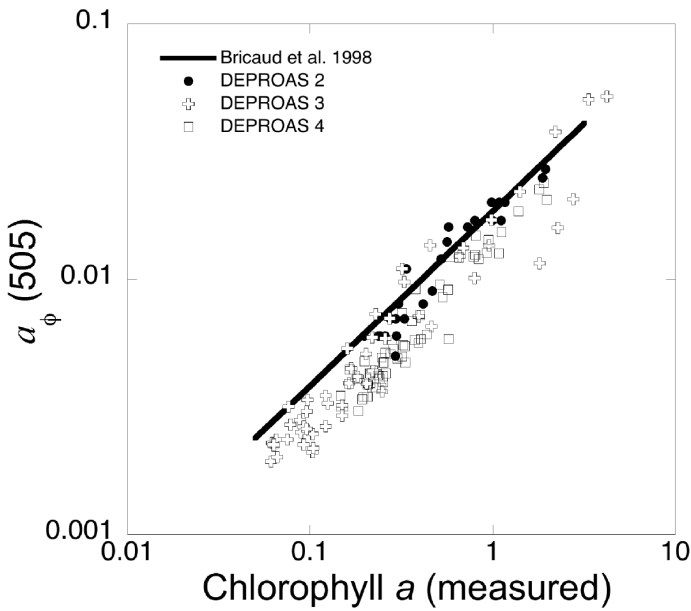


Fig. 3. Variations of the absorption coefficients of phytoplankton at 505 nm, $a_{\phi}(505)$ (in m^{-1}) measured during the DEPROAS cruises as a function of chlorophyll a concentration ($mg\ m^{-3}$), compared to the empirical relationship proposed by Bricaud et al. 1998 (solid line).

then computed for 412, 443, 490, 510, and 555 nm, using equations 8 to 10, and these values are compared to the observed total absorption (i.e., measurements or estimates from the model) as follows:

$$difference = \left(\frac{a_{measured}(\lambda) - a_{estimated}(\lambda)}{a_{measured}(\lambda)} \right)^2 \quad (11)$$

An iterative solver routine is then set up, to simultaneously vary $a_{CDM}(\lambda)$, S_p and S_{CDM} , from the initial guesses, to minimize the differences between observed and estimated values in all 5 bands, by setting the sum of the differences to be equal to zero, with a 5% tolerance error. The values for $a_{CDM}(\lambda)$, S_p and S_{CDM} adjusted by the routines are the final estimates.

Assessment and discussion

Characteristics of data sets—Details on seasonal and spatial distributions of bio-optical properties in the study area are provided elsewhere (A.M. Ciotti and S.A. Gaeta, unpublished data). Here, we will highlight the characteristics that are relevant to the results presented. The coverage areas of DEPROAS-3 and -4 cruises are almost the same (Figure 1), and they were conducted during a summer and a winter period, respectively (Table 1; see also Ciotti et al. 2004). The DEPROAS-2 cruise was also conducted during winter, but the sampled profiles were confined to the north portion, in a single section that was repeated several times, and some additional coastal stations. For the surface data used here, the relative importance of phytoplankton and CDM absorption per cruise was highly variable (Figure 4). The DEPROAS-2 samples showed the highest

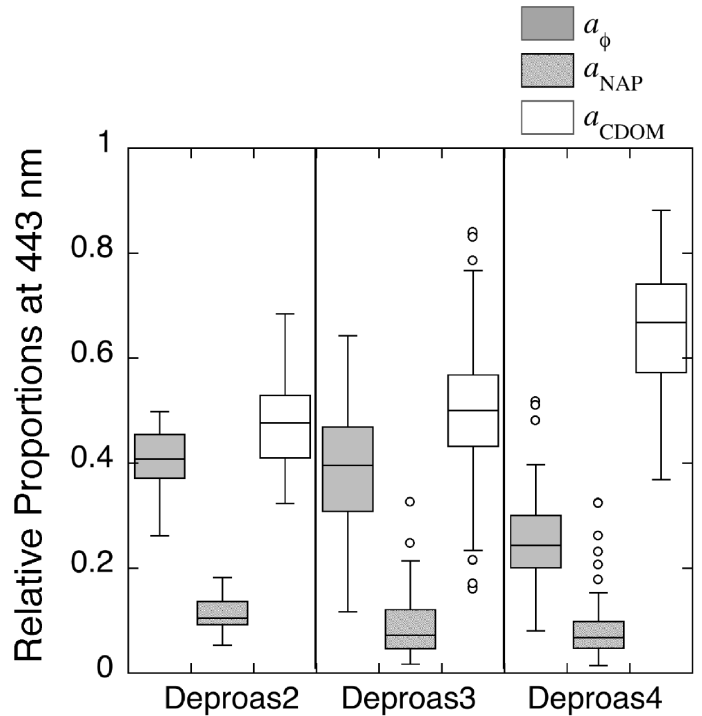


Fig. 4. Box plot for the variation in the relative proportions among CDM, NAP, and phytoplankton absorption coefficients at 443 nm for the 3 cruises. The boxes represent the overall median (central line) and the upper and lower median values. Error bars indicate the range (minimum and maximum values) for each case. Dots illustrate outliers.

relative contribution of phytoplankton, mainly due to the low contribution from continental outflow (i.e., low CDM). The weak variability during DEPROAS-2 is also the result of the restricted area sampled. The higher CDM absorption during DEPROAS-4 is due to the seasonal contribution of a southern continental shelf water mass formed in Argentina under the influence of La Plata River estuary (Piola et al. 2005). The mean ratios between CDM and phytoplankton absorption at 443 nm were 1.25, 1.65, and 3.0 for DEPROAS-2, -3, and -4, respectively. Most stations from the DEPROAS-4 cruise, thus, can be considered as “CDOM-dominated Case 2 waters,” so that the slopes of CDM absorption spectra were, on average, the same as those of CDM ($0.018\ nm^{-1}$). For all DEPROAS cruise data used here, S_{CDM} and S_{CDOM} values were in the range 0.010 to $0.027\ nm^{-1}$ and 0.008 to $0.028\ nm^{-1}$, respectively. For all cruises, the mean nonalgal to algal particle absorption ratio remained around 30% at 443 nm, consistent with the results of Bricaud et al. (1998) for oceanic Case 1 waters, which suggests that no “turbid Case 2 water” was sampled. Hereafter, the DEPROAS cruises will be referred to as D2, D3, and D4.

Retrieval of total absorption from radiances—The results of the LS approach (Loisel and Stramski 2000) used to retrieve total absorption from SeaWiFS radiance measurements are described below. To emphasize the differences between the retrieved and measured absorption values, the spectral light

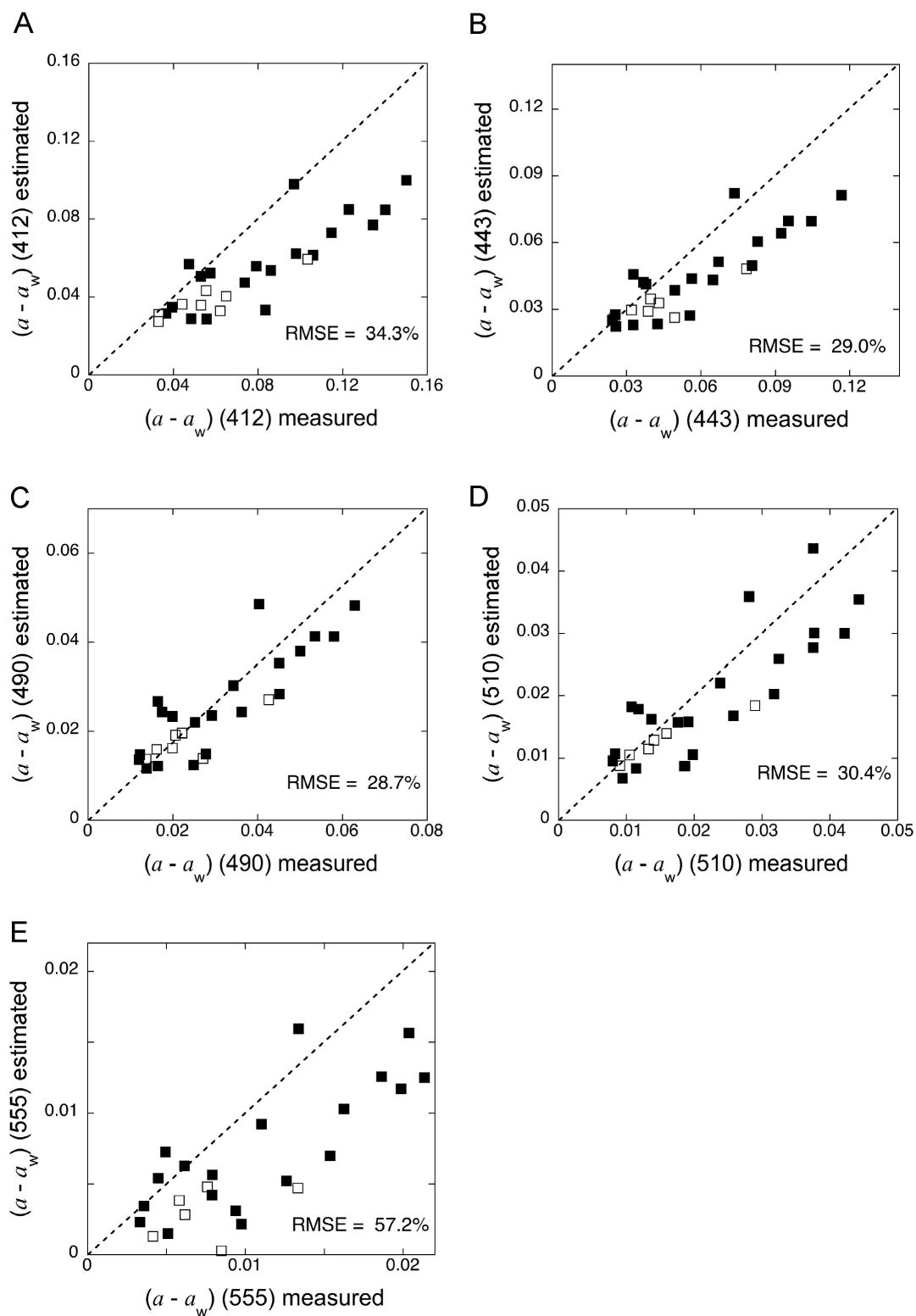


Fig. 5. Comparison between the nonwater absorption coefficients at the SeaWiFS wavelengths as retrieved from the method of Loisel and Stramski (2000) and as measured at sea. The LS method used as input parameters SeaWiFS remote sensing reflectances and the SeaWiFS estimates of chlorophyll a concentration (using the OC4v4 algorithm). The measured absorption coefficients were obtained as the sum of CDM absorption and particulate absorption coefficients measured on samples. Units are m^{-1} . RMSE errors are indicated for each wavelength. For 7 of the 34 stations, the LS method could not be applied (e.g., it provided negative scattering coefficients), so these samples were discarded.

absorption coefficients for pure water (Pope and Fry 1997) were subtracted from these values. The performance of the method (as well as of other methods tested later) was quantified by the RMSE between retrieved and measured absorption coefficients. The RMSEs were computed as relative values (i.e., by normalizing the differences between retrieved and measured values to the measured values) so as to give equal weights to all measurements, and expressed as percentages. They were computed as:

$$RMSE(\%) = 100 * \sqrt{\frac{\sum_{i=1}^n \left(\frac{x_{i,estimated} - x_{i,measured}}{x_{i,measured}} \right)^2}{n}} \quad (12)$$

where x is the variable (nonwater absorption coefficient, in absolute value) and n is the number of observations.

Retrieved total absorption coefficients were compared to simultaneous (i.e., as defined before, collected within 24 h of satellite passage) measurements at the surface for D2 and D4 (Figure 5). Along with uncertainties inherent to the LS method, retrieved coefficients can be affected by errors in atmospheric corrections, which can be problematic for continental shelf areas (e.g., Ruddick et al. 2000). In addition, as we made the choice to not introduce local information in this step, the chlorophyll concentration here is estimated by the OC4V4 global algorithm using SeaWiFS data, which may be different from the in situ measured concentration (see Figure 2).

The LS method tends to provide underestimated absorption coefficients at all wavelengths, especially for D4 (e.g., for 412 nm, nonwater absorption coefficients are underestimated by on average 32% for D2 samples and 47.6% for D4 samples). As mentioned above, part of this underestimation could be attributed to incorrect atmospheric corrections. In addition, most D4 samples are CDOM-dominated; therefore, the K_d values (derived from chlorophyll concentration according to Morel and Maritorena 2001) for these waters could be significantly underestimated. Absorption coefficients, nonetheless, are retrieved with a reasonable accuracy: RMSE values vary from 29 to 34% for the wavelengths 412 to 510 nm. The RMSE is significantly higher (57%) at 555 nm than at other wavelengths, likely owing to the weak measured absorption values ($< 0.02 \text{ m}^{-1}$) and the large associated relative uncertainties. Considering this poor performance, we chose to discard this wavelength when coupling the LS method to the further step described below.

Retrieval of phytoplanktonic absorption, size parameter, and CDM absorption—Our goal is to retrieve magnitudes and spectral shapes for both CDM and phytoplankton absorption coefficients, and then to retrieve a size parameter (S_f) from the spectral shape of phytoplankton absorption. The CDM absorption spectrum is represented by 2 parameters: $a_{CDM}(443)$ and the slope S_{CDM} , whereas the phytoplanktonic absorption spectrum is represented by the $a_\phi(\lambda)$ coefficients at the 5 SeaWiFS channels.

In the following sections, we present the performance of the 2 methods proposed here: method 1 based on the decom-

position of absorption spectra, and method 2 based on a non-linear optimization technique. The performance was evaluated using datasets having increasing uncertainties as follows: (1) from the total absorption values obtained from measurements at sea and (2) from the total absorption values retrieved from SeaWiFS reflectances using the LS model.

Retrieval from measured total absorption (at SeaWiFS channels)—In this step, we compare the 2 methods using absorption measurements as input parameters; therefore, we are evaluating the errors in procedures assuming that the absorption estimates are totally correct. Figures 6 and 7 show the comparison between retrieved and measured parameters for methods 1 and 2, respectively. The RMSE values are computed for all the data, as well as for individual cruises (Table 2), because some differences in the performances of the methods might be related to the relative importance of CDM and phytoplankton absorption, which vary between cruises (see Figure 4).

Overall, magnitudes for both CDM and phytoplankton absorption were better retrieved by method 1, as was the spectral shape of CDM absorption. Method 1, however, is inefficient to retrieve the “true” values of the size parameter S_f (i.e., the values derived from the measured phytoplanktonic absorption spectrum). The retrieved values are actually correlated to the measured values, but with a large offset (about 0.30; see Figure 6, last panel). This divergence probably originates from the fact that this method assumes the quasi-constancy of spectral ratios for phytoplankton (Eqs. 4a and 4b), which imposes some constraints on the spectral shape of their absorption spectrum, and therefore on S_f . Consequently, this method was discarded for S_f estimates in subsequent steps.

Method 2 retrieves $a_{CDM}(443)$ and S_{CDM} , as well as phytoplanktonic absorption coefficients, with higher RMSE. The retrieval of the S_f parameter, however, is much better than with method 1, with a RMSE of 38.7% (Figure 7, last panel). This suggests that method 2 is able to retrieve the shape of the phytoplanktonic absorption spectrum, but with some errors on the amplitude of coefficients. Note also that method 2 generally retrieves high absorption coefficients (for either CDM or phytoplankton) with a better accuracy than method 1, as the corresponding points lie closer to the 1:1 line.

Considering the performance for the individual cruises (Table 2), it can be observed that the retrieval of phytoplanktonic absorption coefficients, with both methods, is better for D3 than for D4 (the performances for D2 are not directly comparable because of the lower number of samples, 27, instead of 58 and 57, respectively, for the other cruises). Conversely, also with both methods, the retrieval of CDM absorption is better for D4. These differences are likely related to the large contribution of phytoplankton and CDM to total absorption for D3 and D4, respectively (see Figure 4). Both methods are expected to retrieve the larger contributors to total absorption with a higher accuracy than smaller contributors.

Retrieval from SeaWiFS remote sensing reflectances at SeaWiFS channels—Here, methods 1 and 2 were combined with the LS

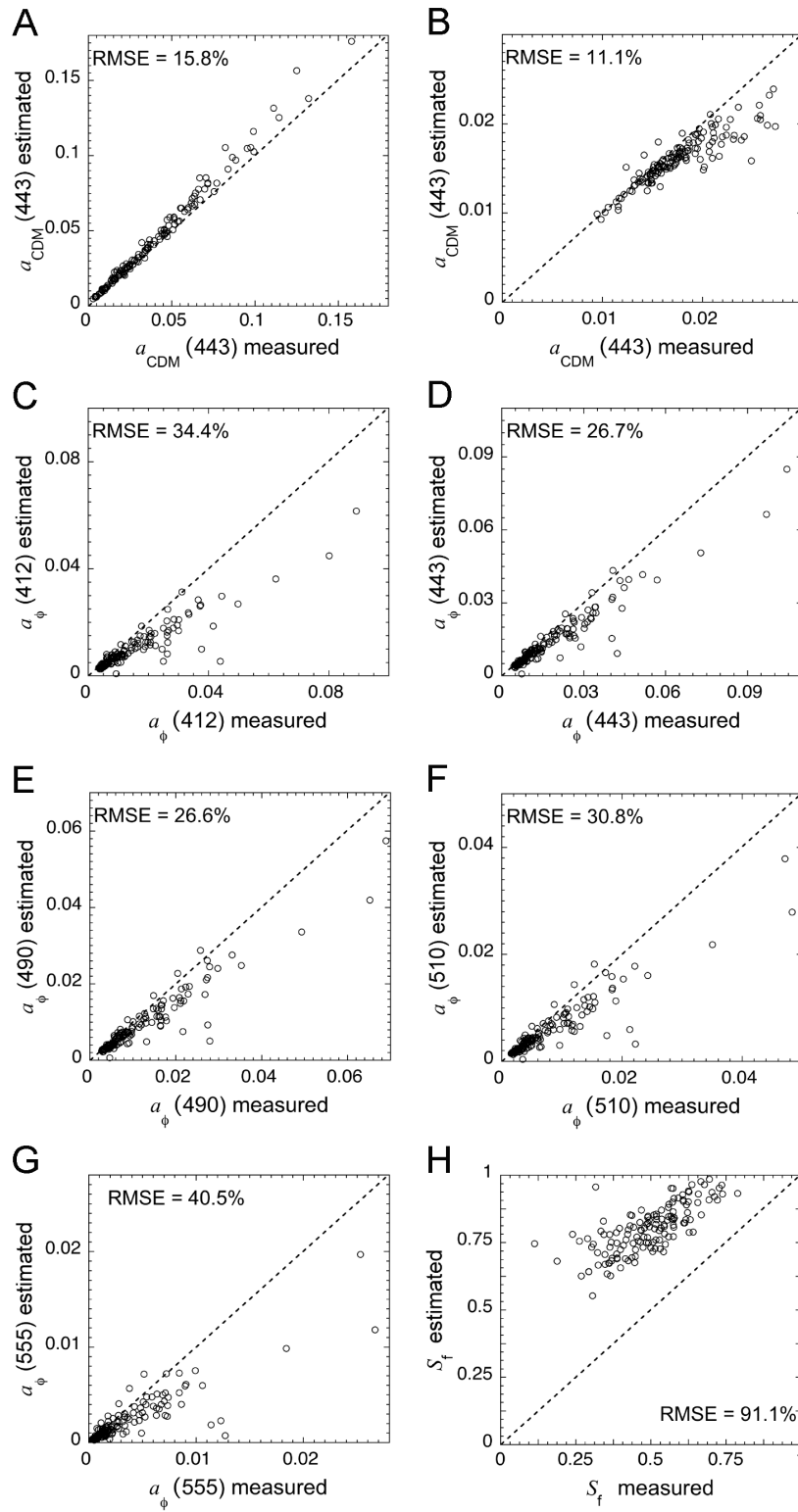


Fig. 6. Comparison between the various coefficients, as retrieved from measured total absorption by decomposition of spectra (Method 1) and as measured at sea. The coefficients are, from left to right and top to bottom: the absorption coefficient of CDM at 443 nm, $a_{\text{CDM}}(443)$ (in m^{-1}), the slope of the CDM absorption spectrum, S_{CDM} (in nm^{-1}), the phytoplanktonic absorption coefficients, $a_{\phi}(\lambda)$, at 412, 443, 490, 510, and 555 nm (in m^{-1}), and the size parameter of phytoplankton, S_{ϕ} (dimensionless). The measured values of CDM absorption were obtained by summing absorption coefficients of CDM and nonalgal particles. The “measured” value of S_{ϕ} is the value derived from the measured absorption spectrum. RMSE errors are indicated for each coefficient. Open symbols are satellite data from a 3-hour window from in situ data.

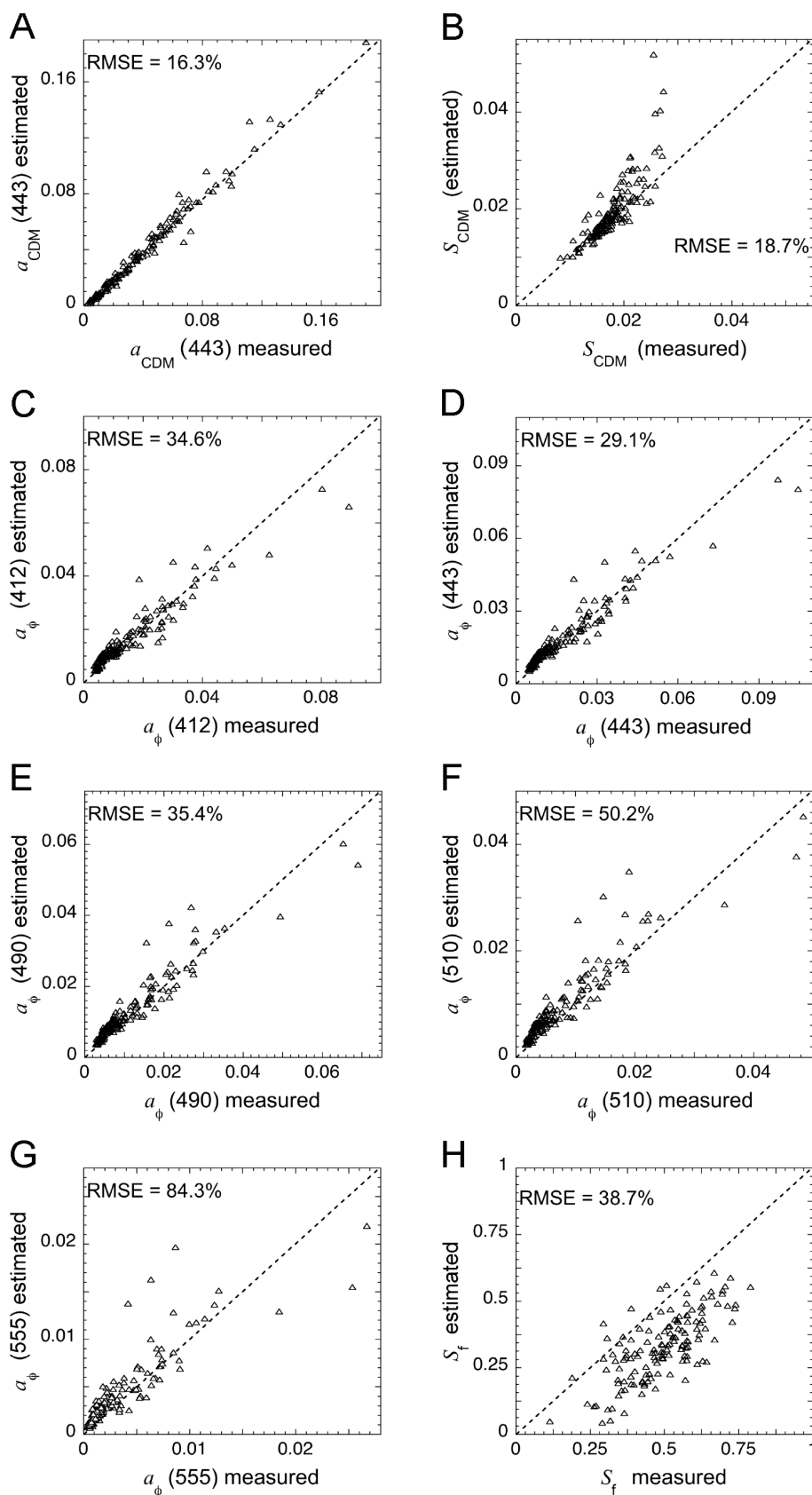


Fig. 7. Same as Figure 6, but with the various coefficients retrieved using a nonlinear optimization technique (Method 2).

method, to retrieve CDM and phytoplanktonic absorption coefficients. SeaWiFS remote-sensing reflectances (transformed into reflectances below the surface) and estimated chlorophyll concentrations using the OC4v4 algorithm were used as input data in the LS method. As before, the 555-nm band was discarded. A total of 27 stations were available for this comparison. Note that one additional station was discarded for method 1, because the system of Eqs. 5a and 5b could not be solved.

The comparison of retrieved and measured values for the various coefficients is shown in Figures 8 and 9 for methods 1 and 2, respectively. Similarly to what was observed when using measured absorption as input data, method 1 performs better than method 2 for retrieving $a_{\text{CDM}}(443)$ and the a_{ϕ} coefficients at 412, 443, 490, and 510 nm (Table 3). Note, however, that here the spectral slope of CDM absorption is slightly better retrieved with method 2 than with method 1, and that $a_{\phi}(555)$ is also better retrieved. With method 2, the size parameter S_f is retrieved with a RMSE of 17%.

When considering the results for the individual cruises (Table 4), it can be observed that with method 2, the retrieval of all parameters is more accurate for D2 than for D4, possibly because of the weaker optical variability in D2 samples (see Figure 4). Surprisingly, however, the a_{ϕ} coefficients retrieved with method 1 for D2 stations are affected by larger errors than those retrieved for D4 stations. The reason for this increased noise was not identified.

To evaluate the degradation in the retrieval of the various parameters when total absorption coefficients are not measured but retrieved from satellite measurements, we have compared the RMSE obtained above to those obtained when using as input data the measured absorption coefficients for the same 27 stations (Table 3). The results demonstrate, as expected, that there is a significant degradation with both methods, for all parameters. This degradation is related to the uncertainties inherent to the LS method (see Loisel and Stramski 2000), especially for waters with high CDOM content. It is also related to errors affecting the SeaWiFS water-leaving radiances (because of uncertainties in the atmospheric corrections) and to those affecting the estimated chlorophyll concentrations (because of uncertainties attached to the global algorithm). Considering these various sources of error, the final performances of the combined methods to retrieve $a_{\text{CDM}}(443)$, S_{CDM} , and S_f from SeaWiFS radiances (RMSE of 33%, 22%, and 17%, respectively) are very encouraging.

Comparison with other methods—Currently, both SeaWiFS and MODIS data can be processed by version 4.8 of SeaDAS, NASA's distributed processing package. Three semi-analytical models are implemented in this version, allowing pixel-by-pixel computation of phytoplankton and CDM absorption coefficients from the sensor's available remote sensing reflectances. For comparison with our results, all L1A images (1 km resolution) were reprocessed by SeaDAS 4.8 (using msl12) to compute a_{CDM} and a_{ϕ} : with the GSM01 semi-analytical bio-optical model ("Garver-Siegel-Maritorena 2001"; Maritorena et al. 2002), the MODIS semi-analytical algorithm (SAA, Carder et al. 1999; see

http://oceancolor.gsfc.nasa.gov/DOCS/atbd_mod19.pdf), and the Quasi-Analytical Algorithm (QAA; Lee et al. 2005). All models were run with standard inputs (e.g., QAA requires the choice of a fixed S_{CDM} value). To be consistent with the previous results, the median value for a 3-by-3 window centered at each station's position was computed for all coefficients at SeaWiFS bands, and RMSE values were calculated (Table 5 shows values for 443 nm only). For comparison, we also present the phytoplankton absorption coefficient at 443 nm retrieved by the empirical relationship proposed by Bricaud et al. (1998), using the oc4v4 chlorophyll algorithm as input. It is important to note that the reduced number of matchup values does not allow any general conclusion regarding which procedures are best at a worldwide scale.

For this particular data set, the methods proposed here performed as well as or better than the available models (see Table 5). It is interesting to note that the RMSE for $a_{\phi}(443)$ retrieved by the simple empirical model by Bricaud et al. (1998) is lower than for GSM01, and also that the QAA shows the best performance of the 3 models. The discussion about the divergence among methods and models at this point would be merely speculative, as a proper comparison should be done for a more extensive dataset (see differences among the cruises that suggest seasonal discrepancies). It is important to note here that the spectral behavior of CDM absorption (S_{CDM}) and phytoplankton absorption (S_f) are not retrieved by the previously published models.

Comments and recommendations

The methods presented in this article have proved able to retrieve a size parameter for phytoplankton, as well as the amplitude and spectral slope of CDM absorption, with a reasonable accuracy from SeaWiFS radiance measurements. Whereas various methods have been recently proposed to retrieve the phytoplankton and CDM absorption coefficients from space, the retrievals of a size parameter for phytoplankton and of the spectral slope of CDM absorption are, to our knowledge, performed for the first time. The procedures were validated using in situ absorption measurements performed on a continental shelf area off Brazil. Considering the many different sources of errors in the data and the assumptions made in both procedures, the performances were encouraging (retrievals of the 3 variables with RMSE of 33%, 22%, and 17%, respectively, for 27 stations). It must be emphasized that the conditions were not the most favorable for a successful validation (occurrence of some CDOM-dominated Case 2 waters and spectral ratios for phytoplanktonic absorption diverging notably from those assumed for the decomposition of total absorption).

It is important to note that no local information was introduced in the development of methods. If they can be locally tuned (e.g., use of a regional algorithm for chlorophyll concentration, adjustment of spectral ratios for phytoplankton), their performance, especially for method 1, is likely to improve. This is clearly indicated by the comparison of the

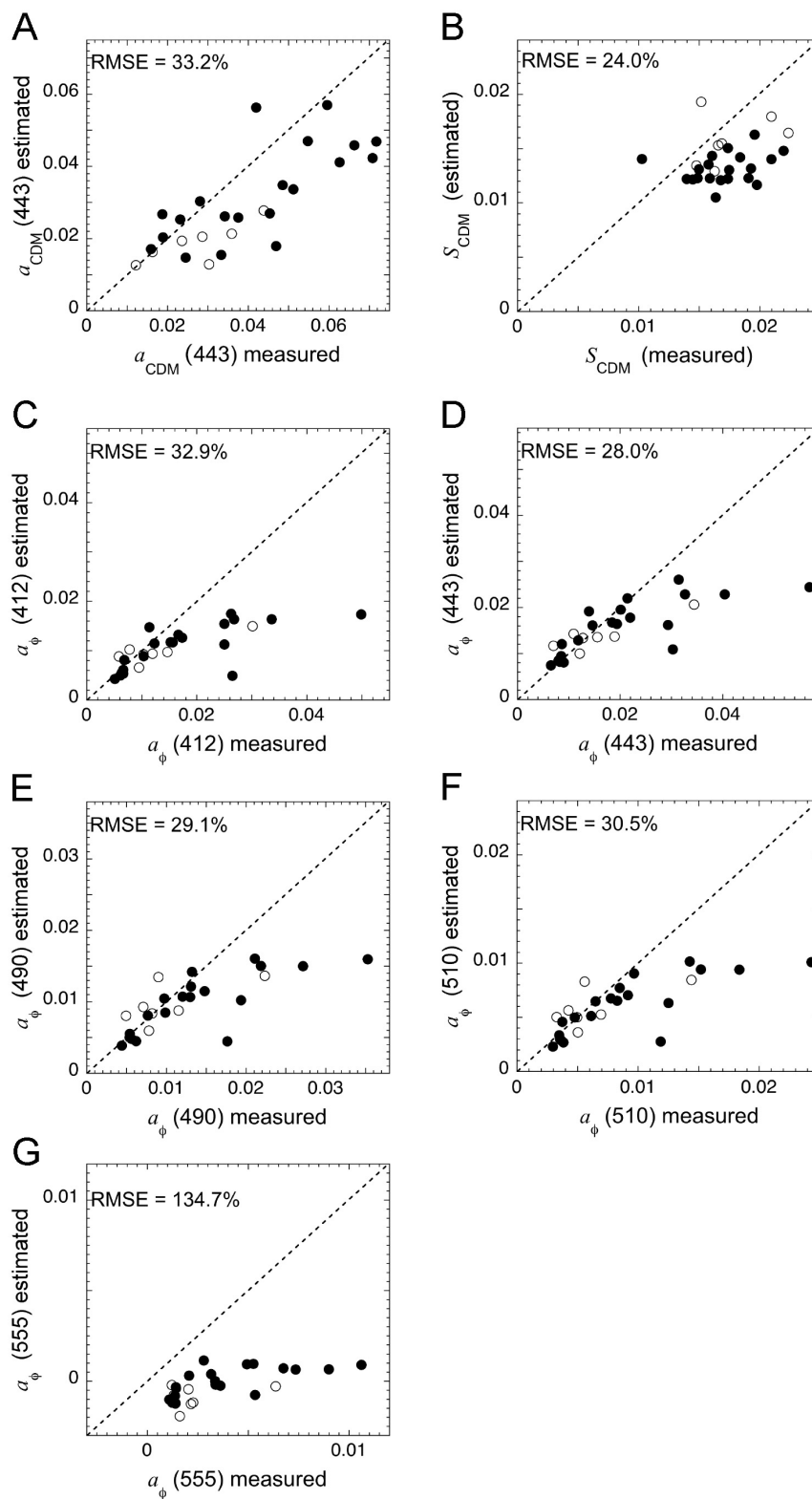


Fig. 8. Same as Figure 6, but with the various coefficients retrieved from SeaWiFS radiances and SeaWiFS estimates of chlorophyll a concentrations. Total absorption coefficients were derived using the method of Loisel and Stramski (2000), then the various coefficients were retrieved using Method 1 (decomposition of absorption spectra). Note that the size parameter of phytoplankton, S_r , was not derived with this method, because of the constraints imposed on the shape of the phytoplanktonic absorption spectrum (see text).

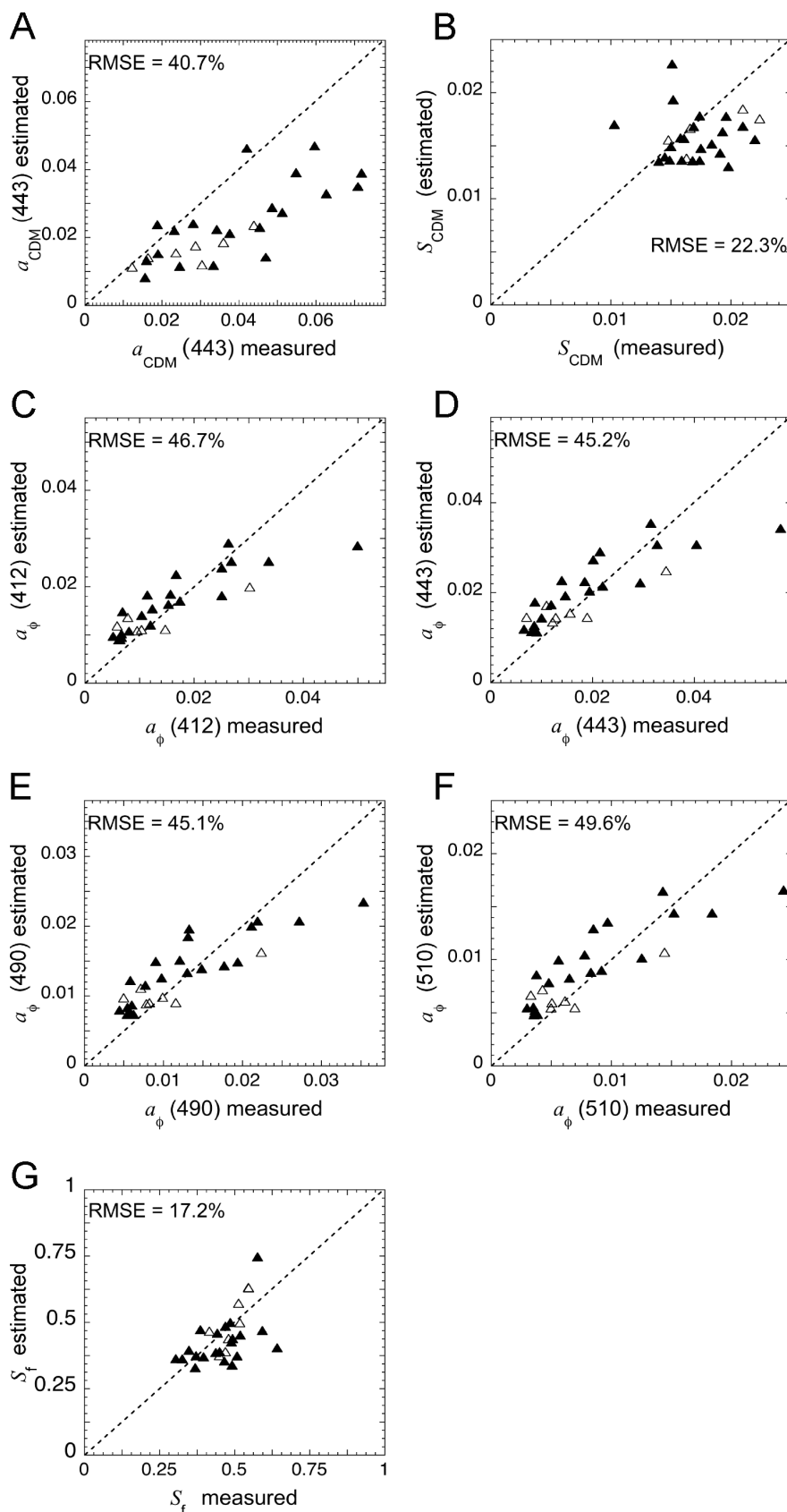


Fig. 9. Same as Figure 8, but using Method 2 to retrieve the coefficients (nonlinear optimization technique).

Table 3. Comparison of relative RMSE, in % (see Eq. 12), obtained when the various coefficients are retrieved using either Method 1 or Method 2.

Retrieved coefficient	Method 1		Method 2	
	measured a§	SeaWiFS + LS‡§	measured a*§	SeaWiFS + LS†‡
<i>n</i>	26	26	27	27
$a_{CDM}(443)$	14.2	33.2	14.5	40.7
S_{CDM}	10.2	24.0	9.5	22.3
$a_{\phi}(412)$	33.8	32.9	36.6	46.7
$a_{\phi}(443)$	26.1	28.0	29.5	45.2
$a_{\phi}(490)$	25.4	29.1	34.0	45.1
$a_{\phi}(510)$	29.6	30.5	47.1	49.6
$a_{\phi}(555)$	37.9	134.7	74.3	56.1
S_{\ddagger}	—	—	35.2	17.2

Both methods were applied either to measured total absorption or to absorption derived from SeaWiFS radiances (in this latter case, the method of Loisel and Stramski 2000, noted "LS," was used). *n* indicates the number of samples. For a meaningful comparison, the RMSE obtained when the coefficients are retrieved from measured absorption were computed here by considering only the 27 stations where SeaWiFS radiances were available. *555 nm band included; †555 nm band excluded; ‡DEPROAS-3 data excluded; §in situ data matching SeaWiFS points; ||unsuccessful decomposition of the retrieved total absorption for 1 of the 27 stations.

performance achieved during the different cruises that indicates a priori the need for a seasonal tuning. For method 2, which is essentially an inversion technique, an increase in the number of available spectral bands in the visible range can potentially improve the retrievals by increasing the degrees of freedom for the statistical fits. It is important to mention that these techniques often have multiple solutions. In our work, this fact was also observed. The solutions tended to change slightly with the way the differences between observed and estimated values were computed (Eq. 11), but no dependence on the initial guessed values was observed.

In their present state, these methods can a priori be extended to other areas (with possibly better performances in more favorable conditions). Before they can be applied at a global scale,

however, it will be necessary to validate them on larger data sets, with more diversified waters. Although global data sets are currently available (e.g., NOMAD and SeaBASS), there is still a need for the assessment of errors that can be generated by the variety of existing methodologies. One of the concerns is that CDOM absorption measurements remain difficult in clear waters. This situation is presently improving, with the more and more systematic use of in situ absorption meters (without and with filters, for measuring total and CDOM absorption, respectively), as well as the recent availability of capillary waveguides, for measuring CDOM absorption with long optical paths (D'Sa et al. 1999, Miller et al. 2002).

The performance of the methods presented here, when applied to satellite measurements, depends on an accurate

Table 4. Comparison of relative RMSE, in % (see Eq. 12), obtained when the various coefficients are retrieved from SeaWiFS radiances (using the Loisel and Stramski method, and then either Method 1 or Method 2), for the individual cruises and for all data pooled together.

Retrieved coefficient	Method 1			Method 2		
	DEPROAS-2	DEPROAS-4	All data	DEPROAS-2	DEPROAS-4	All data
<i>n</i>	13	13*	26	13	14	27
$a_{CDM}(443)$	32.0	34.3	33.2	36.8	44.0	40.7
S_{CDM}	22.9	25.0	24.0	17.8	25.8	22.3
$a_{\phi}(412)$	39.3	24.9	32.9	33.1	56.5	46.7
$a_{\phi}(443)$	32.7	22.5	28.0	29.8	55.8	45.2
$a_{\phi}(490)$	34.4	22.6	29.1	29.4	55.9	45.1
$a_{\phi}(510)$	36.7	22.6	30.5	32.9	61.1	49.6
$a_{\phi}(555)$	126.8	142.2	134.7	39.0	68.3	56.1
S_{\ddagger}	—	—	—	11.4	21.2	17.2

n indicates the number of samples. Note that SeaWiFS radiances during the DEPROAS-3 cruise were not used because of strong cloud contamination. *Unsuccessful decomposition of the retrieved total absorption for 1 of the 14 stations.

Table 5. Comparison of relative RMSE, in % (see Eq. 12), obtained for the retrievals of the 2 methods proposed here and by 3 previously published models integrated to SeaDAS version 4.8 processing package.

Retrieved coefficient	Model or Method	<i>n</i>	DEPROAS-2	DEPROAS-4	All data
$a_{\text{CDM}}(443)$	GSM01	13	75.6	36.7	59.6
	SAA	13	77.0	36.7	60.3
	QAA	13	78.6	33.1	60.3
	Method 1	13	32.0	34.3	33.2
	Method 2	14	36.8	44.0	40.7
$a_{\text{p}}(443)$	GSM01	13	146.9	20.3	104.0
	SAA	13	34.0	64.8	51.7
	QAA	13	35.4	40.9	38.3
	Method 1	13	32.7	22.5	28.1
	Method 2	14	29.8	55.8	45.2
	Bricaud et al. 1998	14	30.7	70.0	54.7

GSM01 is the semi-analytical bio-optical model ("Garver-Siegel-Maritorea 2001"; Maritorea et al. 2002), SAA is the MODIS semi-analytic algorithm (Carder et al. 2003; see text), and QAA is the Quasi-Analytical Algorithm (Lee et al. 2005). Retrievals by the empirical model of Bricaud et al. (1998), using oc4v4 retrieved chlorophyll as input, are shown for comparison.

retrieval of total absorption coefficients from water-leaving radiances. Logically, the performances also depend on the accuracy of the atmospheric correction schemes of remotely sensed ocean color data. The method of Loisel and Stramski (2000) was used in the present study, but a number of models are available, and their performances are presently being evaluated and compared by a Working Group of the International Ocean Color Coordination Group (see http://www.ioccg.org/groups/Lee_OCAG_Report.pdf). This opens the way to future improvements for the procedure presented here, by integrating any other model, which would prove more efficient in retrieving spectral total absorption from ocean color measurements. In addition, fine adjustments on both methods with inclusion of locally adjusted relationships can improve the retrievals as well. Finally, any future improvement in ocean color sensors and processing schemes (such as the recent procedures for correction of directional effects), should obviously also benefit the global performances and consequent application of the methods suggested.

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