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Seasonal variability of the backscattering coefficient in the Mediterranean Sea based on Satellite SeaWiFS imagery

H. Loisel,¹ E. Bosc,² D. Stramski,³ K. Oubelkheir,² and P.-Y. Deschamps¹

Abstract. The annual progression of the particulate backscattering coefficient, b_{bp} , within the whole Mediterranean sea is examined from satellite remote sensing and inverse modeling for the first time. This study reveals that b_{bp} is roughly distributed uniformly over the Mediterranean that differs from the well known east-west gradient in terms of chlorophyll concentration, Chl . In contrast to Chl , b_{bp} is also weakly variable along the seasons, and presents different extrema. These observations are attributed to the presence of high concentrations of submicrometer particles such as detrital particles, heterotrophic bacteria and also possibly mineral particles from aeolian inputs. The interpretation of b_{bp} in terms of particulate organic carbon concentration, POC , is discussed, and a relationship between b_{bp} and POC is developed. Application of our algorithm to SeaWiFS data indicates that the satellite estimates are in good agreement with surface POC measurements.

Introduction

The inherent optical properties (IOP) of seawater depend on the type and the concentration of the various constituents in presence. Besides the water itself, the dissolved and particulate substances determine the IOP. Among these IOP, the backscattering coefficient, b_b , is not sensitive to the dissolved material, and can be used as an index of the particulate load. As an IOP, the backscattering coefficient can be partitioned according to:

$$b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda)$$

where λ is the wavelength of light, $b_{bw}(\lambda)$ is a constant representing the backscattering of the pure seawater, and $b_{bp}(\lambda)$ the backscattering coefficient by particles suspended in seawater. For simplicity the argument λ will be omitted, unless specifically required. The b_{bp} variability is determined by changes in the concentration and composition of the particulate assemblage that mostly consists of particulate organic carbon (POC) within the open ocean. Biogenic $CaCO_3$ particles often encountered during coccolithophore blooms, and mineral particles from aeolian inputs may also contribute episodically to b_{bp} in open ocean waters [Gordon *et al.*, 2001; Guerzoni *et al.*, 1999]. The recent capability to

retrieve b_{bp} from space observation of ocean color [Carder *et al.*, 1999; Loisel and Stramski, 2000] provides the opportunity to investigate the spatial and temporal variability of POC that is an important factor in determining the ocean's role in the global balance of carbon [Eppley and Peterson, 1979]. In contrast to the chlorophyll concentration, Chl , which is the index usually adopted to specify the bio-optical state of a water body, the seasonal variations and the spatial distribution of POC remain poorly known and mostly restricted to ship observations. Until now, only one study was conducted at large scale from ocean color data collected by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) [Stramski *et al.*, 1999]. This study revealed the seasonal progression of POC all around Antarctica that is a very specific environment due to particular phytoplankton assemblages encountered in these high-latitude waters [Mitchell and Holm-hansen, 1991].

The objective of this study is to describe the seasonal variations of b_{bp} from space observation of ocean color within the entire Mediterranean. The patterns of the remotely sensed b_{bp} will be compared to those of the remotely sensed Chl , in order to determine whether b_{bp} provides additional information about the biogeochemical features of the Mediterranean. The interpretation of b_{bp} in terms of POC , and the comparison with *in situ* POC measurements will be discussed. The choice of the Mediterranean is motivated by two main raisons. First, although the Mediterranean represents only 0.8% of the world ocean area, it shows strong trophic variability: from ultra oligotrophic waters during summer in the eastern basin, to eutrophic conditions associated with the spring bloom in some areas of the western basin. In this respect, the Mediterranean sea acts as a miniature ocean for biogeochemical studies. Second, the Mediterranean is characterized by relatively low cloud coverage that allows its frequent observation from space.

Method

Monthly data of the SeaWiFS-derived remote sensing spectral reflectance, $R_{rs}(\lambda)$, were acquired from the Nasa Goddard Distributed Active Archive Center for the years 1998 and 1999. The SeaWiFS- Chl is derived from $R_{rs}(\lambda)$ according to the current SeaDAS processing code [O'Reilly *et al.*, 1998]. The retrieval of b_{bp} at $\lambda=555$ nm from $R_{rs}(\lambda)$ is based on the model recently developed by Loisel and Stramski [2000] and successfully tested against *in situ* measurements performed in offshore and coastal environments [Loisel *et al.*, 2001]. This model accounts for Raman scattering that can significantly affect $R_{rs}(\lambda)$ in oligotrophic waters, and shows relatively little sensitivity to changes in the scattering phase function, and to the vertical structure of the IOP profiles. In the context of remote sensing application, assuming that the error on the retrieval of $R_{rs}(\lambda)$ is small, the relative difference between the modeled and measured b_{bp} never exceeds 30%, and the average value of this difference is 17% [Loisel *et al.*, 2001].

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Figure 1. (a) *Chl* distribution for the Mediterranean sea in March 1998. The location of the DyFAMed site (*DYF*) and the PROSOPE cruise track are superimposed on this composite SeaWiFS image. (b) The seasonal progression of *Chl* within the western, the eastern and the whole Mediterranean for the year 1998 and 1999. The eastern and western basins are separated by the Strait of Sicily.

Monthly values of b_{bp} and *Chl* were derived by summing the products $X_i S_i$ (where X_i is the value of *Chl* or b_{bp} at the pixel i , and S_i is the area of this pixel) and then dividing the result by the total area of the region. We will present only the results for the western and the eastern basins, and for the whole Mediterranean. For the interpretation of particular patterns, however, we also made similar calculations over 10 different subregions as defined by Guerzoni *et al.* [1999]. Turbid waters were excluded from these calculations according to the criteria adopted by Bricaud and Morel [1987].

Results

Because the seasonal and spatial *Chl* features of the Mediterranean were already studied in details by many authors [Antoine *et al.*, 1995 and references therein], we only briefly remind the main patterns. For this purpose, the *Chl* distribution within the whole Mediterranean in March 1998 is shown in Figure 1a, and the monthly variations of *Chl* averaged over the western and eastern basins, and over the whole Mediterranean, are plotted in Figure 1b for the years 1998 and 1999. As seen, the Mediterranean is characterized by a permanent trophic gradient from the western to the eastern basin, with the lowest *Chl* values always confined in the south part of the eastern basin (Figure 1). The maximum *Chl* values are observed within the Adriatic sea in winter, and in the northwestern Mediterranean during the spring bloom period. Note that if the 1998 spring bloom does not appear on the mean spatial *Chl* value (but does exist as seen in Figure 1a), the very broad and intense 1999 bloom clearly affects the *Chl* value averaged over the western basin (Figure 1b). With regards to the seasonal *Chl* variations, they are generally more pronounced in the western basin than in the eastern basin, and

the difference between the two basins vanishes in summer when *Chl* reaches its minimum value (Figure 1b).

In a similar way the distribution of b_{bp} within the whole Mediterranean in March 1998, and its annual course for each basin are plotted in Figure 2. Unfortunately, no *in situ* backscattering data are available for the Mediterranean to verify the consistency of our values. This is due to the lack of optical instrumentation that allows to estimate b_{bp} from *in situ* measurements, until recently. Nevertheless, the retrieved b_{bp} values present the same order of magnitude as those recently measured in other similar oceanic areas [Loisel *et al.*, 2001; Stramska *et al.*, 2000], and are also consistent with recent *in situ* measurements performed in the Adriatic sea (J.-F. Berthon, personal communication). Similarly to *Chl*, the highest b_{bp} values are noticed along the coasts, in front of the river mouths, and in the western Mediterranean during the spring phytoplankton bloom period (Figure 2a). Nevertheless, the comparison of Figures 1 and 2 also highlights some remarkable differences between the *Chl* and b_{bp} patterns, regarding both their spatial and temporal variability. First, the permanent *Chl* gradient between the relatively rich western basin and the relatively poor eastern basin is not always associated with a similar b_{bp} gradient. The west-east contrast is much less pronounced for b_{bp} and can also be slightly reverse from July to December 1999, as clearly seen in Figure 2b. In a similar way, the north-south dissymetry in the eastern basin is much less noticeable in terms of b_{bp} than in terms of *Chl* (Figure 2a). Thus, as a general statement, b_{bp} appears to be more homogeneously distributed within the Mediterranean than *Chl*. Second, in contrast to *Chl*, b_{bp} is weakly variable along the seasons. For example, the ratio of the maximum over the minimum value of *Chl* within the western (eastern) is 3.8 (2.6) compared to 1.74 (1.6) for b_{bp} in 1998. Finally, the extremes values of b_{bp} do not always match those of *Chl*. For example, while *Chl* is minimum in July, b_{bp} reaches his minimum value 3 months later. Moreover, besides the maximum in March 1998 and 1999 owing to the northwestern bloom, b_{bp} also exhibits a distinct maximum in May 1998 or in July 1999 within the two basins. This second maximum in

Figure 2. As in figure 1 but for b_{bp} .

Figure 3. Comparison of the measured (triangles) and retrieved (line and dots) POC concentration for the years 1998 and 1999 at the DyFAMed site.

May or in July does not correspond to any enhancement of *Chl* even if one consider each subregions of the Mediterranean as defined above (the same remark holds for the eastern basin in March 1998).

Discussion

The bulk backscattering depends on both the concentration of particles and the single-particle cross section (the product of the geometrical cross section by the efficiency factor which is a function of the size and of the refractive index). Based upon Mie-scattering calculations *Stramski and Kiefer* [1991] and *Morel and Ahn*, [1991] demonstrated that most of the backscattering (70–90%) in oceanic waters is caused by particles smaller than 1 μm . Among these particles, small (<0.6 μm), non-living (detrital) suspended particles are believed to be the major source of backscattering as they occur in sufficiently high concentrations to dominate b_{bp} in oceanic waters [*Ulloa et al.*, 1994 and references therein]. This is consistent with *in situ* observations that showed that non-living submicronic particles occur at a concentration at least one order of magnitude higher than living particles in surface ocean [*Koike et al.*, 1990]. Heterotrophic bacteria are the second major backscatters in the ocean, and account typically for 5 to 20% of backscattering in oligotrophic waters depending on their concentration [*Stramski and Kiefer*, 1991]. Finally, the contribution of algae cells to b_{bp} is negligible as a result of their weak backscattering efficiency. Nevertheless, under bloom conditions the photoautotrophic picoplankters can contribute significantly to b_{bp} as clearly seen in March 1999 (Figure 2b). Therefore, the seasonal and spatial differences between the *Chl* and b_{bp} patterns are primarily caused by the fact that most of the backscatters in oceanic waters are nonalgal particles such as biogenic detritus, and heterotrophic organisms. For example, the weak b_{bp} longitudinal gradient, that can not be explained by episodic events, suggests an almost uniform spatial distribution of submicrometer particles (living and non-living) within the whole basin. While photoautotrophic picoplankters and especially their associated material may be the major contributors to b_{bp} within the western basin, the great abundance of submicrometer particles typical to an “old” system of production based on the microbial loop, may be responsible of the backscattering process within the eastern basin. This is consistent with the results of *Dolan et al.* [1999] that suggest a shift from the western to the eastern basins in the planktonic food web towards a microbially dominated system.

Submicron Saharan dust in suspension within the upper layer may also contribute, after an aeolian deposition event, to the enhancement of b_{bp} (due to their high refractive index). For example, the maximum in March 1998 within the eastern Mediterranean was attributed to the high b_{bp} values observed within the Levantin basin where no enhancement of *Chl* was noticed. During the second half of March, several Saharan dust events were recorded by the TOMS sensor (and also by SeaWiFS) over the Levantin basin, that could explain these high b_{bp} values. Note that such event does not introduce an artificial bias within the monthly composite of R_{rs} . We verified that the value of R_{rs} at 410 nm (where a bad correction of the aerosol contribution would have the maximum effect) is not correlated with the aerosol optical thickness, τ_{a} , and does not present any depletion when τ_{a} is maximal. Some Saharan dust events have also been recorded in May 1998 and July 1999 that could explain the high b_{bp} values observed during these months. The maxima observed in May 1998 and in July 1999 within the western basin could also be explained by the presence of organic detritus generated in condition of post bloom (the few months shift between 1998 and 1999 can be attributed to the great intensity of the 1999 spring bloom that lasts longer than that in 1998).

Application: estimation of POC from b_{bp}

It is now believed that the dominant contribution to particle organic carbon in the ocean is of submicrometer particles [*Melnikov*, 1976; *Koike et al.*, 1990; *Longhurst et al.*, 1992]. The presence of these submicrometer particles that are in sufficient high concentration to dominate b_{bp} in oceanic waters suggest that b_{bp} and POC, are well correlated. This was confirmed by recent *in situ* measurements of b_{bp} that led to an almost linear relationship between b_{bp} and POC within the Southern ocean [*Stramski et al.*, 1999]. Because no *in situ* b_{bp} data are available for the Mediterranean, the relationship between b_{bp} and POC is established in two steps: first, the dependence of the scattering coefficient by particles, $b_{\text{p}}(555)$, on the POC concentration is analyzed from data collected within the Mediterranean, and second, the relation between $b_{\text{bp}}(555)$ and $b_{\text{p}}(555)$ is developed from the SeaBASS data set. During the PROSOPE cruise conducted within the Mediterranean (see tracks in Figure 1) in late summer 1999, simultaneous determination of $b_{\text{p}}(555)$ and POC led to a highly correlated relationship: $\text{POC} = 453 b_{\text{p}}(555) + 1.3$ ($r^2 = 0.85$) [*Oubelkheir et al.*, submitted]. This relation is similar to that previously established in the north western Mediterranean in December 1998–January 1999 [*Claustre et al.*, 2000]. Analysis of recent *in situ* measurements of b_{p} and b_{bp} made simultaneously in open ocean, and gathered within the SeaBASS data base, aims at fixing the backscattering ratio ($b_{\text{bp}}/b_{\text{p}}$) at 0.012 ($r^2=0.84$; even if $b_{\text{bp}}/b_{\text{p}}$ can covary with *Chl*, we have adopted a constant value at a first approximation). For this analysis, only data with similar *Chl* and b_{p} ranges as observed in Mediterranean were used. This value is consistent with the backscattering ratio based on *Petzold's* measurements (= 0.019), which is commonly assumed to represent “average” ratio for marine particles [*Mobley et al.*, 1993]. By combining the relation of POC versus $b_{\text{p}}(555)$ and $b_{\text{p}}(555)$ versus $b_{\text{bp}}(555)$ we then obtain: $\text{POC} = 37750 b_{\text{bp}}(555) + 1.3$. This relationship allows us to estimate POC within the Mediterranean for the first time.

This approach is tested through a comparison of the retrieved and measured *POC* at the French-JGOFS time serie DyFAMED site (see Figure 1a), where regular measurements of *POC* are performed. These measurements were not included in the set of data used in the development of the relationship between b_p and *POC*. Figure 3 compares the monthly estimated *POC* concentration, with the daily measured *POC* surface values at the site Dyfamed. As seen, the seasonal progression of *POC*, which is only dependant on the seasonal progression of b_{bp} , is well reproduced. This point is a good indication of the linearity between b_{bp} and *POC*. The mean ratio of the satellite-to-*in situ* *POC* values is 1.13 ± 0.24 ($N=10$). The relatively good agreement between the measured and retrieved *POC* concentration is surprising according to the different possible sources of errors involving in this comparison. It should be noted, however, that no attempt has been made to tune the algorithm to the measurements.

Concluding remarks

This approach can directly be applied over the global ocean to analyze the spatial distribution and the seasonal variations of the particulate matter stock (through the spatial and temporal variations of b_{bp}). The estimation of *POC* concentration, however, requires future *in situ* investigations in various oceanic areas in order to derive regional parameterizations of the *POC*- b_{bp} relationship. Such investigations will also give access to the *POC/Chl* ratio from remote sensing, which is related to the relative carbon mass of autotrophs and heterotrophs.

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