Environmental monitoring with the POSEIDON system's optical instruments: Chlorophyll retrieval from ocean colour

P.G. Drakopoulos[1*], **G. Petihakis**[2] **and K. Nittis**[2]
[1]Dep. of Optics, Technological Educational Institute of Athens, Ag Spyridonos 12210, Athens, Greece
[2]Dep of Oceanography, Hellenic Centre for Marine Research, P.O. Box 712, Anavissos Greece,

*Corresponding author: E-mail: pdrak@teiath.gr, Tel +30 2105385747

Abstract
In a exclusively designed experiment optical data from the POSEIDON system Cretan Sea station, above water surface reflectance measurements and *in situ* chlorophyll-a profiles were collected and combined in order to evaluate the existing remote sensing chlorophyll retrieval algorithms. It was found that both SeaWiFS and MODIS global algorithms overestimate the chlorophyll concentration by >35%, but another more interesting finding was that the algorithms developed specifically for the Mediterranean, underestimate the concentration by a similar factor. Further investigation is under way.

Keywords: Environmental monitoring; Marine Optics; Optical Oceanography.

1. INTRODUCTION

Algal biomass distribution is an important factor for the assessment of marine environment condition. Advances in satellite remote sensing techniques during the last 25 years have made possible a considerable progress in our knowledge of spatial and temporal variations of phytoplankton in diverse regions of the world ocean. Traditionally, a proxy to this distribution is chlorophyll concentration, which in turn can be estimated with the implementation of optical methods. More specifically, this is achieved either by monitoring chlorophyll's stimulated fluorescence or simply the effect it has in the colour of the ocean. Satellite collected ocean colour data provide a cost effective way for this purpose provided that the chlorophyll retrieval algorithms have been validated for the region of interest. Drakopoulos *et al.* [1] found that for the Cretan Sea oligotrophic Case *I* waters, the global SeaWiFS algorithm, namely OC4v4 [2], overestimates *in situ* chlorophyll by ~37%. Other authors reported even larger discrepancies for certain regions in the Mediterranean (e.g. [3], [4]). This lead to the development of new empirical relations tuned to the Mediterranean waters (MedOC4 for SeaWiFS, [4], and MedOC3 for MODIS, [5]).

In order to monitor algal biomass for the needs of the prognostic system Poseidon (Nittis et al.[6]), optical sensors have been installed in operational level on the multi-parameter observation platform (E1-M3A) in the Cretan Sea (Drakopoulos et al. [7]). This platform is moored at a 1400m depth, 20 miles north of Iraklion, exactly the same location that SeaWiFS global chlorophyll retrieval algorithm was investigated 10 years ago [1]. The availability of new optical measurements and the lack of proper validation of ocean colour products for that region, lead us to undertake a relevant experiment. Its scope was oriented towards assessing the performance of the newly developed local algorithms. It was executed during the regular maintenance visit to the E1-M3A platform in March 2011. The purpose of this paper is to report preliminary results of this effort.

2. MATERIALS AND METHODS

2.1 The instruments

The basic optical instruments installed on the multi-parameter observation platform E1-M3A are:

- Radiometer (OCR-507 irradiance): It records the irradiance of water entering solar irradiance at seven wavelengths (compatible with the SeaWiFS και MODIS satellites - 412, 443, 490, 555, 665, 683, 705 nm). It is installed 2.2 meters above sea surface and is equipped with an anti-fouling shutter.
- Radiometer (OCR-507 radiance): It records the radiance of water leaving radiant flux over the above mentioned seven wavelengths. It is installed at a depth of 40 cm below sea surface and is equipped with an anti-fouling shutter.
- PAR photometers (LI-193SA): They record the scalar photon flux per unit surface integrated at a solid angle 4π sr over the range 400 – 700 nm. They are installed at depths of 25, 50, 75 and 100 meters.
- Turbidity/ Fluorescence meters (FLNTU): They record the backscattering at 700 nm which is proportional to the turbidity (units NTU) and the fluorescence at 685 nm produced by chlorophyll-a when excited at 470 nm (units of concentration). They are installed at depths of 25, 50, 75 and 100 meters and they are equipped with bio-fouling protection shutter. The photometers and turbidity/fluorescence sensors are controlled by CTD SBE-16 central units by Seabird placed at the corresponding depths.

Additionally, for the requirements of this experiment, a portable spectroradiometer (Ocean Optics HR4000) was also engaged. The radiance measurements were performed with an 8^o FOV Gershun tube attached to the end of the fiber. For downwelling irradiance estimation, the diffuse reflectance of a calibrated Spectralon plate was measured. Complimentary data included *in situ* vertical profiles obtained with an SBE25 CTD equipped with PAR, transmittance and fluorescence sensors.

2.2 Calibration

Owed to their operation principle, the optical instruments are sensitive to bio-fouling and aging and frequent calibration is necessary. For this reason the experiment was carried out immediately after the redeployment of the buoy when all optical instruments were free of fouling and calibrated.

For the calibration of the fluorometer which was attached to the CTD, local chlorophyll concentrations from bottle samples were measured. The procedure included data (bottle and fluorescence profiles) collected during six recent visits to the buoy, covering a span of one year. In-vivo calibration ensured proper tuning of the fluorometer for the local species of phytoplankton.

2.3 Methods

The quantity that is monitored by satellites and is directly related to the chlorophyll concentration is the remote sensing reflectance which is defined as the ratio of upwelling radiance to the downwelling irradiance just above the water surface. This quantity for the below surface measurements as obtained by the Satlantic OCR can be estimated as:

$$R_{rs}(0+) = \frac{L_w(0+)}{E_d(0+)} = \frac{0.54 L_u(0-)}{E_d(0+)}$$

Where L_u(0-) is the upwelling radiance monitored by the underwater instrument and E_d(0+) the downwelling irradiance monitored by the instrument on the top of the buoy. For the above the surface measurements obtained with the HR4000 spectroradiometer, the remote sensing reflectance was calculated following the standard Mobley protocol [8]:

$$R_{rs}(0+) = \frac{L_w(0+)}{E_d(0+)} = \frac{[L_u(0+) - \rho L_{sky}(0+)]R_g}{\pi L_d(0+)}$$

Here $L_u(0+)$ is the measured upwelling radiance at an azimuth viewing direction of 135^o and a zenith angle of 40^o. $L_d(0+)$ is measured by viewing the spectralon plate and $L_{sky}(0+)$ by viewing the sky, all at the same angles. The quantity R_g is the known reflectance of the spectralon plate and ρ a parameter depending on wind speed and sun elevation evaluated according to reference [8]. An average of 10 scans was accumulated for each collected spectrum.

For the 'blue' oligotrophic waters of the Creatan Sea, chlorophyll concentration is derived by:

$$C = 10^{(a_0 + a_1 R + a_2 R^2 + a_3 R^3 + a_4 R^4)}, \quad R = \log_{10} \max\left(\frac{R_{rs}^{443}}{R_{rs}^{555}}, \frac{R_{rs}^{490}}{R_{rs}^{555}} \right)$$

where R is the logarithm of the reflectance ratios at the denoted wavelengths for OC4v4 and MedOC4 algorithms. The coefficients a can be found in reference [4]. For the case of OC3 and MedOC3 algorithms the corresponding wavelengths monitored are slightly modified to 443, 488 and 551 nm and the coefficients can be found in [5].

The remote sensing chlorophyll concentration is directly comparable with the weighted concentration [9]:

$$C_w = \frac{\int_0^\tau C(z)\exp(-2kz)dz}{\int_0^\tau \exp(-2kz)dz}, \qquad \tau = \frac{1}{k} = \frac{z_e}{4.6}$$

Here C(z) is the in-situ concentration as obtained from the fluorescence vertical profile and τ, the optical or penetration depth , while z_e represents the depth that PAR irradiance is reduced to 1% of its surface value i.e. the euphotic layer depth [3]. The essence of this expression is that 90% of the emanating radiation results from the optical depth τ and that the radiance signal is modified exponentially twice (during its downward and upward propagation).

3. RESULTS

The CTD profiles were calibrated according to the linear fit (Figure 1a) against the bottled data and then were integrated down to one optical depth as was estimated from the PAR radiance profiles (e.g Figure 1c). For the day of the experiment τ was estimated to be around 19 meters.

The corresponding depth integrated weighted concentration was found to be 0.12 $mg/m^3$with an estimated accuracy of 15%. This value is also expected to be measured by the radiance measurements (both above and below surface) provided that the retrieval algorithms used are properly tuned.

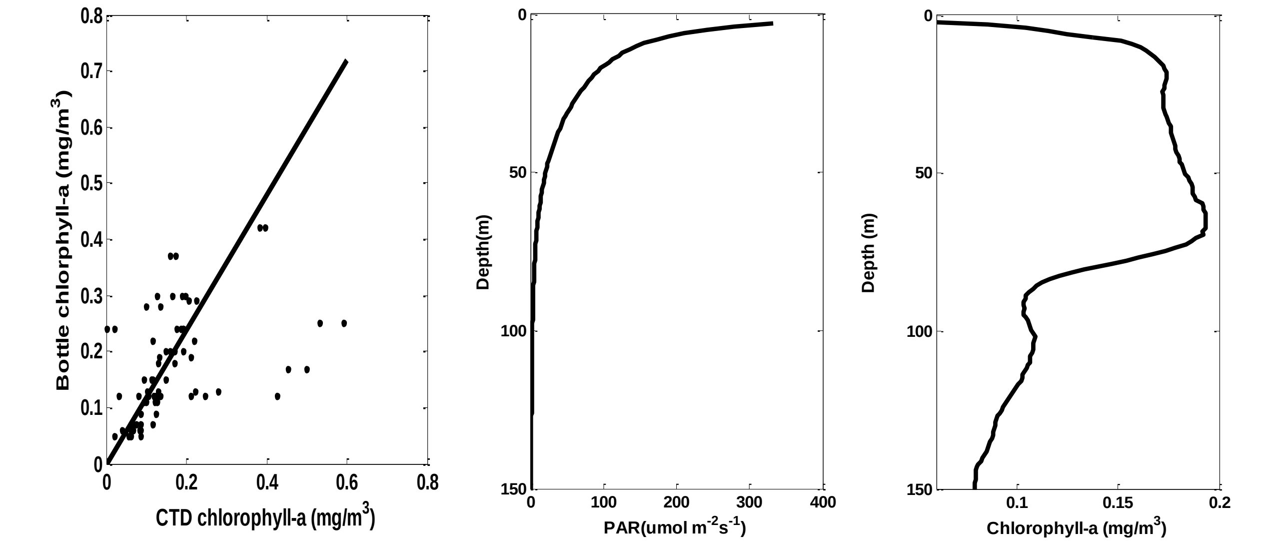

Figure 1: (a) Water sample vs CTD chlorophyll concentration. (b) Variation of PAR irradiance with depth and (c) concurrent Chl-a concentration profile obtained with the calibrated florometer.

Typical spectra obtained by the spectroradiometer are depicted in

Figure **2**a. The upwelling radiance already corrected for the contribution of the stray component reflected by the sky is denoted as L_w. The reflectance ratio was derived from the ratio of 443 nm to 555 (or 551), the largest in all circumstances during the experiment.

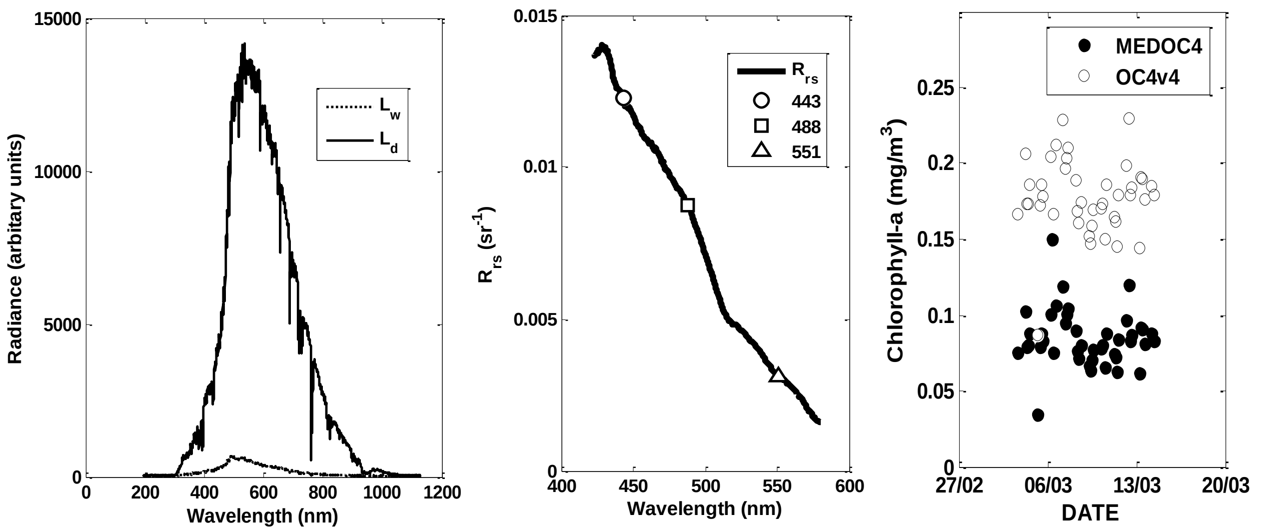

Figure 2: (a)The downwelling irradiance L_d reflected from the spectralon plate and the water leaving radiance L_w as a function of wavelength. (b) The corresponding remote sensing reflectance. The wavelengths monitored by MODIS satellite are highlighted. (c) Time series of chlorophyll concentration in M3A location monitored by the OCR7 radiometers and estimated using the MEDOC4 (solid circles) and OC4v4 (transparent circles) algorithms. The starting date is the March 3 of 2011, which was the day of the experiment.

The evaluation of MedOC4 and OC4v4 algorithms for the OCR507 measurements on the E1-M3A platform are depicted in

Figure **2**c. The first datum corresponds to the time of the experiment. The statistical significance of the reflectance measurements is demonstrated with the stability exhibited in the subsequent monitoring during the following next 10 days.

All the results are tabulated in Table 1. Both the above and under surface measurements gave comparable results. Undoubtedly, the global algorithms OC4v4 and OC3 overestimate concentration (>35 %) which was also the case presented in [1]. Surprisingly enough, we found that the local algorithms for the Mediterranean Sea are also biased and underestimate the ground truth by a similar amount (>35%). This figure was also evident in concurrent MODIS pictures readily processed with the MedOC3 algorithm and archived in the site of CNR [10].

Table 1: Chlorophyll concentration according to various radiance measurements during the experimental period. The 'ground truth' observation is presented separately in the last column.

Algorithm	Above surface	Below surface	MODIS pictures	In-situ optically weighted
OC4v4	0.14	0.16		
MedOC4	0.06	0.07		0.12
OC3	0.13	-		
MedOC3	0.05	-	~0.06	

4. CONCLUSIONS

It is apparent that satellite retrieved chlorophyll concentration is similar to the one obtained with ground radiance measurements. This makes us confident that the atmospheric correction procedure for the satellite product does not introduce any observable bias in the final estimation. As a consequence, from this experiment we can conclude that the algorithms tuned for the Mediterranean and obtained with calibration against *in situ* data covering the western sub-basin, do not perform adequately for the Cretan Sea. Most probably this can be attributed to the local phytoplankton community structure and distribution.

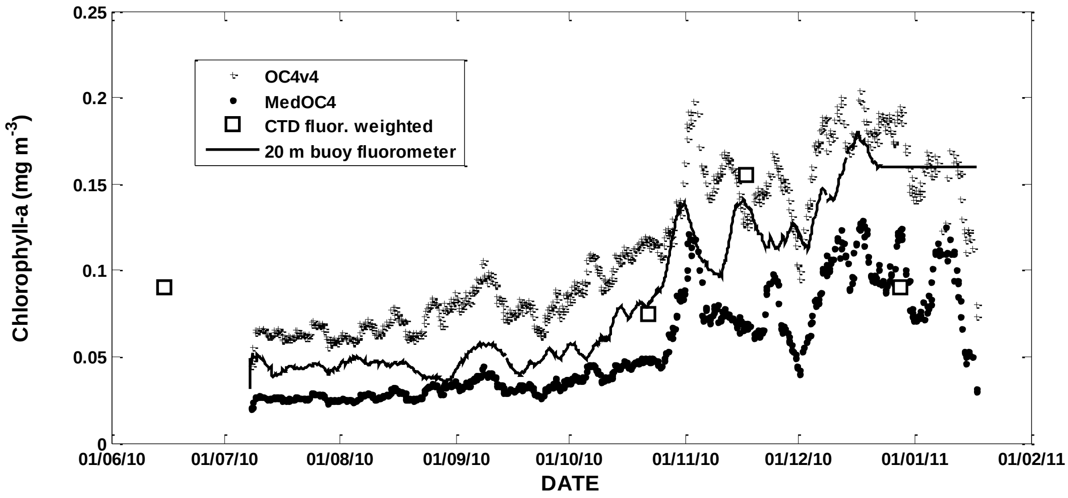

Figure 3: Available data before the current experiment. In situ collected data fall, on average, in-between the values obtained from buoy reflectance measurements evaluated according to the two different algorithms.

Unfortunately reliable ground radiance measurements (from OCR507's) and concurrent *in situ* chlorophyll profiles were available only for two more circumstances (Figure 3). However, even in this limited dataset the inadequacy of the MedOC4 algorithm is evident. Undoubtedly, the development of a locally tuned algorithm is not possible with the existing data up to date. New visits to the site are scheduled for the near future, in order to accumulate enough data for estimating regional empirical coefficients. Refined optical measurements, such as collection of profiles with a hyperspectral absorption-transmission meter, should aid the investigation towards explaining the causes behind the peculiarities of the local water colour.

Acknowledgements

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