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Bio-Optical Environmental Assessment of Marginal Seas

Progress Report 1

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Preface

The research described in the present report has been undertaken in the frame of Collaboration Agreement N. 21698-2004-02 S0SC ISP CH between the Institute for Environment and Sustainability (IES), Joint Research Centre (JRC) of the European Commission (EC), and the University of Geneva, Section of Earth Sciences, Remote Sensing and GIS Unit. The joint activities on Bio-optical Environmental Assessments of Marginal Seas were conducted at the JRC EC, within the FP6 Action 2121 ECOMAR, as part of Ms B. Weber's PhD Program at the University of Geneva.

Abstract

Optical remote sensing can highlight recurring and anomalous algal blooms in marginal and enclosed seas. The SeaWiFS-derived (1998-2003) database of chlorophyll-like pigment concentration (chl) was used to monitor algal growth in the Mediterranean basin. Yearly and monthly chl means were computed for the 6 years available, and climatological mean images derived. Then, interannual and seasonal variability was assessed computing yearly and monthly chl anomalies, as the difference between each individual year/month and the corresponding climatological year/month. The analysis of these anomalies provides a novel insight into the Mediterranean biological cycles, demonstrating algal blooms dynamics and related environmental boundary conditions.

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Executive Summary

The research program on "Bio-optical Environmental Assessments of Marginal Seas" aims to exploit (optical) remote sensing to characterize eutrophic phenomena in the European Seas. Phytoplankton growth patterns can be assessed, at large (basin) scales and over long (seasonal and annual) periods, by means of systematic observations in the visible, which allow the determination of algal blooming markers such as chlorophyll-like pigments (*chl*). The analysis of the historical record of bio-optical satellite data, to monitor the concentration of *chl*, provides information on recurrent and/or anomalous algal blooms, and related environmental boundary conditions, to be used for the development of an indicator for (harmful) algal blooms.

Data collected by the SeaWiFS, in the period 1998-2003, have been used to explore the main features of the *chl* field in the Mediterranean Sea. The database was processed to correct for atmospheric errors and to derive *chl* values. In order to evaluate the background variability that could be found for the *chl* indicator, the first issue approached was a trend analysis of the SeaWiFS data set. Annual and monthly *chl* mean images were obtained for all available years, and then compared with the corresponding annual and monthly climatologies. The anomalies determined by this comparison were analysed in terms of the oceanographic climate of the basin. Climatologies derived from the data set collected by the CZCS, in the period 1978-1985, were used to provide an historical reference for the evaluation of the SeaWiFS imagery. The main features appearing in the SeaWiFS record are reminiscent of those already noted in the CZCS case. The SeaWiFS-derived *chl* values are quite consistent with the CZCS climatological means. The main differences appear in the northwestern (and westernmost) part of the basin, where more intense blooming seems to have occurred in the SeaWiFS period.

The assessment of interannual variability in the SeaWiFS data set was carried out by generating annual means of *chl* and then comparing each year with the climatological record. The *chl* anomalies at the annual scale were obtained as the difference between each individual year and the climatological year. The oligotrophic character of most sub-basins is the main feature of the Mediterranean Sea appearing in the climatological annual mean. The western and eastern basins are not dissimilar in the offshore domain, with an overall basin average of *chl* around 0.2 mg m^{-3}. The inshore domain presents higher *chl* values in the northwest and west, and lower *chl* values in the south and southeast. The features of the climatological annual mean image appear to be recurrent in the annual means. The average basin value of *chl* derived from the annual means shows a decrease on the order of 10% of the climatological average value for the entire basin. The *chl* annual anomalies highlight the geographical spread and intensity of blooming patterns, which differed in each year from the climatological

annual mean. The basin shows mostly positive anomalies in the first 3 years and mostly negative anomalies in the second 3 years.

The assessment of seasonal variability in the SeaWiFS data set was carried out by generating climatological monthly means of *chl* (*i.e.* 12 monthly means obtained as the average of the 6 realizations available for each month in the period 1998-2003), and then comparing single monthly means with the climatological record. A time component was coupled to the evaluation of space patterns, by computing the monthly sequence of *chl* anomalies, as the difference between each individual month and the corresponding climatological month. The spatial patterns in the climatological monthly means are not dissimilar from those observed at the annual scale, but show enhancements over (variable) seasonal periods. The SeaWiFS-derived time series presents a seasonal cycle of *chl* analogous to the one appearing in the historical CZCS data set, *i.e.* a bimodal pattern with *maxima* in the colder season, from late fall to early spring, followed by *minima* in the warmer one, from late spring to early fall. This is evident in the fluctuations of the average basin value of *chl* derived from the monthly means (*i.e.* a single *chl* value computed as the total average of all pixels composing each monthly image). As noted already for the annual means, the *chl* indicator displays a decreasing trend, over the period of SeaWiFS coverage, on the order of 20% of the climatological average value for the entire basin.

The climatological seasonal trend, obtained computing an average basin value of the *chl* indicator from the climatological monthly mean images, confirms for the Mediterranean Sea a behaviour similar to that of a sub-tropical basin, where the light level is never a limiting factor (so that its decrease in winter does not inhibit algal growth), but the nutrient level always is. Unlike what is seen in the historical CZCS data set, though, the climatological seasonal cycle in the SeaWiFS-derived time series shows that *chl*, after the summer low, grows systematically in fall, only to reach its absolute *maximum* in the middle of winter and then decrease rapidly in spring, toward its summer *minimum* again. This does not affect the general validity of the sub-tropical scenario, but points to the fact that some regions, namely the western sub-basins, have a somewhat different seasonality, so pronounced that it affects basin statistics, when integrated *chl* values are considered to summarize the behaviour of the basin as a whole.

The analysis of SeaWiFS-derived *chl* anomalies provides a novel insight into the space and time patterns of biological cycles in the Mediterranean Sea, demonstrating algal blooms dynamics and related environmental boundary conditions. Future activities include an in-depth analysis of both the *chl* monthly mean record and the sequence of monthly anomalies computed on the basis of the climatological data record, as well as the development of a “bloom anomaly algorithm” designed to detect short-term (albeit also recurring) events.

1. Introduction

Broad theme of the research program on "Bio-optical Environmental Assessments of Marginal Seas" is the exploitation of (optical) remote sensing data for the environmental assessment of the European Seas. The planned activities focus on the appraisal of recurring and/or anomalous phytoplankton growth patterns in enclosed seas – in the Mediterranean basin, in a first phase, and then in the other continental basins – with implications ranging from water quality to climate issues. The final goal is to characterize eutrophic phenomena in surface waters, monitoring the concentration of chlorophyll-like pigments (*chl*), as appearing in the historical record of bio-optical satellite data, to develop an indicator of (harmful) algal blooms.

Phytoplankton growth patterns can be assessed, at large (basin) scales and over long (seasonal and annual) periods, by means of systematic observations in the visible spectral range, which allow the determination of algal blooming markers such as *chl* (see Barale, 1994, and references therein). In near-coastal waters, significant uncertainties can arise in the computation of *chl* absolute values, due to the presence of other optically active materials (*i.e.* dissolved organic matter and suspended inorganic particles). Nevertheless, the analysis of historical times of satellite data can provide information on recurrent and/or anomalous algal blooms, and related environmental boundary conditions (Barale and Schlittenhard, 1994).

In this report, data collected by the Sea-viewing Wide Field-of-View Sensor (SeaWiFS), in the period 1998-2003, will be used to explore the large-scale, long-term features of the *chl* field in the Mediterranean Sea. In order to understand the degree of background variability that could be found for this indicator – background variability on which anomalies could appear to be superimposed – the first issue approached was a trend analysis of the SeaWiFS data set at hand. Annual and monthly *chl* mean images were obtained for all available years, and then compared with the corresponding annual and monthly climatologies. The anomalies determined by this comparison will be discussed in terms of the oceanographic climate of the basin.

1.1 Historical Data Records

At this time, sizeable times series of historical bio-optical data collected from satellite have been generated only by the *Coastal Zone Color Scanner* (CZCS), from November 1978 to May 1986, and by the *Sea-viewing Wide Field-of-View Sensor* (SeaWiFS), from September 1997 to present. Other orbital sensors that operated in the past, like the *Moderate Optoelectrical Scanner* (MOS), did not have the wide swath needed to ensure quasi-daily coverage of the Earth's surface, or had short-lived (less than 1 year long) missions, like the *Ocean Color and Temperature Scanner* (OCTS), the *Global Imager* (GLI), and the

sensors devoted to assess *POLarization and Directionality of the Earth's Reflectances* (POLDER, I and II), failing to provide full seasonal coverage of the oceans. New sensors, like the *Moderate Resolution Imaging Spectroradiometer* (MODIS), *Terra* and *Aqua* versions, and the *MEdium Resolution Imaging Spectrometer* (MERIS), are currently generating time series of bio-optical data, but these are not yet comparable to those of the CZCS and the SeaWiFS.

The historical data record generated by the CZCS mission has been used in several studies for an analysis of phytoplankton dynamics in the Mediterranean Sea. Examples of basin-scale assessments are provided by Morel and André (1991) and by Antoine et al. (1995), who looked at algal biomass and primary production in the western and eastern Mediterranean, respectively. Regional assessments have been conducted also for selected sub-basins, characterized by peculiar spatial and/or seasonal variations in the *chl* field, such as the Adriatic Sea (*e.g.* Barale *et al.*, 1986), the Alboran Sea (*e.g.* Arnone *et al.*, 1990), the Levantine sub-basins (*e.g.* Gitelson *et al.*, 1996). More recently, Barale (2003) summarized the indications coming from the CZCS-derived climatological data, for a comparison with other satellite data on sea surface temperature and wind speed, collected over the entire Mediterranean Sea during the last two decades.

The CZCS climatological *chl* record (1979-1985) for the Mediterranean Sea, obtained by the Ocean Colour European Archive Network (OCEAN) Project (see Barale et al., 1999, and Sturm et al., 1999, for a detailed description of the data set and of the algorithms used to generate it), is shown in the Plates 1, 2 and 3. Annual means are not shown for 1978 and 1986, when data were collected by CZCS only for the last three and first four months of the year, respectively. The annual mean of 1985 is also excluded, due to the fact that data collection was rather poor, during that year, except for the summer season. Therefore the yearly statistics are not directly comparable with those of previous years, even though the individual images were included in the proper climatological data products for shorter periods. This data set has been considered, and is included in the present report, with the aim of providing an historical reference for the evaluation of the SeaWiFS imagery.

The climatological annual mean (Plate 1), derived from the single-year means (Plate 2), shows the classical geographical subdivision of the Mediterranean Sea between western and eastern basins, inshore and offshore domains, northern and southern near-coastal areas. The western basin has higher *chl* values and localized mesotrophic patterns, while the eastern basin has lower *chl* values and a more uniform oligotrophic appearance. Notable features are the Alboran Sea gyre system, generated by water exchange with the Atlantic Ocean; the Ligurian-Provençal Sea enhanced patterns, due to offshore (seasonal) blooming; the Adriatic Sea coastal plumes, dominated by the impact of

river plumes; and the mesoscale gyres in the Levantine basin between the islands of Crete and Cyprus.

The climatological monthly means (Plate 3) show a seasonal cycle with higher values in the cold season – when continental runoff and vertical mixing are supposed to be the key factors contributing to the biological enrichment of surface waters – and lower values in the warm season – due to reduced runoff and stratification of the water column. The northwestern basin instead shows the sequence of winter low *chl* values (elsewhere referred to as the Gulf of Lyon "blue hole", appearing from January to March) and of large spring blooms (in April and May), sequence which has been linked to the Mistral wind seasonal pattern and the convection processes in this region, leading to deep (and bottom) water formation.

1.2 The SeaWiFS-derived *chl* Database

The SeaWiFS-derived database of the *chl* indicator, used in the present work, originates from several projects, which have built up a time series of individual daily images, collected when favourable meteorological conditions occurred over (at least part of) the European Seas. In those cases when two images were collected by SeaWiFS in the same day, due to the overlap of two consecutive orbits at high latitudes, only one value per pixel was retained in the processing chain (*i.e.* the value from the scene for which that pixel was observed with the lowest viewing angle). Each image was treated on a pixel-by-pixel basis, to correct for atmospheric contamination and to derive *chl* values. The data were originally processed using the SeaDAS software package (Fu *et al.*, 1998), with additional modifications described in Melin *et al.* (2000) and in Sturm and Zibordi (2002). Individual *chl* images, with a nominal resolution at nadir of 1.1 km, were re-mapped on an equal-area (Alber's) projection grid, covering the whole Mediterranean area, with a pixel resolution of 2 km. Composite fields, at the monthly and yearly scales, were derived from the re-mapped images, by means of simple weighted averaging techniques, while climatologies for the monthly and yearly intervals were computed using the composite images of the available period.

The SeaWiFS data were used to assess the evolution of *chl* in the Mediterranean Sea over a period of 6 years (1998-2003). The main features appearing in the SeaWiFS record are reminiscent of those already noted for the CZCS climatology. From the quantitative point of view, variations in *chl* are expected because of the differences in the sensors' characteristics and calibration (performed *a posteriori* in the CZCS case), as well as in the processing algorithms (in particular, due to the improved performance of those used for SeaWiFS, with respect to those used for CZCS, which tended to overestimate *chl* in winter, due to low sun elevation angles and consequent multiple scattering effects, in the blue band in particular, and further to overestimate *chl*

in case 2 waters, where optically active materials other than chlorophyll-like pigments contribute to water optical properties). A systematic inter-comparison of CZCS and SeaWiFS data, and of data from other sensors as well, is provided by Bricaud *et al.* (2002). In the present case, the SeaWiFS-derived *chl* values appear to be systematically lower, but consistent with the OCEAN climatological means. The main differences appear in the northwestern (and westernmost) part of the basin, where more intense blooming seems to have occurred in the SeaWiFS period.

In the present report, all SeaWiFS-derived images have been mapped to the same pixel grid and coded with the same colour bar, so that they are all directly comparable from both the geographical and the quantitative point of view. This includes Plate 9, where no colour bar could be displayed due to space limitations. The colour coding coherently represents *chl* values in mg m^{-3}. Anomalies are coded with a two-colour (blue-red) bar, also representing *chl* values in mg m^{-3}. So-called "excess anomalies" are simply coded in blue (< -1 mg m^{-3}) and green (> +1 mg m^{-3}). Numbers along the horizontal and vertical axis of the images, when present, show longitude and latitude values, respectively. Although the geographical grid includes – and the images always display – parts of the Bay of Biscay, to the north west, and part of the Black Sea, to the north east, all statistical processing showed in the reported graphics does not include the value of any pixel from these areas. Inland lakes, also displayed in the imagery, were excluded from the statistical processing as well.

Plate 1. CZCS-derived chl Climatological Annual Mean

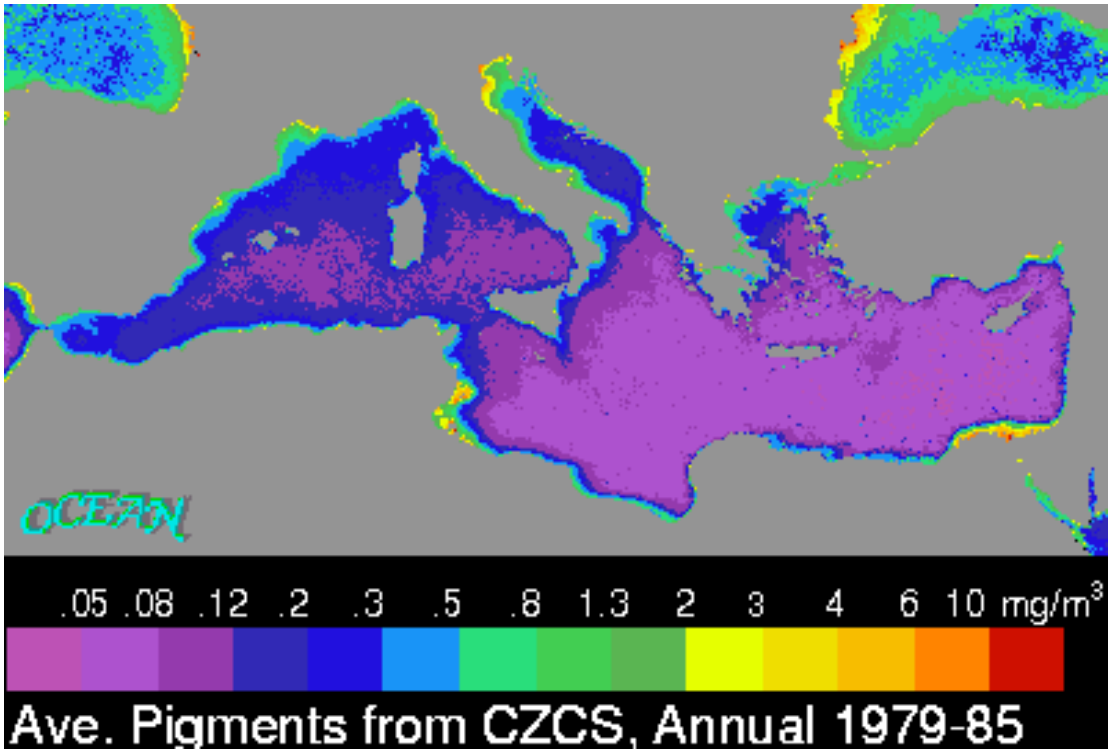

Plate 2. CZCS-derived chl Annual Means