# Algal Blooms in the Mediterranean Sea: a Retrospective Analysis Comparing the CZCS and SeaWiFS Historical Records

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**Abstract – Yearly and monthly means of chlorophyll-like pigment concentration in surface waters, derived from the CZCS (1979-1984) and SeaWiFS (1998-2003) time series, were compared for the Mediterranean Sea. Both historical records show differences in pigment concentrations (lower for SeaWiFS than for CZCS) and blooming patterns between the various sub-basins, and the recurrence of several regional features. Higher concentrations recur in the cold season, when runoff and vertical mixing contribute to the enrichment of surface waters, and lower concentrations in the warm season, due to reduced runoff and water column stratification. This comparative analysis contributes to characterize the main Mediterranean ecological provinces.**

**Keywords:** algal blooms, Mediterranean Sea, optical remote sensing, CZCS, SeaWiFS.

## 1. INTRODUCTION

Since the start of Earth Observations (EO) from satellite, only the Coastal Zone Color Scanner (CZCS), which operated from November 1978 to May 1986, and by the Sea-viewing Wide Field-of-View Sensor (SeaWiFS), from September 1997 to present, have generated sizeable times series of marine bio-optical data. 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 two instruments 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), in both its Terra and Aqua versions, and the MEdium Resolution Imaging Spectrometer (MERIS), are currently generating global time series of bio-optical data, but these are not yet comparable to those of the CZCS and the SeaWiFS.

The historical data set generated by the CZCS mission has been used in a number of studies for the 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. Assessments at regional scales have been reported also for selected sub-basins, characterized by peculiar spatial and/or seasonal variations in the pigment 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, in a comparison with other EO data on sea surface temperature and wind speed, collected over the entire Mediterranean Sea during the last two decades.

The SeaWiFS data set has been used as well in studies of the Mediterranean Sea, dealing with the general space/time distribution of optical properties (Loisel *et al.*, 2001) or the assessment of specific regional phenomena (*e.g.* Barale *et al.*, 2002, Gade *et al.*, 2003, Garcia-Gorriz *et al.*, 2003). As for large-scale bloom assessments, Bricaud *et al.*, 2002, approached the problem of algal biomass and primary production in the Mediterranean basin, in a thorough intercomparison of data collected by CZCS, OCTS, POLDER I and SeaWiFS with historical and concurrent *in situ* data.

In the following, composite images, derived from the data collected by the CZCS, in the period 1979-1984, and by the SeaWiFS, in the period 1998-2003, will be used to explore the large-scale, long-term features of the chlorophyll-like pigment concentration (*chl*) field in the Mediterranean Sea. In order to understand the degree of background variability that could be found for this environmental indicator, as related to the space/time distribution of algal blooms, the first issue approached was an analysis of the trends appearing in the CZCS and SeaWiFS data sets. Yearly and monthly *chl* mean images were obtained for both databases, and then used to derive the corresponding yearly and monthly climatologies. The features emerging from the comparison of the two sets of imagery will be discussed in terms of the oceanographic climate of the basin and of its main ecological provinces.

## 2. HISTORICAL DATA RECORDS

The CZCS *chl* data set (1979-1984) for the Mediterranean Sea is that released by the Ocean Colour European Archive Network (OCEAN) Project (Barale *et al.*, 1999). Statistical images were not considered for 1978 and 1986, when CZCS collected data only for the last three and first four months of the year, respectively. Data from 1985 were 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 individual images could still be included in

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** Research funded by the Institute of Environment and Sustainability, Joint Research Centre of the European Commission and the University of Geneva, in the framework of Collaboration Agreement N. 21698-2004-02 S0SC ISP CH.

the climatological data products for shorter periods. All daily images composing the data set were originally processed to correct for atmospheric contamination and to derive *chl* values using the *OCEANcode* software package (Sturm *et al.*, 1999).

The SeaWiFS data were also used to assess the evolution of *chl* in the Mediterranean Sea over a period of 6 years (1998-2003). The climatological record 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 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 0.825 km for CZCS and of 1.1 km for SeaWiFS, were re-mapped on equal-area projection grids, covering the whole Mediterranean area, with a pixel resolution of 1 km for CZCS data products and of 2 km for SeaWiFS data products. In the SeaWiFS case, pixels at both edges of the images, where actual resolution exceeded 2 km, were excluded from the re-mapping. Although the geographical grids include – and the images always display – part of the Bay of Biscay, to the north-west, and part of the Black Sea, to the north-east, as well as inland lakes, pixels from these areas were excluded from the processing of all statistical quantities (*e.g.* the *chl* average basin value) reported below. Finally, composite fields, at the monthly and yearly scales, were derived from the re-mapped images, by means of simple weighted averaging techniques. Climatological means, for monthly and yearly intervals, were computed using the composite images of the available period.

## 3. OBSERVED SPACE AND TIME FEATURES

The features determined by algal blooming, appearing in the CZCS and SeaWiFS *chl* record, diplay systematic similarities and a few striking differences. From the quantitative point of view, variations in absolute values of *chl* were expected because of the differences in the sensors' characteristics and calibration (performed *a posteriori* in the CZCS case), as well as in the data processing algorithms (in particular, due to the improved performance of the algorithms used for SeaWiFS, with respect to those used for CZCS, which tended to overestimate *chl* in case 2 waters, where optically active materials other than chlorophyll-like pigments contribute to water optical properties, and further to overestimate *chl* in fall/winter, due to low sun elevation angles and consequent multiple scattering effects, in the blue spectral region in particular). Indeed, in the (yearly and monthly) mean images, the CZCS-derived *chl* values appear to be systematically higher, by a factor 2, with respect to the SeaWiFS-derived ones. The main differences appear in the northwestern (and westernmost) part of the basin, where more intense spring blooming seems to have occurred in the SeaWiFS period.

The climatological annual mean, in both the CZCS (Fig. 1) and SeaWiFS (Fig. 2) case, shows the classical geographical subdivisions of the Mediterranean Sea (to which basic ecological provinces can be related) between western and eastern basins, inshore and offshore domains, northern and southern coastal margins. The western basin has higher *chl* values and localized mesotrophic patterns; the eastern basin lower *chl* values and a more uniform oligotrophic appearance.

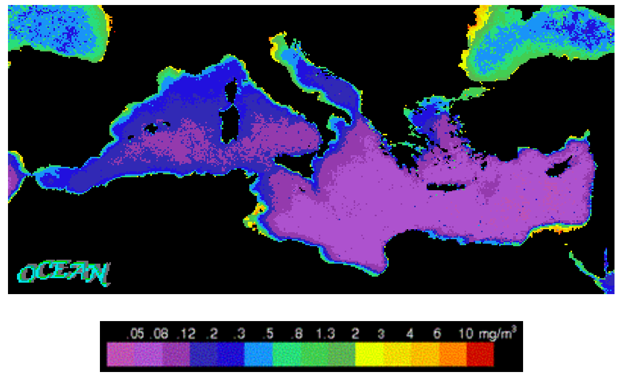


Figure 1. Climatological annual mean of *chl* from CZCS data. The colour coding shows pigment concentration in [mg m$^{-3}$].

Notable features, linked to recurrent and/or anomalous algal blooms, are the Alboran Sea gyre system, generated by the inflow from the Atlantic Ocean; the Ligurian-Provençal Sea enhanced patterns, due to offshore (seasonal) blooming; the Adriatic Sea near-coastal zone, dominated by the impact of river runoff; the northern Aegean Sea, affected by the inflow from the Marmara Sea; the plume areas of the main rivers (Ebro, Rhone, Po, Nile); and the mesoscale gyres in the Levantine basin (between the islands of Crete and Cyprus). In the Gulf of Gabes, off southern Tunisia, instead, the apparent enhanced pigment concentration is due to direct bottom reflection in shallow and clear waters, around the Island of Kerkenna, and not to local runoff patterns (Jaquet *et al.*, 1999).

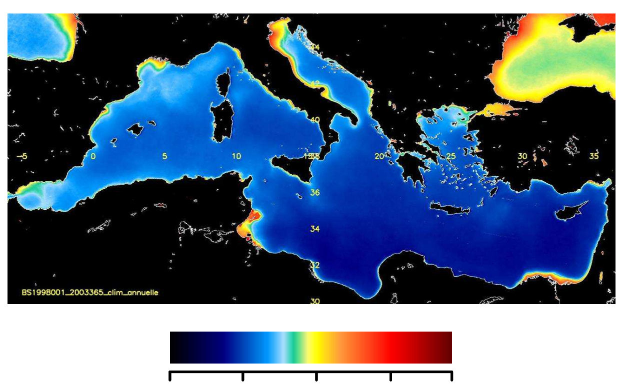


Figure 2. Climatological annual mean of *chl* from SeaWiFS data. The colour coding shows pigment concentration in [mg m$^{-3}$]. Numbers along the horizontal and vertical axis of the image show longitude and latitude values, respectively.

The climatological monthly means (not shown here) illustrate the seasonal cycle followed by the geographical units above. Deriving a *chl* average basin value from each of the monthly means, both the CZCS and SeaWiFS series present a bimodal cycle with *maxima* in the colder season, followed by *minima* in the warmer one. The CZCS climatological seasonal trend (Fig. 4) – albeit possibly biased in fall/winter by the mentioned overestimate of *chl*, due to low sun elevation angles and consequent multiple scattering effects – suggests that the Mediterranean Sea as a whole behaves like 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 that the nutrient level always is (Barale, 2000). In such a scenario, coherently with what observed in the monthly mean images and with the Mediterranean climate, algal blooming, indicated by higher *chl* values, would occur in the cold, windy and wet (winter) season, and would be related to the enrichment of surface waters due to surface cooling, vertical mixing and continental runoff – as opposed to lower *chl* values occurring in the warm, calm and dry (summer) season, when the water column is strongly stratified and no nutrient supply, from deeper layers or coastal zones, would be readily available.

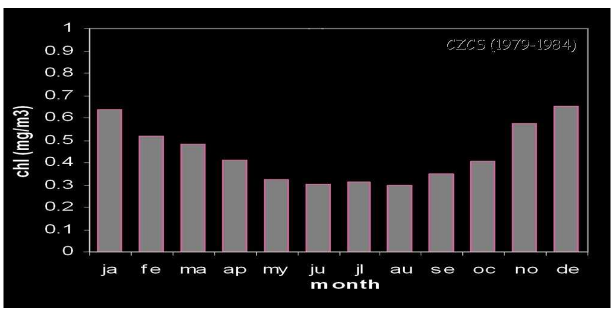


Figure 3. Seasonal trend of the *chl* average basin value, from CZCS climatological monthly means, Mediterranean Sea.

In the SeaWiFS climatological seasonal trend (Fig.4) – which should not have a fall/winter bias, since multiple scattering effects were taken into account – unlike what is seen in the CZCS case, absolute *maxima* do not appear from December to January. Instead, peak *chl* values occur in February and March, corresponding to widespread algal blooming at the basin scale, with reduced values in January and even more so in December.

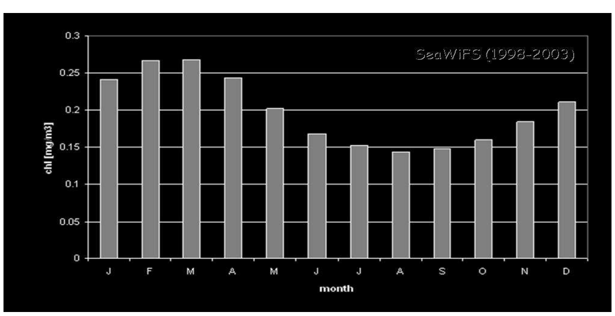


Figure 4. Seasonal trend of the *chl* average basin value, from SeaWiFS climatological monthly means, Mediterranean Sea.

The SeaWiFS climatological seasonal cycle shows that, after a summer low, *chl* 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, described earlier when considering the cycle of the entire Mediterranean basin, but points to the fact that some ecological provinces may have a different seasonality. And that such a difference can be so pronounced as to affect the basin statistics, when integrated *chl* values are considered to summarize the behaviour of the basin as a whole. Possibly, this is the case of the Ligurian-Provençal Sea (see Fig. 5).

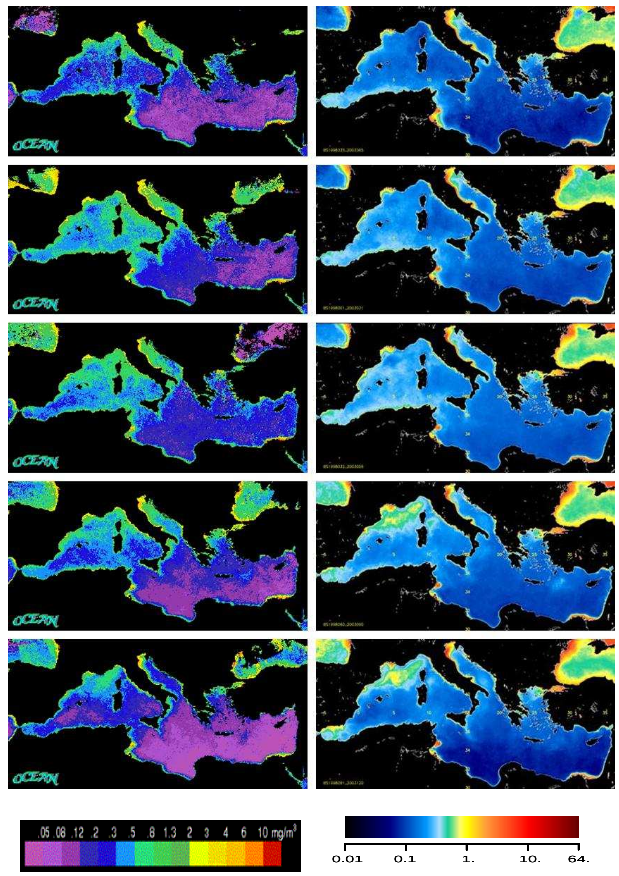


Figure 5. Climatological monthly means of *chl*, for CZCS (left column) and SeaWiFS (right column), from December (top row) to April (bottom row). The colour coding, in both cases, shows pigment concentration in [mg $m^{-3}$].

The north-western sub-basin is, in fact, the most notable exception to the seasonal cycle of higher values in the cold season and lower values in the warm season suggested by the climatological monthly means. This ecological province shows a sequence of low *chl* values in winter (a feature elsewhere referred to as the *blue hole*, in the Gulf of Lyon, but extending also in the Ligurian Current area) and of extensive spring blooms. The sequence has been linked to the Mistral wind seasonal pattern and the convection processes in this region, leading to deep (and bottom) water formation (Barale, 2003).

Interestingly, as seen in Fig. 5, the convection period appears to be longer in the CZCS climatology, since the monthly mean images show an extensive *blue hole* occurring as early as December and then most intensely in January, February and March as well, only to be replaced by widespread blooming in April. In the SeaWiFS climatology, instead, this feature can hardly be recognized in December, starts to become evident in January, and is obvious only in February, while the usual blooming takes place already in March (and continues in April). The variation in timing and strength of the blooming in this particular sub-basin might be responsible for the different seasonal trend derived from the climatological monthly means.

## 4. CONCLUSION

Yearly and monthly means of *chl*, derived from the CZCS (1979-1984) and SeaWiFS (1998-2003) time series, and the respective climatological images, were considered to highlight phytoplankton growth patterns in the Mediterranean basin. Due to the presence of diverse optically active material (*i.e.* dissolved organic matter and suspended inorganic particles), in addition to phytoplankton, especially in near-coastal waters, the uncertainities in *chl* absolute values and statistics must be taken into account, when addressing the variations of pigment levels in these databases. In the present comparison, absolute values of *chl* appeared to be systematically higher in the CZCS than in the SeaWiFS statistics, but this occurrence was assigned to an improved performance of the algorithms used for the SeaWiFS data processing. The main features appearing in both the CZCS and SeaWiFS historical record are the differences in pigment concentrations and blooming patterns between various sub-basins (*e.g.* western vs eastern) or in specific hot spots (*e.g.* river plume areas, but also the Alboran Sea, the Ligurian-Provençal Sea, the Adriatic Sea, the northern Aegean Sea, and sites in the Levantine basin). In general, the basin as a whole shows higher concentrations in the cold season, when runoff and vertical mixing are supposed to be the key factors contributing to the enrichment of surface waters, and lower concentrations in the warm season, supposedly due to reduced runoff and stratification of the water column. Notable differences between the CZCS and SeaWiFS periods occurred in the the Ligurian-Provençal Sea sequence of low winter concentrations and massive spring blooms. The results of this comparative analysis for the two different periods, separated by an interval of 20 years, provide a novel insight in the biological patterns of the Mediterranean Sea, contributing to the assessment of the basin's main ecological provinces.

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