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Spatio-temporal variability of micro-, nano- and pico-phytoplankton in the Mediterranean Sea from satellite ocean colour data of SeaWiFS

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Abstract

The seasonal and year-to-year variability of the spatial distribution of the Phytoplankton Size Classes (PSCs) has been examined in the Mediterranean Sea using the entire time series of Sea-viewing Wide Field-of-view Sensor (SeaWiFS) space observations (1998 to 2010). PSCs daily maps have been determined using an empirical model based on a synoptic relationship between surface chlorophyll *a* and diagnostic pigments referred to different taxonomic groups. The validation of model PSCs estimates using a Mediterranean HPLC pigments dataset revealed that the model is able to correctly detect the contribution of pico-, nano- and micro-phytoplankton to TChl *a*. The analysis of micro-, nano- and pico-phytoplankton satellite time series (1998–2010) describes quantitatively the seasonal and inter-annual variability of the spatial distribution of the algal assemblage structure over the basin. The analysis reveals that in most of the Mediterranean Sea the main contribution to the chlorophyll *a* all around the year comes from the pico-phytoplankton component, above all in poor nutrient conditions. Regions with different and peculiar features are the northwestern Mediterranean Sea, the Alborán Sea and several coastal areas, such as the north Adriatic Sea. In these areas, local interactions between physical and biological components modulate the competition between the three phytoplankton size classes. It results that, during the spring bloom season, micro-phytoplankton dominates in areas of intense vertical winter mixing and deep/intermediate water formation; while, in coastal areas, micro-phytoplankton dominates in all seasons, thanks to the nutrients supply that comes from the terrestrial inputs. In the Alborán Sea, in which the Atlantic inflow modulates the nutrient availability, any predominance of one class over the other two has been observed. Nano-phytoplankton component instead remains widespread over the entire basin along the year, and its contribution to the TChl *a* is of the order of 30–50 %.

The inter-annual variability is observed in the whole basin, but the largest inter-annual signal occurs in the northwestern Mediterranean Sea, driven by the year-to-year variation in intensity and extension of the spring bloom.

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In absence of sufficient in situ data of community composition, the satellite-based analysis demonstrated that pico, nano and micro classes often coexist. The predominance of one group over the other ones is strongly dependent on the physical-biological processes occurring at mesoscale. These processes directly influence the nutrient and light availability, which are the principal forcing for the algae growth.

1 Introduction

Phytoplankton represents an important element for the survival and comprehension of the marine ecosystem. Its scientific importance is owing to its ecological role in the global carbon cycle and greenhouse effect. It plays a key role in the biological carbon pump, thanks to its great contribution to the primary production, due to a rapid phytoplankton turnover and to the great extension of the ocean on the earth's surface.

Phytoplankton biomass bio-geographic distribution, on global and regional scales, is directly influenced by biological, chemical and physical factors such as light, nutrients availability, presence of competitors, predators, as well as pH, which are all connected to the local dynamic of water masses. These biotic and abiotic factors create a complex system in which the phytoplankton plays a relevant role. Being a primary producer, it represents the base of the aquatic system and the first step of the ecological pyramid as well as the food web.

The phytoplankton community composition seems to be also an index of environmental anomalies (Racault et al., 2012), since it shows new morphological and physiological adjustments whenever the conditions evolve, just like the change of size for each specific trophic stadium (Thingstad and Rassoulzadegan, 1999).

Thanks to the relationship between dimensions and pigmentary content, different taxa or stages of growth in the same taxon, photosynthetic efficiency and bio-optical phytoplankton properties (Chisholm, 1992; Organelli et al., 2007; Raven, 1998), "cell size" becomes an important descriptor of the community structure. The common

Phytoplankton Size Classes (PSCs) classification divides the community into micro (> 20 µm), nano (2–20 µm) and pico (< 2 µm) (Sieburth et al., 1978) respectively.

In terms of biogeochemical function and role, size structure of phytoplankton communities provides important information such as the knowledge of the community composition itself (Vidussi et al., 2001; Chisholm, 1992; Raven, 1998).

Nowadays, it is known the predominance of the pico-phytoplankton on the total content of chlorophyll *a* (sum of chlorophyll *a*, divinyl-cholorophyll *a*, chlorophyllid *a*, allomers and epimers, here henceforth referred as TChl *a*, or just chlorophyll *a*) in the oligotrophic waters. On the contrary, the larger cells prevail in the presence of rich nutrients. This is also due to the effect of the molecular diffusion on the feeding of the large cell under very low nutrient conditions (Chisholm, 1992). Moreover, the pigment “package effect”, describing the chlorophyll *a* efficiency in the light harvesting, is a direct function of the dimension of the cell (Chisholm, 1992; Raven, 1998; Basset et al., 2009).

In some cases, several biogeochemical functions correspond to a particular taxon or size class. For example, cyanobacteria often represents a large group of pico-phytoplanktonic nitrogen-fixers. They are able to fix and use the forms of atmospheric nitrogen, thereby having a direct impact on the climate change. Again, the principal components of the micro-phytoplankton, diatoms and dinoflagellates, play a dominant role in the Carbon flux into deeper waters (Nair et al., 2008; Sathyendranath, 2014).

Information about the composition of phytoplankton community structure can be obtained from the analysis of in situ samples. This approach is based on laboratory techniques such as: the flow-cytometry, that provides information about the number and the dimensions of the fluorescent cells in a specific water sample volume; HPLC (High Pressure Liquid Chromatography), used to retrieve the composition and concentration of the pigments content of the cells, and the spectrophotometry which provides the pigment light absorption in the visible spectrum. As a result, it is possible to collect a considerable dataset of in situ dimensional classes measures, which could be used, also, for other applications like calibration and validation of satellite algorithms.

The composition of the community is also reflected in the different optical properties of the water column. This allows the use of satellite ocean colour data to estimate the PSCs or PFTs (Phytoplankton Functional Types), which are defined as a grouping of different species with an ecological function in common, using either empirical or semi-analytical models.

Concentration of chlorophyll *a*, light absorption and backscattering are the main variables used by remote sensing to provide synoptic and multi temporal information about phytoplankton distribution.

Several satellite models have been developed in the recent years to classify the algal cells on the basis of the optical variable measured from space. These are usually divided into two main classes: direct models, which exploits the optical properties directly captured by the sensor; indirect models, as those based on the strong relationship between the chlorophyll *a* concentration and the functional groups or taxa (Moisan et al., 2012).

Among the direct models, Alvain's et al. (2005, 2008) method is able to determine some phytoplankton groups starting from the normalized *water leaving radiance* (nL_w). It exploits the anomalies in the spectral signature of a specific taxon or a specific type of community by removing from the radiance measure the chlorophyll *a* effect.

Most of the satellite PSCs models are based on a single variable: e.g. the absorption coefficient of the cells as defined in Sathyendranath et al. (2001), or the backscattering coefficient (Kostadinov et al., 2009). Others are mixed types, just as in the case of Fujiwara et al. (2011), in which the algorithm sunders the pico + nano-phytoplankton community from the micro one, involving the absorption and backscattering coefficients. The simultaneous use of in situ and remote measures allows us to understand the marine photoautotrophic system in a more complete way.

All the models above described, were developed and applied only at global scale, to infer phytoplankton composition and study seasonal and inter-annual variability of phytoplankton classes at global and regional scales (Brewin et al., 2010, 2011; Hirata et al., 2008, 2011; Uitz et al., 2006; Mouw and Youder, 2010).

In this paper, we used chlorophyll *a* based models to estimate phytoplankton composition in the Mediterranean Sea with the aim of studying the spatial and temporal variability of phytoplankton assemblage dynamics.

The Mediterranean Sea, although relatively small, is of sufficient size which is to be governed by large-scale ocean dynamics in its circulation. It is among the most interesting of the semi-enclosed seas because of the great range of processes and interactions that occur within it (Robinson and Golnaraghi, 1994). Most of the physical and biological processes, which characterize the global ocean, many of which are not well known or understood, occur analogously in the Mediterranean Sea (Siokou-Frangou et al., 2010; Lacombe et al., 1981; Robinson and Golnaraghi, 1994). These biological and physical processes interact with each other via feedbacks and influence, directly, the distribution of the phytoplankton and zooplankton community and the optical properties of the seawater. Unlike the other seas and oceans, the Mediterranean Sea shows singular optical properties of the water column, with “oligotrophic waters less blue (30 %) and greener (15 %) than the global ocean” (Volpe et al., 2007). This peculiarity has made it necessary to develop regional bio-optical algorithms to estimate chlorophyll *a* concentration from in situ optical measurements and satellite data (D’Ortenzio et al., 2002) and has suggested verifying whether Phytoplankton Size Classes (PSCs) model designed for global ocean applications can perform similarly in the Mediterranean Sea.

Therefore the objective of this work is dual: the first is to understand how well a simple empirical model solely based on chlorophyll *a* data, as Brewin et al. (2010, 2011) or Hirata et al. (2011), can describe the phytoplankton biomass distribution in the Mediterranean Sea; the second is to study the spatial–temporal variability of the three phytoplankton size classes (micro, nano and pico) in this basin, applying the selected model to the ocean colour products.

Presently, chlorophyll *a* estimates from ocean colour data were widely used to study the phytoplankton biomass variability at basin and sub-basin scales (e.g. Antoine and Morel, 1996; Santoleri et al., 2003; Bosc et al., 2004; Volpe et al., 2012b). Only recently, Navarro et al. (2014), adapted the PHYSAT method of Alvain et al. (2005) to the Mediterranean Basin bio-optical characteristics, thereby providing a regional algorithm to estimate dominant phytoplankton groups (Nanoeukaryotes, *Prochlorococcus*, *Synechococcus*, diatoms and coccolithophores) from MODIS water leaving radiance measures.

This paper will be the first attempt to describe the seasonal and inter-annual evolution of the phytoplankton size classes assemblage in the basin. It is organized as follows: in Sect. 2, we presented the satellite and in situ data, in Sect. 3 the selected PSCs models, based on chlorophyll *a* determination, are briefly described. The validation of the models over the Mediterranean Sea, using HPLC observation, is discussed and used to select the suitable model for buildup of the PSCs time series (Sect. 4). Then, the variability and distribution of PSCs is analyzed at different scales of time and space (Sects. 5, 6 and 7). The final section summarized the results of this work and presents the future perspectives.

2 Data

2.1 Satellite data

The satellite data used in this work comes from Sea-viewing Wide Field-of-view Sensor (SeaWiFS). They are daily chlorophyll *a* Level 3 (L3) data (resolution 1.1 km), from 1998 to 2010, produced by the Satellite Oceanography Group (GOS) of the Institute of Atmospheric Sciences and Climate (ISAC) of the Italian National Research Council (CNR), (Volpe et al., 2012a).

We used the so called Mediterranean Case1Case2 merged chlorophyll *a* product (GOS Chl_1-2). These daily chlorophyll *a* fields are derived using two different algorithms for open and coastal waters: the MedOC4 algorithm, applied to the Case 1 waters (Volpe et al., 2007) and the Ad4, used for the Case 2 waters (Berthon and Zibordi, 2004). The identification of the optical properties of each pixel is based on the D'Alimonte's method (D'Alimonte et al., 2003), which takes into account the entire spectrum from the blue band to NIR, for both Case1 and Case2 waters types. For intermediate waters, a weighted average of the two algorithms based on the distance between the actual reflectance spectra and the reference one for the Case 1 and 2 waters is applied (see Volpe et al., 2012a, for the details of processing).

The choice of applying an algorithm born specifically for the Mediterranean Case 1 waters, as MedOC4, provides a more realistic value of TChl *a*; as demonstrated in Volpe et al. (2007), which shows that NASA SeaWiFS chlorophyll *a* fields are affected by an uncertainty of the order of 100 % (Volpe et al., 2007). Moreover, all the data distributed by GOS and those distributed by MyOcean OCTAC to the end-users are quality checked. The daily TChl *a* fields, used as input in this work, are subjected to quality assessment trough an offline validation (Volpe et al., 2012a). As showed in Volpe et al. (2012a), the SeaWiFs products well performs with the in situ data (offline validation) for the most of the statistical parameters, such as the correlation coefficient (r^2) 0.815, Root Mean Square Error (RMS) 0.253, bias −0.019, relative (RPD) 15 % and absolute (ADP) 51 % percentage differences.

2.2 In situ data

In order to validate the Brewin et al. (2010, 2011) and Hirata et al. (2011) models in the Mediterranean Sea waters, in situ PSCs were determined using a specific subset of SeaBASS HPLC pigments dataset (Werdell and Bailey, 2005). These data were collected during several cruises and in periodic maintenance activities of moorings or fixed monitoring sites. The Mediterranean subset used in this work consists of measures acquired during the Propose cruise (1999), Boussole mooring (for a time range from 2001 to 2006) and Boum cruise (2008).

In situ quantification of PSCs was carried out, for both models, following the methods described in Vidussi et al. (2001) and Uitz et al. (2006) as modified in Brewin et al. (2010).

The performance of the two models when applied on basin pigment concentration dataset were evaluated by computing the Mean Bias Error (MBE), Root Mean Square Error (RMSE) and Correlation Coefficient (R) (Table 1).

3 PSCs global models

The models here considered are two: Hirata et al. (2011) and Brewin et al. (2010, 2011).

Hirata et al. (2011) method arises from a synoptic relationship between surface chlorophyll *a* and diagnostic pigments referred to different taxonomic groups. Besides a classification of phytoplankton in size classes (micro, nano and pico), the Hirata's model can identify seven functional types, by exploiting a Diagnostic Pigment Analysis (DPA) (for the phytoplankton classification see the details in Vidussi et al., 2001; Uitz et al., 2006).

The model establishes a correspondence between single PFTs and a combination of Diagnostic Pigments (DP), in order to determine the relative abundance of each class as a function of the satellite derived TChl *a*.

The second method (Brewin et al., 2010, 2011) was born as an extension of a previous model of Sathyendranath et al. (2001) from two to three components. The TChl *a* concentration is expressed as the sum of pico, nano and micro-phytoplankton chlorophyll *a* fraction, and each of them is computed as a separate exponential expression. Once known the contribution of each dimensional group, dividing them for TChl *a*, we obtain the fraction of the single size class, as absolute value with respect to the TChl *a*. For more details about the algorithm, see Brewin et al. (2010).

4 Comparison of Hirata and Brewin model performances over the Mediterranean Sea

To evaluate the Brewin et al. (2010, 2011) and the Hirata et al. (2011) models over the Mediterranean Sea, we extracted all the Mediterranean HPLC pigments data from the SeaBASS dataset (Werdell and Bailey, 2005).

Micro, nano and pico-phytoplankton fractions, determined from HPLC in situ pigments, were plotted as a function of the TChl *a* and were compared with the two models (Fig. 1).

A rather large scatter of the data around the models curves suggest that, in the real world, the relative abundance of micro, nano and pico-phytoplankton cannot be a simple function of the total chlorophyll *a* concentration alone.

Micro fraction scatter plot, (Fig. 1a) shows that Hirata's model tends to underestimate the fraction of micro-phytoplankton, especially for low values of TChl *a*, whereas, Brewin's one seems to fit better with in situ data.

For nano component, the scatter plot reveals an inverse behavior (Fig. 1b). In this case, the Hirata model falls well within the observations; on the contrary, the Brewin model shows a strong underestimation with respect to the in situ data, in the whole range of TChl *a*.

Finally, for pico-phytoplankton, the scatter plot reveals a better fit of Hirata algorithm than that of Brewin, which shows an overestimation of the model, for low values of TChl *a* (Fig. 1c).

The basic statistical parameters of the difference between the models and the in situ data suggested the performance of the two models in the Mediterranean Sea and are reported in Table 1.

This statistical analysis suggests that the Hirata model works better than that of Brewin. Therefore, we adopted the Hirata et al. (2011) algorithm to estimate the PSCs from satellite.

Daily PSCs maps, at 4 km of resolution, were used to compute the monthly and climatological maps covering the SeaWiFS era (1998–2010) and were employed for the subsequent analysis. Moreover, TChl *a* fields at monthly and climatological scales were produced to support the analysis of phytoplankton biomass variability. In these maps, the chlorophyll *a* concentration is expressed as base 10-log transformed, to reflect the log-normal distribution of this pigment.

The temporal pattern of TChl *a* and PSCs variability was summarized in the interannual time series of two representative months (April and August), as described in Sect. 6.

At last, a zoom of monthly PSCs field was reported for some areas, such as North Adriatic Sea and Aegean Sea, which are used for a sub-basin scale analysis, while the temporal pattern of PSCs fraction, in northwestern basin, Alborán Sea, Levantine Sea and North Adriatic Sea was summarized by specific histograms.

5 Seasonal variability of spatial distribution of the PSCs in the Mediterranean Sea

The seasonal evolution of the chlorophyll *a* distribution in the Mediterranean Sea is driven by the life cycle of the phytoplanktonic organisms that follows the typical succession of temperate areas, with a high biomass increase in late winter/early spring and a decrease in summertime, and a second smaller bloom in autumn. PSCs variability follows this oscillation mostly driven by the evolution of the chlorophyll *a* concentration and its West-East gradient. This spatial gradient is one of the dominant features of the chlorophyll *a* distribution in the Mediterranean Sea and reinforces the paradigm of an extremely oligotrophic eastern basin and a more productive western side (D'Ortenzio et al., 2009). We investigated the seasonal variability of this spatial gradient by computing the variation of monthly chlorophyll *a* mean from West to East along a basin transect for the time series 1998–2010 (Fig. 2). In this case, pixels closer than 20 km from the coast have been excluded from the computation so as to restrict the calculus to open ocean waters.

A decreasing trend of this surface chlorophyll *a* mean concentration, moving from West to East, is observed in all the months of the year (Fig. 2). The curves suggest the occurrence of an enhanced seasonal cycle in the western Mediterranean with respect to the eastern Mediterranean Sea, generally characterized by oligotrophic conditions in all the months of the year. Oligotrophic conditions dominate in the western Mediterranean Sea during summer. During spring, the occurrence of the blooms is marked by two distinct peaks at 4 and 9° E relative to the Gulf of Lions and Ligurian Sea respectively. The peak at 13° E is the signature of the rich chlorophyll *a* area of the North Adriatic Sea.

The observed West to East decreasing trend is consistent with a similar trend observed in the nutrient concentrations by Siokou-Frangou et al. (2010) and by Santinelli et al. (2012). These concentrations are generally very low, according with the general oligotrophy of the basin, mainly linked to the lack of phosphorous, P, which represents a limiting factor for phytoplankton community's growth (Zohary and Robarts, 1998; Ribera D'Alcalà et al., 2003; Krom et al., 2004).

In the next sessions we describe the variation of the spatial distribution of micro-, nano-, and pico-phytoplankton in the Mediterranean Sea in the spring chlorophyll *a* bloom maximum (April) and the summer oligotrophic minimum (August), resulting from the Hirata et al. (2011) model. The monthly average is computed over almost the entire SeaWiFS era from 1998 to 2010.

Maps of the remaining months of the year can be found in the Supplement.

5.1 Micro-phytoplankton

The seasonal spring to summer excursion of micro-phytoplankton, in the first optical depth, is shown in Fig. 3.

During summer (August) the spatial distribution of the micro-phytoplankton contribution to the total chlorophyll *a* in the offshore areas is uniform and very low, about 1 % in the Ionian-Levantine Basin and of 2 % in the western Mediterranean Sea, with peaks of 18–20 % in the Alborán Sea.

These low values are associated to low chlorophyll *a* concentrations. Indeed, in summertime, the water becomes warmer and the stratification of the column is more marked, thereby producing a resistant thermocline, which limits the rising of nutrients to surface and consequently determines a reduced photosynthetic activity (Siokou-Frangou et al., 2010).

In August, high values of micro-phytoplankton contribution are observed in some coastal regions characterized by an high nutrients supply due to upwelling phenomena or river runoff: the Alborán Sea, the north Adriatic Sea, the gulf of Lion and the gulf of Gabes with values ranging between 20–75 %. In the Alborán Sea, the higher micro-phytoplankton contribution is highlighted by water upwelled along the Spanish coasts and entrained in the west Alborán gyre (Sarhan et al., 2000).

In April, the fraction of micro-phytoplankton significantly grows in the northwestern Mediterranean Sea ranging from values of 20 to 57 %. This area, included by D'Ortenzio et al. (2009) in the bloom cluster, is characterized by a local dynamic in which cold winter winds can induce deep mixing extending down to several hundred up to thousand meters, which is much greater compared to the seasonal winter overturn. This deep overturning process also brings up an additional supply of nutrients complementary to that furnished by seasonal convection, thus modulating the spring bloom. The bloom observed in April (Fig. 3) is the result of winter upwelled nutrients and phytoplankton trapped in the euphotic zone by the spring re-stratification process and of the increased insolation. After this high productivity's period, micro-phytoplankton contribution to the TChl *a* decreases in the whole basin, reaching its minimum in July–August.

In April, high micro-phytoplankton values are still present in the same coastal areas mentioned for August with the addition of the north Aegean Sea where the signature of the Black Sea outflow is now more evident (Fig. 3). Differently from August, the Spanish coastal water reaches also the eastern Alborán Gyre, resulting in a widespread of micro component in this region.

In the Ionian-Levantine Basin, in April, the contribution of the micro-phytoplankton remains low with values about of 2–3 % and with higher values ranging from 4 to 10 % in the western side of the Ionian Sea and in the Rhodes Gyre, which is at west of the Rhodes Island.

A second micro bloom occurs in autumn/winter (not shown) due to a new mixing of the water afterwards the break of the thermocline (Bosc et al., 2004). Unlike the previous one, this bloom shows lower values of chlorophyll *a*, in agreement with previous observations (Siokou-Frangou et al., 2010). This phenomenon leads to a minor percentage of micro-phytoplankton such as 2–15 % of the TChl *a*, with some peaks along the Algerian Current in the southern part of the west side of the Mediterranean Sea (30–40 %).

5.2 Nano-phytoplankton

The amplitude of the seasonal cycle of the nano-phytoplankton component is less pronounced than for micro (Fig. 3). In summer, the contribution of the nano-phytoplankton to the total chlorophyll *a* is between 20 and 45 %. In coastal areas, such as the North Adriatic Sea, its contribution to total chlorophyll *a* reaches 30–50 %, with a decrease for pixels more close to the coast where micro-phytoplankton still dominates (Fig. 4a).

In April, the contribution of the nano-phytoplankton remains between 30 and 40 % in most of the Ionian-Levantine Basin, with the exception of the Rhodes gyre, where it reaches values of about 48 % and the western Ionian Sea, where values up to 45–50 % are observed approaching the coasts of Italy (Fig. 3). In the western Mediterranean Sea, the values of nano contribution to total chlorophyll *a*, vary from 25 to 50 % (Fig. 3). Again, in the North Adriatic Sea, the nano fraction, in April, is always between 20 and 40 %, but with a more evident decrease, with respect to August, for pixels being more close to the coast where the micro-phytoplankton remain predominant (Fig. 4b).

5.3 Pico-phytoplankton

Due to the high ratio surface/volume, pico-phytoplankton seems to be more suitable to poor nutrient environments often characterized by high salinity, such as those that occur in the Levantine Basin (Le Quéré et al., 2005). As suggested by Uitz et al. (2012), its capacity to survive in this type of environments justifies its great abundance in eastern basin, thus becoming the principal producer in ultra-oligotrophic waters.

Indeed, in our maps (Fig. 3), in August, the pico-phytoplankton contributes to 60–80 % of the TChl *a* of the first optical depth, in the offshore waters. Lower values are observed in coastal waters: about 20–30 % in the western Alborán Gyre, 15–20 % in the North Adriatic Sea and 20–30 % in the Gulf of Lions.

In April, in the Ionian-Levantine Basin, the pico fraction's values remain high but lower than those of August (50–65 %), while in the northwestern Mediterranean Sea, a large area of low pico TChl *a* concentration occurs with values between 18 and 22 % (Fig. 3). Similarly, low values are observed in coastal regions, e.g. in the north Aegean Sea, where the outflow of the Black Sea influences the distribution of pico class, with values ranging from 35–44 % in August (Fig. 4c). In April, the outflow of the Black Sea waters is marked by a minimum which ranges between 15 and 27 %, that now affects all the northern part of the Aegean Sea (Fig. 4d).

6 Inter-annual variability of chlorophyll *a* and PSCs in the Mediterranean Basin

The inter-annual variability of the surface chlorophyll *a* and PSCs distribution in the Mediterranean Sea is shown in Figs. 5 and 6 for the two opposite months of April and August respectively. The sequence of the maps reveals that year-to-year variations are very small in August, while significant variations occur in April.

The time series chlorophyll *a* and PSCs average, computed over the offshore pixels in the entire basin, reveals that in August, the surface chlorophyll *a* mean concentration varies between 0.043 $\mu g L^{-1}$ in 2009 to 0.051 $\mu g L^{-1}$ in 2001 (Fig. 7e), while in April it oscillates between 0.10 $\mu g L^{-1}$ in 2001 and 0.23 $\mu g L^{-1}$ in 2005 and 2008 (Fig. 7a). The spatial and temporal distribution of the PSCs contribution to the total chlorophyll *a* varies accordingly with these concentrations (Fig. 7b–d, f–h).

In August (Fig. 7f), the spatial average of the pico-phytoplankton contribution is about 68 % from 1998 to 2003. Since 2004, this contribution increases and reaches nearly 70 % in 2010, with a minimum of 67.5 % in 2007. In April (Fig. 7b), the pico-phytoplankton contribution was between 50 and 54 %, with an isolated maximum of about 58 % in 2001. The temporal evolution of the nano-phytoplankton in August and April (Fig. 7g and c respectively) was nearly specular to that of the pico-phytoplankton. In August, a quite constant contribution is observed between 1998 and 2003, with values around 30 %; after which, it starts to decrease, reaching a minimum of 28.5 % in 2010 (Fig. 7g). This decreasing trend is interrupted in 2007 by an isolated maximum of 30.5 % (Fig. 7g). In April, the values of nano fraction oscillate between 39 and 44 % (Fig. 7c). The micro-phytoplankton contribution to the total chlorophyll *a* is always very small: nearly to zero (1–2 %) in August and between 4 and 9 % in April (Fig. 7h and d).

The basin scale analysis of the seasonal (Sect. 5) and inter-annual (this section) variability of the TChl *a* and pico-, nano-, and micro-phytoplankton contributions gives a general picture of the order of magnitude of their mean values and variations at time scales, ranging from months to years. Nevertheless, this analysis filters out important processes that occur at a local scale, with variations that can also reach an order of magnitude larger than those at the basin scale.

7 Seasonal and year-to-year variability of chlorophyll *a* and PSCs at local scales

Local processes play an important role in the ecosystem of the Mediterranean Sea interacting with the physical system that contributes to drive its evolution but which, in turn, is affected by it (bio-feedbacks). To investigate the year-to-year variability of processes that occur at local scale in the Mediterranean Sea, we selected four sub-regions representative of local but relevant processes: the Northwestern Mediterranean Sea (NWMed), the Levantine Basin (LEV), the Alborán Sea (ALB) and the North Adriatic Sea (NADR) (Fig. 8).

In NWMed Sea (Fig. 9a) the seasonal cycle of chlorophyll *a* concentration shows an increase of TChl *a* values from the initial part of the year, January–February, with maxima values in April ranging from 0.4 to 1.2 $\mu g L^{-1}$, or sometimes in March. In summer, the chlorophyll *a* decreases up to 0.1 $\mu g L^{-1}$, and then, in autumn, it rises again. The analysis of the year-to-year variability reveals an absolute spring maximum in 2005 (Fig. 9a), with a concentration of about 1.2 $\mu g L^{-1}$, followed by a decreasing trend from 2006 to 2007 and a new rising in 2008 (0.8 $\mu g L^{-1}$).

The mean annual value of chlorophyll *a* concentration for NWMed and ALB (Fig. 9c) are quite similar, but in the latter (Fig. 9c), the seasonal cycle is less "clean" and the year-to-year variability is marked by minimal values of the spring maxima from 2001 to 2004 ranging from 0.5 to 0.8 $\mu g L^{-1}$ and relative maxima in 2000, 2005, 2006 and 2007 ranging from 1.0 to 1.3 $\mu g L^{-1}$. Intermediate values of the spring maximum are observed in the remaining years of the series.

Unlike from the ALB Sea, in the LEV basin (Fig. 9b), the seasonal cycle of the chlorophyll *a* concentration is more regular. It rapidly increases from early winter months, reaching local maxima values in January–February. In summer, the chlorophyll *a* reaches minima values and then it increases again in autumn. In Fig. 9b peak values appears in 2004, 2007 reaching chlorophyll *a* concentrations of about 0.1 $\mu g L^{-1}$.

The oligotrophic nature of the LEV basin is reflected in the low concentration of chlorophyll *a*, which is of an order of magnitude that is less than that of other bioregions.

On the contrary, the NADR (Fig. 9d) time series show the highest range of chlorophyll *a* concentration among all four sectors. In NADR, the ratio between minima and maxima is not as high as in the other three regions and a seasonal cycle is not so evident. The NADR inter-annual variability of the chlorophyll a concentration is expressed by an irregular trend from 1998 to 2002, a local minimum during 2003 and then a more weakened variability from the end of 2005 to 2009. The main peak values occur in 2000, 2004 and 2010 while, 2003, represent the year of the lowest oscillation.

In the NWMed basin (Fig. 9a), the contribution of pico-phytoplankton to the seasonal cycle seems to be constant from year-to-year, with values not higher than 0.19 $\mu g L^{-1}$, as that in 2005, and a mean concentration of 0.07 $\mu g L^{-1}$. Although the differences between minima and maxima of pico in each year are low, it, however, follows a seasonal variability, with high values in late winter–early spring, and lower in summer.

Nano-phytoplankton shows the same seasonal cycle of pico (Fig. 9a). The maxima and minima occur in the same months of the smallest cells, but, in this case, the excursion among them, are higher with respect to those of pico. The peaks occur during the early spring season, reaching 0.28 $\mu g L^{-1}$ in April 2005, and an annual mean of 0.09 $\mu g L^{-1}$.

In NWMed Sea, the largest seasonal variability is due to micro-phytoplankton. Maxima values occur even during spring blooms with an absolute peak of about 0.7 $\mu g L^{-1}$ in April 2005. During summer, micro-phytoplankton reaches a very low concentration, below 0.01 $\mu g L^{-1}$ on the TChl *a*.

The LEV basin (Fig. 9b) shows, in contrast with the NWMed sector, a particular behavior and PSCs ratios.

Pico-phytoplankton predominates on the TChl *a* with a mean concentration of 0.03 $\mu g L^{-1}$ (Fig. 9b). Its seasonal cycle appears to be constant from year-to-year. More variable is the nano component, which shows higher seasonal differences between minima and maxima. The peak values, usually, occur in January–February; on the contrary, the lowest concentrations are reached in summer. The mean value of nano-phytoplankton is 0.018 $\mu g L^{-1}$. Therefore, in the LEV, most of the variability is due to nano component, instead of pico-phytoplankton.

Furthermore, the strong and well-known oligotrophy of this basin is reflected in the fraction of micro-phytoplankton, the lowest among the three PSCs, with a mean that is very close to zero $\mu g L^{-1}$.

Among all the four sectors, the NWMed (Fig. 9a) and LEV (Fig. 9b) show a cycling seasonal variability and a constant inter-annual tendency of PSCs, whereas the ALB (Fig. 9c) and NADR (Fig. 9d) basins appear more irregular.

Along the time series, in the ALB basin, (Fig. 9c), pico-phytoplankton persists at relatively low concentration (mean value of 0.1 $\mu g L^{-1}$), with small peaks occurring during spring months. Nano-phytoplankton follows the same pattern of pico, but with a higher excursion between minima and maxima. The absolute peak for nano component is in March 2005, with a concentration of 0.27 $\mu g L^{-1}$ on the TChl *a*.

For the ALB Sea, it is not so easy to define a regular seasonal cycle and a year-to-year variability, above all for micro-phytoplankton fraction. It shows a seasonal oscillation with the usual increase during spring blooms and a decrease in summer, as a result of a stratification of the water column. The mean contribution of micro-phytoplankton to the TChl *a* is about of 0.21 $\mu g L^{-1}$, while the maximum is 0.84 $\mu g L^{-1}$ in March 2006.

The NADR basin (Fig. 9d) shows unique features. Among all, it is the most complicated and irregular sector. In contrast with the previous basins, the chlorophyll *a* content of NADR Sea is very high, and the PSCs ratios show a different behavior with respect to the other sectors.

Pico-phytoplankton fraction is nearly constant from year-to-year. Pico mean value, as a fraction of the TChl *a*, is 0.14 $\mu g L^{-1}$, which is higher with respect to the mean value 0.03 $\mu g L^{-1}$ of the LEV Sea (Fig. 9b and d).

In the PSCs NADR time series (Fig. 9d), the pico signal slightly decreases in summer months. As pico, nano-phytoplankton shows the same spring and summer oscillation; but the ratio between maxima and minima is higher (3.03) than the previous one for pico (2.58).

In NADR, the highest contribution to the TChl *a* is provided by the micro-phytoplankton. It does not show a regular inter-annual variability, but, from a seasonal point of view, it shows peaks in spring season, a decrease in summer and a second bloom in late autumn–early winter. In Fig. 9d and a constant increase of micro values occur from 2001 to 2002, while the main peaks are registered in November 2000

(2.6 µg L^{-1}) and in May 2004. The lowest values occur in 2003, all over the year. In this basin, the chlorophyll *a* fraction due to micro-phytoplankton class has a mean value of 0.8 µg L^{-1}.

8 Discussion and conclusions

In this work, we estimate the contribution of micro-, nano- and pico-phytoplankton to the total chlorophyll *a* over the Mediterranean Sea using the entire time series of the SeaWiFS mission. The use of the Mediterranean regional daily reprocessed chlorophyll *a* data allows us to take into account the optical characteristics of the basin and to evaluate the PSCs distribution in the open ocean and coastal water. The validation of the Mediterranean PSCs estimates was first made by applying the models to in situ TChl *a* and comparing the results with phytoplankton size classification resulting from SeaBASS HPLC pigments dataset; then comparing the pattern and distribution of the satellite PSCs maps with the general knowledge resulting from the few in situ observations of phytoplankton size classes. The results showed that, in the Mediterranean Sea, the Brewin model strongly underestimates the nano fraction, while, the Hirata model is able to detect the contribution of the three size classes to TChl *a*. Our analysis revealed that the Hirata model, even if developed for the global ocean, can be used also in the Mediterranean Sea without tuning its empirical coefficients. The use of the GOS Chl_1–2 dataset ensures that the SeaWiFS estimates are reliable with respect to the in situ chlorophyll *a* data, with zero bias (−0.02 mg m^{-3}) and a relative small RMS (0.25 mg m^{-3}) (Volpe et al., 2012a). This implies that our approach, which is based on a global model, applied to regional satellite chlorophyll *a* estimates, is a valid alternative with respect to the development of regionalized methods, such as the Navarro et al. (2014) PFTs model recently developed for the Mediterranean Sea. Therefore, we selected the Hirata model to compute the daily PSCs maps and to understand the distribution and variability of the algal biomass in this basin.

The analysis of micro-, nano- and pico-phytoplankton satellite time series (1998–2010) allowed, for the first time, to describe quantitatively the seasonal and inter-annual variability of the spatial distribution of the algal assemblage structure. The results indicate that pico-phytoplankton dominates all around the year in most of the Mediterranean Basin, above all in ultra-oligotrophic waters. Nevertheless, exceptions are: the northwestern Mediterranean Sea (during the spring bloom), the Alborán Sea and several coastal areas such as the north Adriatic Sea. In the coastal areas, the contribution of micro-phytoplankton to TChl *a* is always effectively more evident, and can be explained by the high typical nutrients condition of these regions, that favor the predominance of micro-phytoplankton with respect to the other two size classes (e.g. Siokou-Frangou et al., 2010). On the contrary, in the offshore waters, the contribution of nano-phytoplankton to TChl *a* is of the order of 30–50 % and it remains mainly constant along the year (Fig. 3). This is consistent with the nano-phytoplankton constant contribution to the mediterranean primary production observed by previous authors (Uitz et al., 2012, 2010).

In ultra-oligotrophic waters, such as those of the Levantine Basin, pico-phytoplankton prevails in the PSCs climatology (Sect. 5). This is justified by the ability of the smallest cells to exploit better the poor nutrients environments, according to their high surface/volume ratio (Le Quéré et al., 2005; Timmermans et al., 2005). Indeed, the summer stratification of the water column, causes a strong decrease in micro chlorophyll *a* contribution, whereas, nano-phytoplankton and pico-phytoplankton survive, adapting to the warmer water state (Fig. 3, and Marty and Chiaverini, 2002).

The typical chlorophyll *a* seasonal cycle of the temperate regions occurs in the Mediterranean Sea, with maxima in spring and minima in summer. It results into a seasonal signal of the PCSs distribution, characterized by an increase in the micro fraction in spring and the pico fraction in summer (Fig. 3). This mean seasonal cycle can be significantly distorted in coastal regions, such as the North Adriatic Sea (Fig. 3), where terrestrial inputs from rivers play an important role in modulating the nutrients supply in the upper layer of the water column. In this basin, the micro class dominates all around the year, in accordance with the knowledge resulting from in situ measurements of the LTER (Italian Long Term Ecological Research Network) North Adriatic station (Fonda Umani et al., 2005; Cataletto et al., 2012). In addition, in the Alborán Sea, in which the Atlantic inflow modulates the nutrient availability, an intermediate temperate and subtropical seasonal cycle is observed, with a chlorophyll *a* maximum in late winter–early spring (Siokou-Frangou et al., 2010). In this region, our analysis reveals that there is not an evident predominance of one class over the others all along the year. Micro, nano and pico contribution to TChl *a* is modulated by intermitted processes, such us the variation of the Atlantic flow and the upwelling events occurring along the Spanish coast, which can cause a vertical uplift of nutrients, especially nitrates, to the surface water layer (Mercado et al., 2005).

Inter-annual variability is observed in the entire basin, but the largest inter-annual signal occurs in the northwestern Mediterranean Sea driven by the year-to-year variation in intensity and extension of the spring bloom (Figs. 5 and 6). High values of chlorophyll *a* are observed in the whole basin (Fig. 7a and e), but above all in the western basin, from 1998 to the beginning of 1999, as reported in Volpe et al. (2012b). On the other side, a general decrease of chlorophyll *a* concentration occurs in spring 2001, affecting mostly the eastern basin, confirming Bosc et al. (2004) results. This decrease is reflected in a lower contribution of the micro fraction on the TChl *a* (Fig. 7d). A peak of chlorophyll *a* signal occurs in April 2005, accompanied by an increase of microphytoplankton with respect to previous years (Fig. 7d). These anomalous high values of averaged spring chlorophyll *a* field are associated with an overall increase in the concentration of chlorophyll *a*, that occurs in the entire western Mediterranean Basin. They are also linked to an intensification of the spring bloom in the Gulf of Lion (see Fig. 5), where an unusual and strong winter convention occurred in the 2005 (Volpe et al., 2012b; Font et al., 2007; Smith et al., 2008). This phenomena results in an increase of the micro-phytoplankton with respect to previous years, even if the nano and pico contribution to total chlorophyll *a* remain dominant (Fig. 7b–d), since micro fraction are present only in a limited areas of the basin such as those where deep convection

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occurs (Fig. 5). A second spring maximum is observed in 2008 in both chlorophyll *a* and micro-phytoplankton (Fig. 7a and d), related again to the enhancement of the spring bloom in the Gulf of Lion.

The analysis of the year-to-year variability in the PSCs of the NWMed (Fig. 9a) confirms the occurrence of an evident seasonal and inter-annual signal. The seasonal cycle of chlorophyll *a* and thus the PSCs is typical of temperate areas, with maxima in March and/or April (Fig. 9a). During these spring blooms, the micro-phytoplankton exceeds the other classes, in light of the great amount of nutrients available in the water column. Indeed, in this area, the winter deep and intermediated convection allows to bring up nutrients from the deeper layer (Lévy et al., 1998a, b). This process modulates the year-to-year variability of intensity and duration of spring bloom (Santoleri et al., 2003), which results into a strong inter-annual signal of the micro-phytoplankton concentration, as revealed by our analysis (Fig. 9a).

The micro-phytoplankton dominates the inter-annual signal also in the NADR, while nano and pico-phytoplankton show slight variations (Fig. 9d). The large contribution of the biggest cells to the high values of TChl *a* can be related to the presence of big rivers, such as: Po, Brenta, Livenza, Adige and Isonzo. Every year, their runoff causes the release of a large amount of organic particles and nutrients, which support the micro cell size growth and development. Our analysis shows that the peaks of micro-phytoplankton biomass, usually, occur in May and November (Fig. 9d), when the river runoff grows up due to more intense rainfall and the snowmelt (Struglia et al., 2004; Malej et al., 1995). Anomalous events are recorded in November 2000 and May 2004 (Fig. 9d). In the former, the prevalence of micro-phytoplankton on the TChl *a* is probably due to particular conditions that occurred in that year. This is in agreement with in situ observations of the LTER station, located in the Gulf of Trieste, which shows biomass peaks of micro fraction in the same year (Cataletto et al., 2012). Moreover, intense precipitation occurred in November 2000 in the Po hydrographic basin (Stravisi, 2006; Russo et al., 2005), with a consequent intensification of the river outflow, and can represent one of the causes of the increasing of micro-phytoplankton fraction revealed by our analysis.

An opposite case is the Levantine Sea. In this basin, the ultra-oligotrophic regime influences the distribution and, above all, the contribution of the three PSCs to the TChl *a*. In Fig. 9b, most of the TChl *a* is due to pico-phytoplankton class, which is predominant all along the year. This can be related to the ability of the smallest cells to live and survive in extreme conditions, such as poor nutrients environment and stratified water column (Siokou-Frangou et al., 2010; Le Quéré et al., 2005). When the bloom occurs (February), the nano fraction increases and its contribution to TChl *a* becomes equivalent and sometime predominant with respect to pico class.

In summary, in absence of sufficient in situ data of community composition, our time series analysis demonstrates the potential usefulness of ocean colour imagery for monitoring the phytoplankton assemblage in the Mediterranean Basin. We clearly demonstrated that pico, nano and micro classes often coexist and their relative contribution to TChl *a* cannot be neglected. The possibility to identify all the components of the phytoplankton assemblage, in terms of dimensional size, allowed us to provide complementary information to the present knowledge of the Mediterranean phytoplankton composition, which is based only on the dominant phytoplankton types (Navarro et al., 2014). Our analysis demonstrated that the predominance of one group over the other ones is strongly dependent on the physical-biological processes occurring at the mesoscale, that directly influence the nutrient and light availability, which are the principal force for the algae growth.

As a future perspective, we would like to extend our analysis to other satellite sensors in order to enlarge the PSCs time series, but we will also consider and test other models, based on different variables, with the aim to track, as more as possible, the phytoplankton community evolution from space.

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Table 1. Statistical results of the two models applied on the Mediterranean in situ dataset (see also Fig. 1).

Model	PSCs	MBE ($\mathrm{mg\,m^{-3}}$)	RMSE ($\mathrm{mg\,m^{-3}}$)	R
Brewin et al. (2010, 2011) model	Pico	0.1191	0.2065	0.5469
	Nano	−0.1602	0.2118	0.3722
	Micro	0.0411	0.1517	0.6185
Hirata et al. (2011) model	Pico	0.0770	0.1526	0.6412
	Nano	−0.0221	0.1384	0.4632
	Micro	−0.0549	0.1697	0.6207

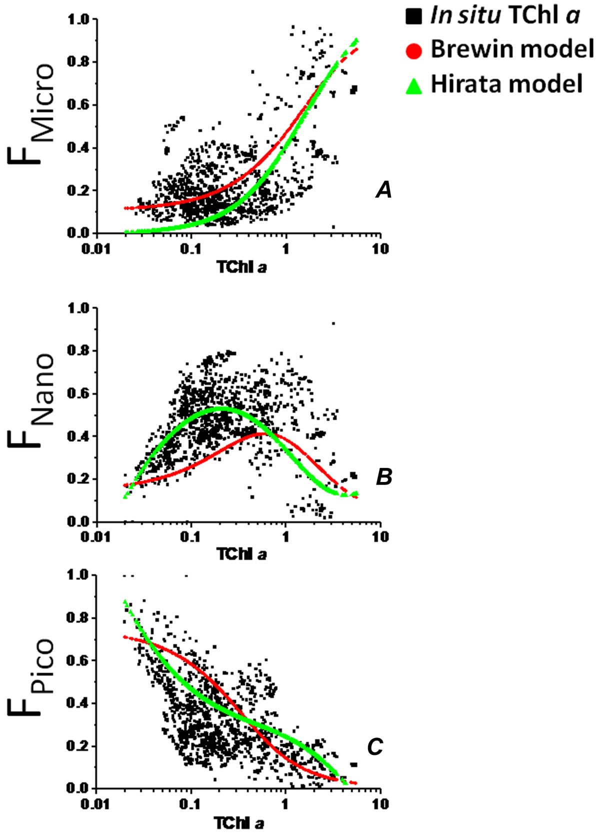

Figure 1. Comparison of the two models vs. in situ PSCs classification. Red and green line represents respectively the Brewin and Hirata model applied to in situ TChl *a*, while the black spots denotes the in situ fractions derived from the Mediterranean SeaBASS dataset.

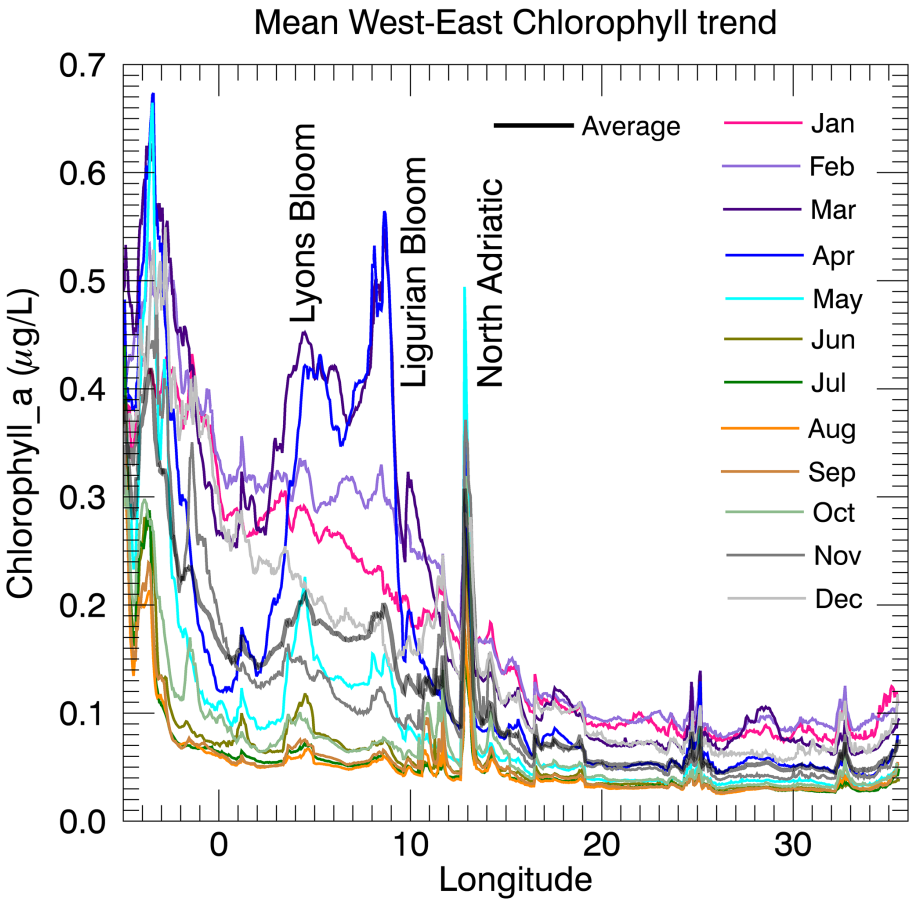

Figure 2. West–Eastward monthly mean chlorophyll *a* concentration (mg m^{-3}) along a basin transect for the time series 1998–2010. The high chlorophyll *a* values of Gulf of Lion, Ligurian Sea and North Adriatic Sea are highlighted in the figure.

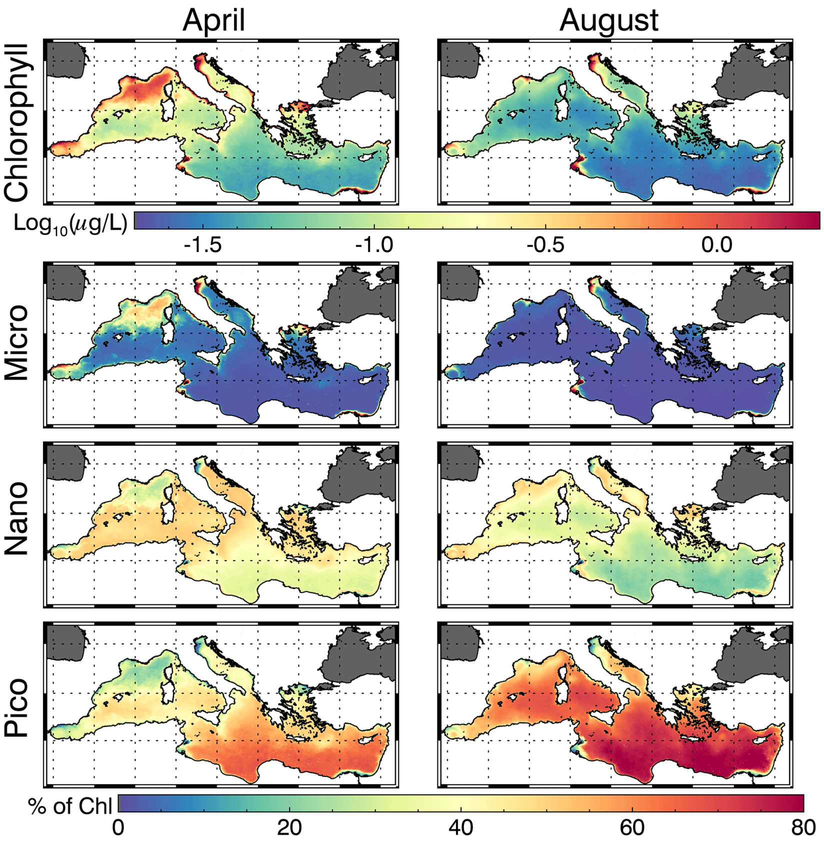

Figure 3. Seasonal spring to summer excursion in the Mediterranean Sea of chlorophyll *a* and PSCs. On the left panel, the April climatology (1998–2010) maps of TChl *a* ($\mu g\,L^{-1}$) and PSCs (%). On the right panel, the August climatology (1998–2010) maps of TChl *a* ($\mu g\,L^{-1}$) and PSCs (%).

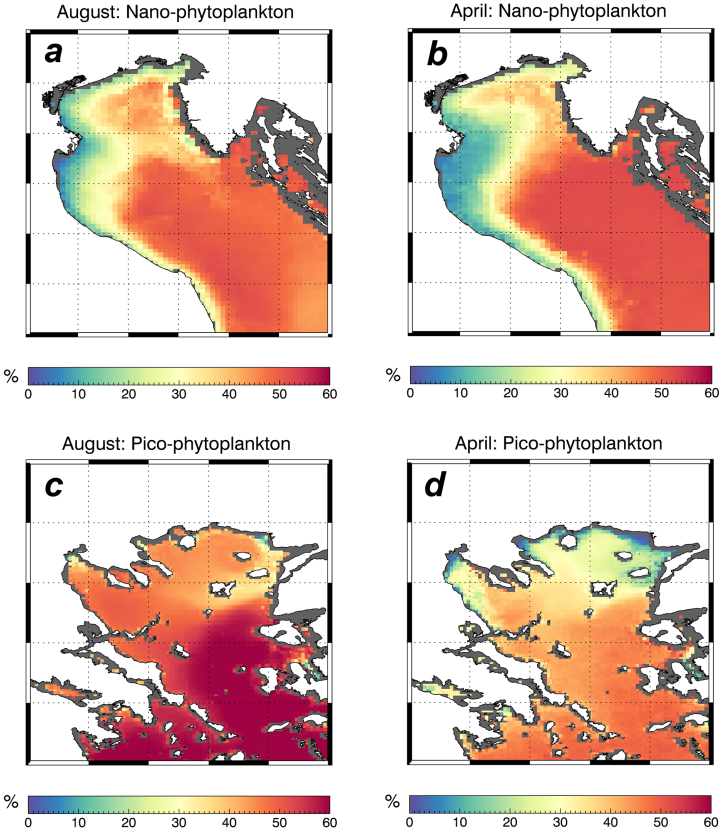

Figure 4. Seasonal spring to summer excursion of nano- and pico-phytoplankton fraction (%) on TChl *a* in two sectors. Nano percentages (%) in the North Adriatic Sea for August **(a)** and April **(b)** climatology (1998–2010). Pico percentages (%) in the Aegean Sea for August **(c)** and April **(d)** climatology (1998–2010).

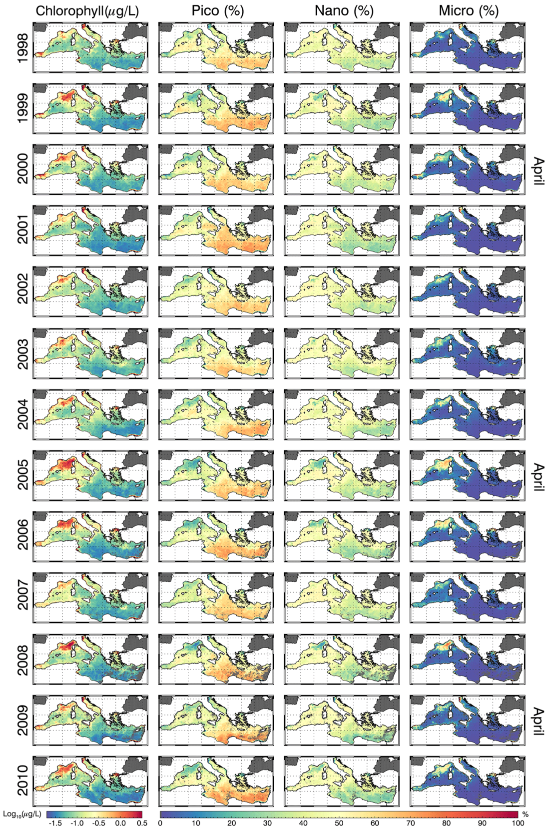

Figure 5. Maps of inter-annual variability (1998–2010) of chlorophyll *a* and PSCs over the entire basin for April. The first panel refers to TChl *a* ($\mu g\, L^{-1}$), the second to Pico fraction on TChl *a* (%), the third and the fourth respectively referred to Nano and Micro fraction (%).

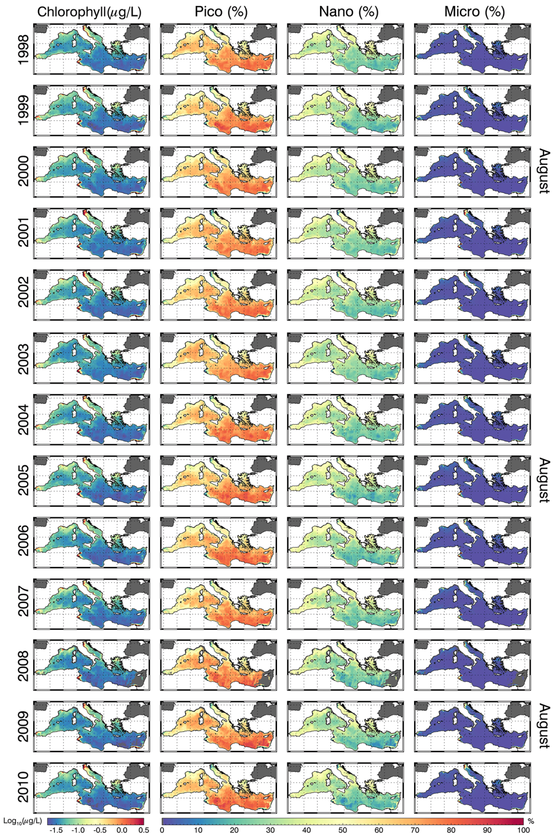

Figure 6. Maps of inter-annual variability (1998–2010) of chlorophyll *a* and PSCs over the entire basin for August. From the left to right, the first panel refers to TChl *a* (µg L^{-1}), the second refers to Pico fraction on TChl *a* (%), the third and the fourth respectively referred to Nano and Micro fraction (%).

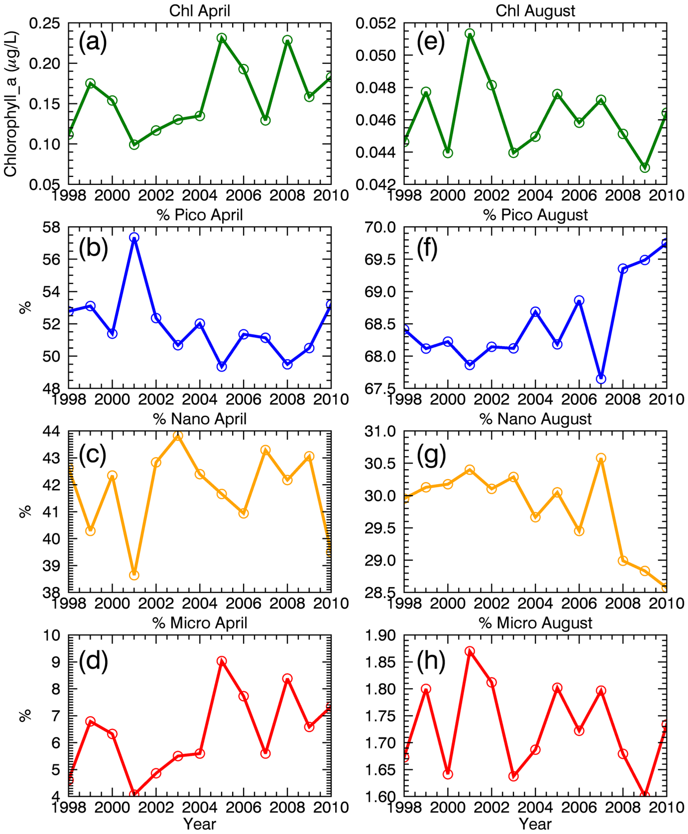

Figure 7. Inter-annual monthly mean chlorophyll *a* ($\mu g\,L^{-1}$) and PSCs (%) time series over the Mediterranean Sea for SeaWiFS Era (1998–2010) **(a–h)**. (April on the left panel and August on the right panel).

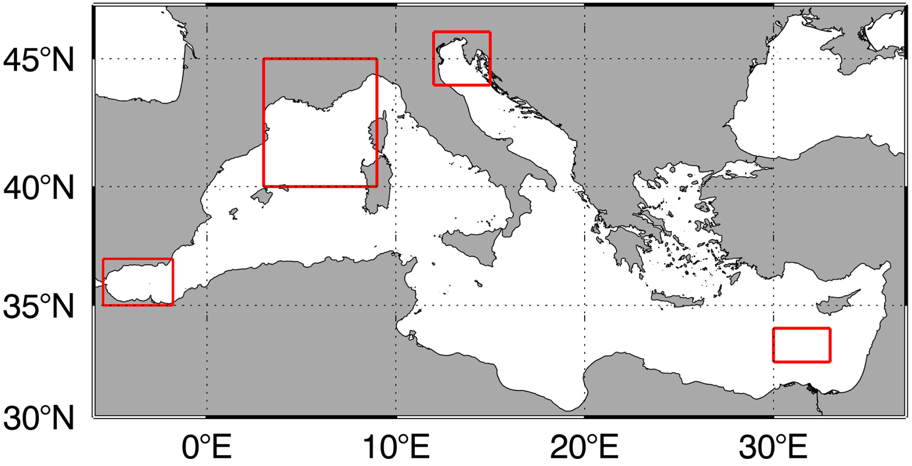

Figure 8. Maps of the four sectors used to analyze the temporal PSCs variability at local scale: ALB (Alborán Sea), NWMed (north Western Mediterranean Sea), NADR (North Adriatic Sea), LEV (Levantine Sea).

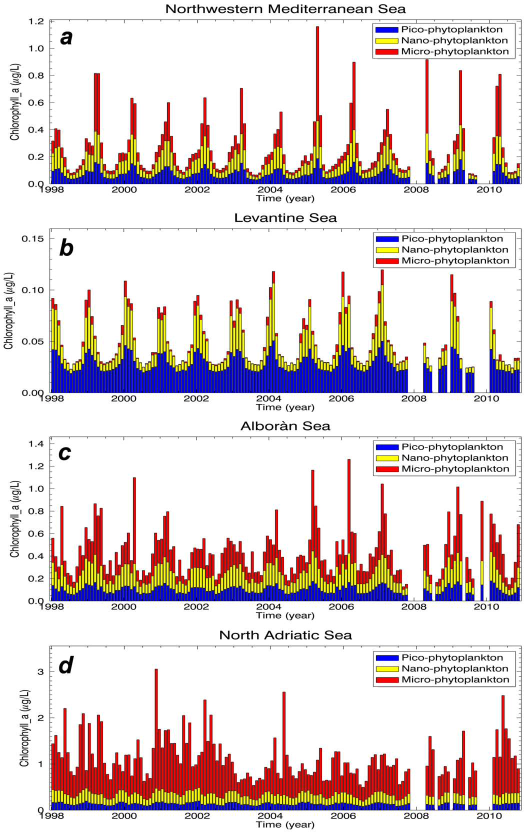

Figure 9. Inter-annual variability of the contribution of micro-, nano- and pico-phytoplankton to the TChl *a* ($\mu g\,L^{-1}$) from 1998 to 2010 in the four sectors: North Western Mediterranean Sea **(a)**, Levantine Sea **(b)**, Alborán Sea **(c)**, North Adriatic Sea **(d)**.