Satellite observations of bio-optical indicators related to dinoflagellates blooms in selected Mediterranean coastal regions

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ABSTRACT: Satellite data were used to assess phytoplankton dynamics in the Mediterranean Sea, in relation to blooming episodes of *Alexandrium*, the dinoflagellates *genus* which causes most (harmful) algal blooms in the basin. A comparison of *in situ* data, collected on the coast of Catalonia, Sardinia and Sicily in 2002-2003, with images recorded by the SeaWiFS– albeit hampered by space/time resolution too poor to discern small features in harbours, bays or beach areas, and by other limitations – suggests that the recurrence of *Alexandrium* is linked to local (near-coastal) factors, and only occasionally to larger mesoscale features typical of open waters. Examples are provided of the frequent decoupling between inshore and offshore blooming regimes, even in those cases when they seem to co-vary (*e.g.* considering inter-annual variability). Correspondences between imaged patterns and *Alexandrium* outbursts are seen to occur episodically, implying that the processes shaping the local (harmful) algal blooms and the regional blooms are different, or overlap only marginally. Thus, local measurements cannot be taken as representative of "larger scale" phenomena, while the satellite data might be useful to place local events into a regional contest, but not to explore the dynamics of "smaller scale" phenomena, which require direct *in situ* monitoring.

1 INTRODUCTION

Anomalous algal blooming, related to changes of the ecological balance in coastal and marine environments – as well as a growing incidence of Harmful Algal Blooms (HAB) in unusual areas, like the Mediterranean Sea – is becoming an increasing environmental concern. Novel data on this topic can be obtained by means of advanced tools such as RS (RS) from Earth orbit, supporting *in situ* observations of phytoplankton dynamics with measurements performed at large scales (*i.e.* from a few km to thousands of km) and over long periods (*i.e.* from days to years). In particular, optical RS allows basin-wide, multi-annual monitoring of algal bloom indicators, such as the concentration of chlorophyll-like pigments (*chl*). Significant uncertainties can arise in the computation of *chl* absolute values, especially in near-coastal areas, due to the complexity of separating the contributions to the spectrum of visible light emerging from the sea surface due to different water constituents, and to the limitations in space/time resolution of orbital sensors. Nevertheless, the analysis of historical times of satellite data can provide at least qualitative information on recurrent or anomalous algal blooms, and related environmental boundary conditions.

In the present case, data collected by the Sea-viewing Wide Field-of-View Sensor (SeaWiFS), which started its mission in September 1997 and is still operating at present, were used to explore the large-scale phytoplankton field of the (western) Mediterranean Sea, in correspondence to blooming episodes of *Alexandrium*, the dinoflagellate *genus* which causes most Harmful Algal Blooms

(HABs) in the basin. Various species of *Alexandrium*, such as *A. minutum* Halim, *A. catenella* (Whedon & Kofoid) Balech and *A. taylori* Balech, have been recorded in the western Mediterranean basin, where blooming takes place primarily in near-coastal areas. In particular, blooms have been recurring in several sites along the Catalan coast (i, ii), as well as selected sites on the coast of the Sardinia (iii) and Sicily (iv, v), in the late 1990s and early 2000s. Interestingly, the appearance and recurrence of such *Alexandrium* blooms in the Mediterranean Sea seems to correspond to a general decreasing trend of the *chl* indicator, estimated on the order of 10% of the annual mean value for the entire basin, in the period of SeaWiFS coverage (vi).

Although a significant body of information exists on recurring *Alexandrium* blooms at local scales, in some cases (vii) it is difficult to demonstrate whether such blooms start in confined waters, or stem from episodes occurring in open waters, just on the basis of *in situ* studies. Furthermore, if a bloom starts in confined waters, it is not clear whether, and under which circumstances, it can then be exported to open waters. The main objective of this study was to determine if there is any (qualitative) relationship between inshore HABs – of target *Alexandrium* species – and large-scale, long-term offshore phytoplankton blooms, observed in satellite imagery. Hence, the time series of SeaWiFS image data collected by the ECOMAR Activity (vi) was used to monitor phytoplankton dynamics at the regional scale, for a multi-annual period (1998-2003). A comparison of these satellite data and *in situ* data from the Catalonia, Sardinia and Sicily shorelines was conducted for the last two years of the available period (2002-2003), when extensive data on *Alexandrium* blooming were collected at the coastal sites of interest by the STRATEGY Project (viii).

In the following, after a brief description of the satellite and in situ measurements adopted, a joint analysis of the SeaWiFS and STRATEGY databases will be presented. The analysis will address the relationship between local (*Alexandrium*) and regional phytoplankton dynamics, exploring the possible links of coastal blooms to either local factors or the impact of offshore conditions.

2 METHODS

The satellite data record considered to examine the evolution of *chl* in the Mediterranean Sea, collected by the SeaWiFS from 1998 to 2003 and assembled by the ECOMAR Activity, comprises a time series of individual daily images, collected when favourable meteorological conditions occurred over (at least part of) the European continent and seas. In those cases when two images of the same area were collected by the sensor 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 of the available images was treated on a pixel-by-pixel basis, to correct top-of-the-atmosphere radiances from atmospheric contamination and then to compute the concentration of water constituents (including *chl*) from the obtained water-leaving radiances. In particular, the data were processed using the SeaDAS algorithm set (ix), with additional modifications described in (x, xi).

Individual *chl* images covering the Mediterranean area were re-mapped on a common equal-area (Alber's) projection grid, degrading the original nominal resolution (at nadir) of 1.2 km to a pixel resolution of 2 km. Sections at image edges, where the original resolution exceeded 2 km, were excluded from the re-mapping. Composite fields, at the monthly and yearly scales, were derived from the re-mapped images by means of simple weighted averaging techniques, for the entire 1998-2003 period. Climatologies at the monthly and yearly intervals were computed using the composite images of the available period. Moreover, a*d hoc* time series of (*quasi*) cloud-free images were selected for the Catalan Coast (90 images in 2002, and 96 in 2003) and the Islands of Sardinia (93 images in 2002, and 91 in 2003) and of Sicily (95 images in both 2002 and 2003).

As mentioned above, if the evaluation of *chl* absolute values in open waters can be accomplished with considerable accuracy, several limitations hamper the potential usefulness of optical RS for the assessment of near-coastal blooms. Uncertainties can arise in the computation of *chl* absolute values and statistics, owing to the presence in coastal waters of different optically active materials (*i.e.* dissolved organic matter and suspended inorganic particles) other than phytoplankton and related pigments, with partially overlapping spectral signatures. Furthermore, It must be recalled that remote sensors working in the visible spectral range measure the amount of electromagnetic radiation coming from the ground footprint of each picture element (pixel) – amount from which *chl* and other surface parameters are later derived – as an integrated value over a three-dimensional water element having dimensions given by the sensor spatial resolution (about 1.2 km × 1.2 km at nadir, for SeaWiFS) and the 1st optical depth (which in turns depends on the presence, nature and concentration of water constituents). On one hand, the pixel-integrated *chl* value is hardly comparable with the corresponding punctual measurement performed *in situ*. On the other, the same pixel-integrated value may have been computed with a spatial resolution (in the present case reduced to a constant 2 km, across each scan line, after re-mapping) too poor to distinguish individual near-coastal blooms, which can occur at scales well below the nominal pixel size. Even if a relatively highly reflective target, such as a sub-pixel bloom, could be bright enough to affect the spectral signature of a whole pixel, it should be also considered that, in general, the first pixel adjacent to the coast is composed by a mixed signal, coming from both the water side and the land side of the coastal interface, and this prevents the assessment of accurate *chl* values for that very pixel. In some cases, the impact of coastal reflectivity, the so-called adjacency effect, can actually extend to several pixels, altering the accuracy of the retrieved signal for a considerable distance from the coast in the offshore direction. Moreover, for inshore shallow waters, direct reflection from the bottom, above the 1st optical depth, would alter the signal measured by the remote sensor, so as to overestimate the real amount of phytoplankton in the water column. Conversely, in offshore deep waters, the possible presence of a deep chlorophyll maximum, below the 1st optical depth, would lead to an underestimate of the amount of phytoplankton in the water column. All these limitations suggest that the information on coastal blooms, obtainable from optical observations, should be restricted to spatial and temporal patterns and gradients, rather than absolute values, a fact that was kept in due account, when carrying out the present analysis of SeaWiFS imagery.

As for the *in situ* data record, a number of stations were examined by the STRATEGY Project in 2002-2003 – along the Catalan coast of Spain, the coast of Sardinia and both the Ionian and Tyrrhenian coasts of Sicily – to establish the distribution of 3 target *Alexandrium* species (*A. minutum, A. catenella* and *A. taylori)* in each area. The sampling areas are shown in Figure 1, overlaying the mean *chl* concentration derived from SeaWiFS data for the 1998-2003 period. Given that blooms of *Alexandrium* in the Mediterranean Sea are observed in two main types of coastal environment, *i.e.* harbours and bays *(A. minutum, A. catenella)* and beach areas *(A. taylori)*, the

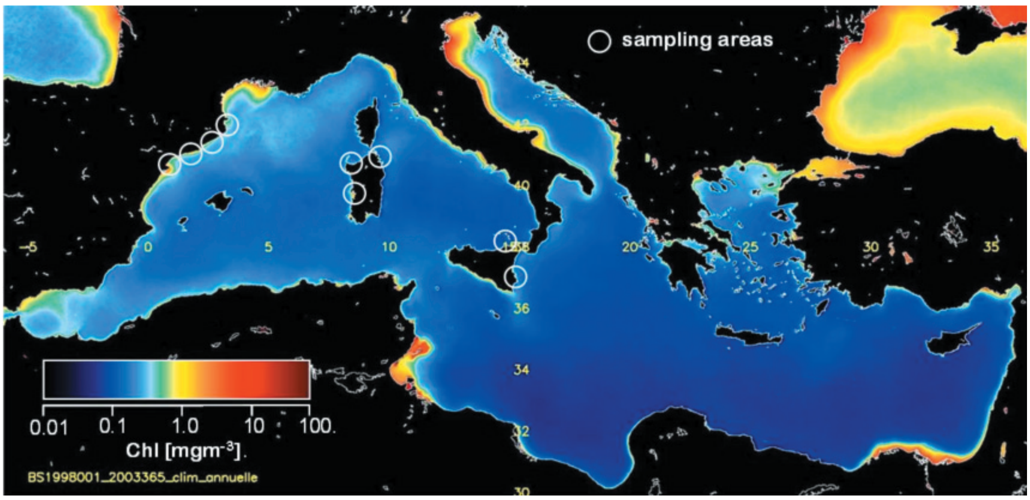

Figure 1. SeaWiFS-derived *chl* climatological mean (1998-2003) in the Mediterranean basin. Colour coding: *chl* in [mg m^{-3}] over water areas, landmask in black. Latitude and longitude markings appear as yellow numbers. The white circles identify the STRATEGY Project sampling areas.

stations selected for sampling included both kinds of systems. In order to understand the results described later, it should be pointed out that the field sampling points were selected as representative of the potential worse environmental situation, in the most confined areas, and not as representative of the general characteristics in a given area. Temperature and salinity were measured *in situ* and water samples were collected at the surface for nutrients, phytoplankton and chlorophyll-*a* analyses. The samples were Lugol's fixed, settled and counted in an epifluorescence inverted microscope. Cells were stained with calcofluor and identified following Balech 1995. A detailed description of methods is given in papers enumerated above for the 3 areas studied. In Catalonia, sampling in harbours was carried out on 2 to 4 occasions per month, from March to September, and once or twice a month for the rest of the year. Catalan beaches were sampled once a week in summer. A similar sampling frequency was used to monitor coastal areas of Sardinia and Sicily.

3 RESULTS

In the SeaWiFS-derived climatological mean (Figure 1), the *chl* values appear to be one order of magnitude higher in the north-western part of the basin with respect to the south-eastern part. The imagery composing this mean shows that most of the high *chl* events observed offshore, in the (western) basin, are shaped by interacting mesoscale structures such as pelagic eddies and meanders. The observable inshore events, at least in the sampling areas considered here, appear to co-vary with the offshore patterns, but to develop primarily as independent features along the innermost coastal area. When these near-coastal features do interact with the larger basin-wide patterns, they seem to do so extending from to coast seawards, and not to develop under the impact of phenomena taking place in open waters.

Examples of the decoupling between inshore and offshore regimes, even in those cases when they seem to co-vary, are provided by the monthly mean images of the north-western Mediterranean basin, for February, March and April 2002 and 2003, shown in Figure 2. In both years, a massive

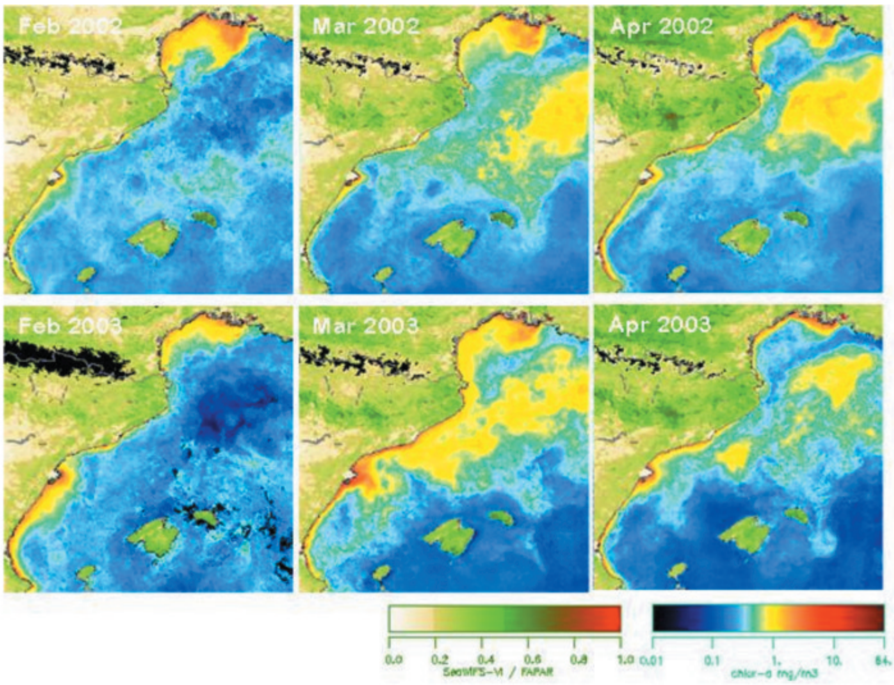

Figure 2. SeaWiFS-derived monthly mean *chl* in the north-western Mediterranean basin, for February (left), March (center) and April (right) of 2002 (upper row) and 2003 (lower row). Colour coding: *chl* in [mg m^{-3}] over water areas, dimensionless vegetation index (Fraction of Absorbed Photosynthetically Active Radiation, FAPAR) over land areas; missing data in black.

spring bloom is seen to develop off the Gulf of Lions, where the deep convection processes occurring in winter (note the patch of blue waters, the so-called "blue hole", in the February images) generate favourable conditions for blooming to occur (xii). When the offshore structures develop, they appear to be separated from the inshore ones by a tongue of blue waters, extending from the Liguro-Provençal basin into the Balearic basin, possibly corresponding to the southward-flowing "Northern Current" – *i.e.* the Ligurian, Liguro-Provençal and Catalan Currents system (xiii). Only the March 2003 image suggests an exception to such conditions along the Catalan coastline. However, even in this case, the series of daily images composing the monthly mean (see below) demonstrate that the apparent continuity is actually due to a number of coastal plumes meandering in the offshore direction, which are merged together by the monthly compositing procedure.

The variety of surface features appearing along the Catalan coast, in the daily images for 2002 and 2003, can be observed in the series of Figures 3 and 4. These Figures comprise a selection of

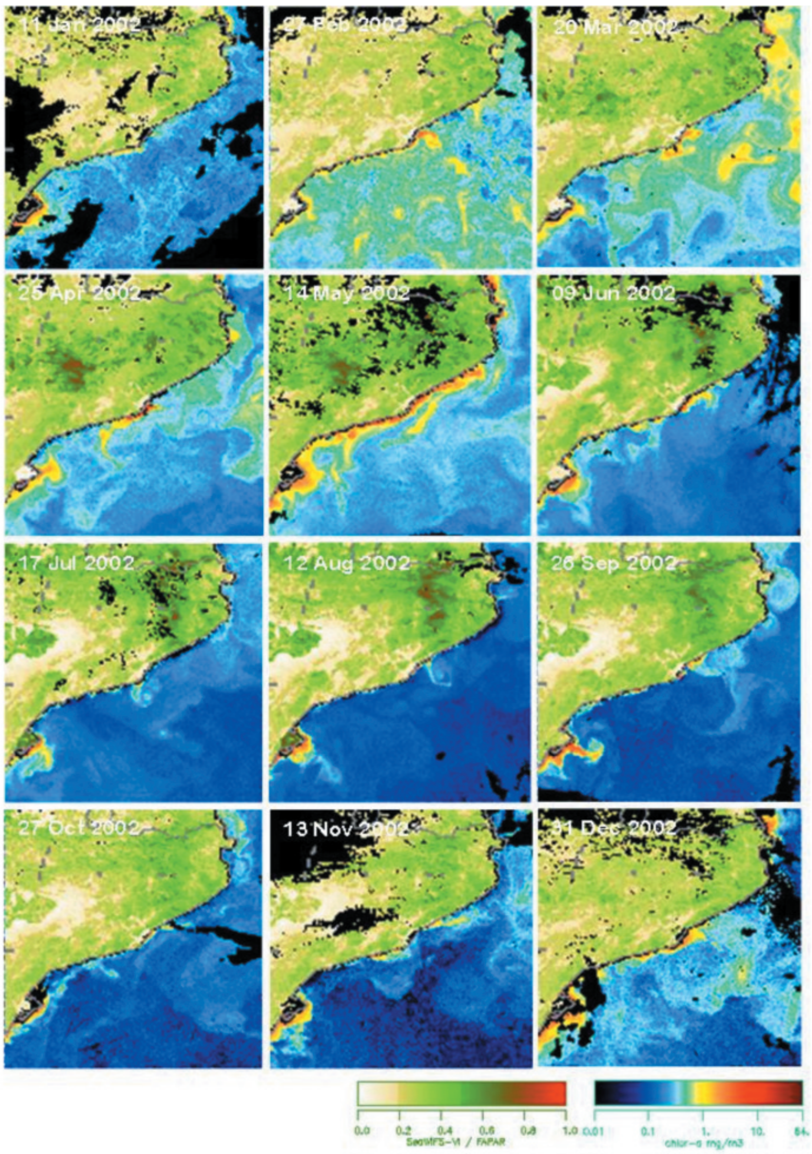

Figure 3. SeaWiFS-derived *chl* off the Catalan coast, daily images representing the 12 months of 2002. Colour coding: *chl* in [mg m^{-3}] over water areas, dimensionless vegetation index (Fraction of Absorbed Photosynthetically Active Radiation, FAPAR) over land areas; missing data in black.

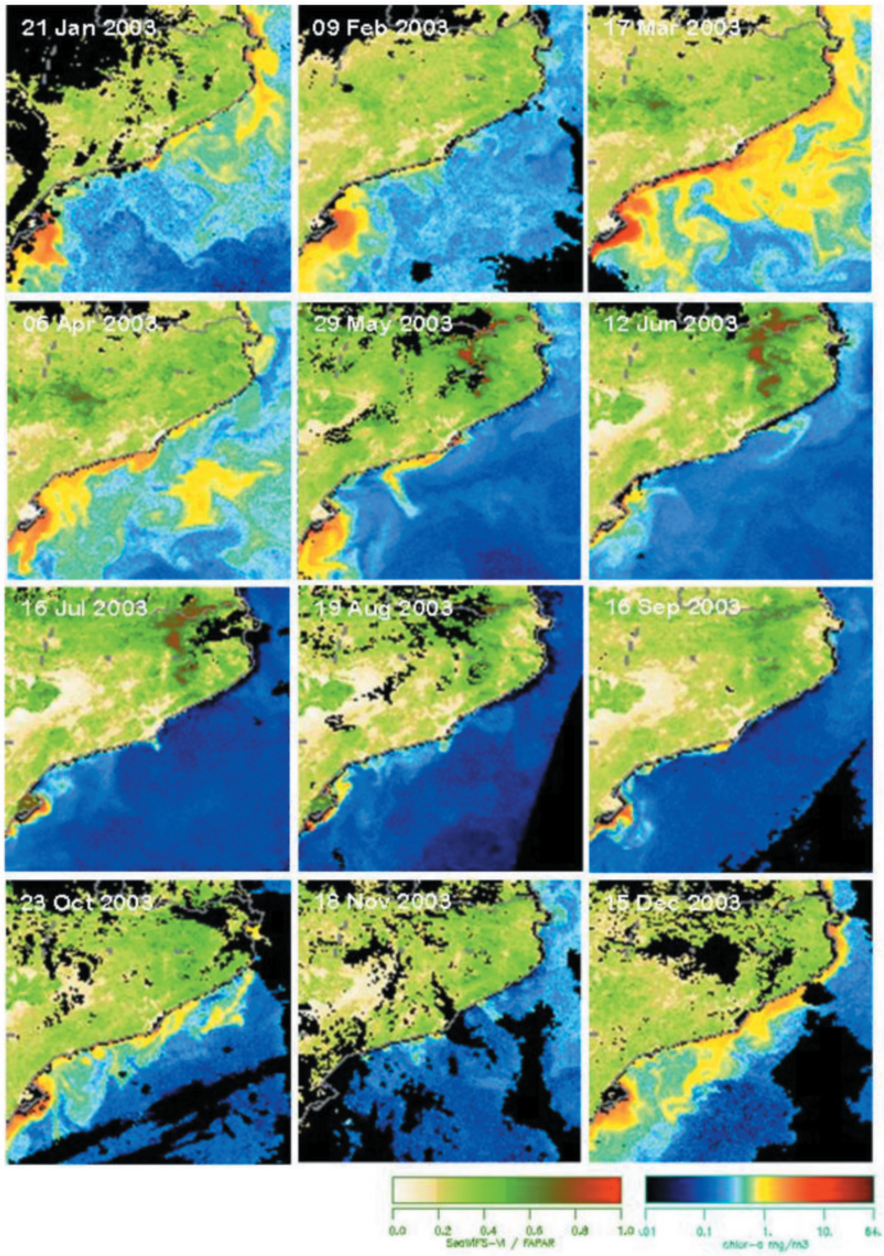

Figure 4. SeaWiFS-derived *chl* off the Catalan coast, daily images representing the 12 months of 2003. Colour coding: *chl* in [mg m^{-3}] over water areas, dimensionless vegetation index (Fraction of Absorbed Photosynthetically Active Radiation, FAPAR) over land areas; missing data in black.

daily images chosen to represent the 12 months of both years. The *chl* values of the coastal patterns, colour-coded to indicate the computed concentrations, can be compared with the total chlorophyll-a measured at various stations along the same stretch of shoreline, as shown in Figure 5. Although some of the high *chl* events seen in the imagery do correspond, repeatedly in some cases, with the *in situ* chlorophyll-a relative maxima (*e.g.* in Arenys, Villanova, Tarragona), in both years the general trend of the two data records does not present any consistent agreement. To the contrary, while the imagery appears to indicate a systematic *chl* maximum in late winter and early spring, followed by *chl* minimum in summer, the field data are characterized by summer maxima at most coastal stations. A comparison with the *Alexandrium* blooming record, shown in Figure 6, point to

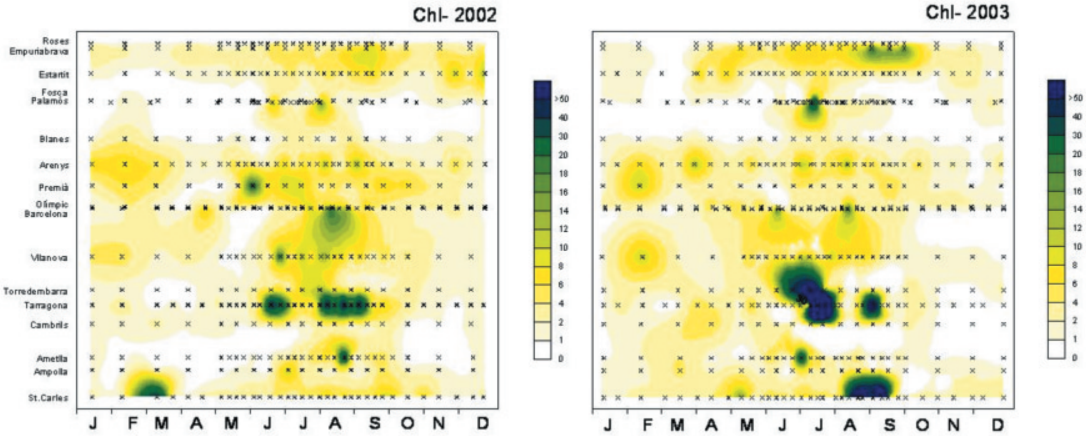

Figure 5. Total chlorophyll-a measured at coastal stations along the Catalan shoreline.

the fact that correspondences occur only episodically (*e.g.* Estartit in May 2002, or Tarragona in August 2003), while at other times opposite indications seem to come from the satellite and in situ data (*e.g.* Arenys in February 2002, or Barcelona and Vilanova in June 2003).

When considering interannual variability of the general blooming patterns, a striking coherence emerges from the satellite and *in situ* data records, as suggested by the images and stations of Sardinia. Figure 7 shows the monthly mean images for March 2002 and 2003, as well as some representative daily images selected among those used to compute the means. In both monthly mean images, higher *chl* values can be found east of the Strait of Bonifacio. This is possibly related to the vertical mixing, and consequent enrichment of surface water with nutrients from deeper layers, induced by the funnelling effect of the Corsica and Sardinia orography on north-westerly winds, and due to the ensuing dipole eddies created in the western Tyrrhenian basin. In the 2002 mean image, this feature is separated from the near-coastal regime of lower *chl* values, extending along the eastern coast of Sardinia, while the western coast presents somewhat higher *chl* values. Conversely, in the 2003 mean image, the same feature is connected to a pattern of convoluted structures, traced by higher *chl* values, extending southward along the eastern coast of Sardinia, while the western coast presents much lower values.

The total chlorophyll-*a* measurements (Figure 8), performed in the same two months at Oristano, on the west coast, Porto Torres on the north coast and Olbia, on the east coast, offshore and inshore (3 km from the coastline and inside the corresponding harbours), show corresponding gradients in good agreement both for trends and absolute values. On the other hand, the remote sensor did not record the *maxima* occasionally reached by *Alexandrium* species in the Gulf of Olbia, in May/June 2002 and April/May 2003 – associated to Paralytic Shellfish Poisoning (PSP) toxicity in mussels – possibly because these never reached typical "blooms" densities (*i.e.* $>50 \times 10^3$ cells l^{-1}).

Finally, the 2003 series of daily images, selected as the most representative for Sicily (Figure 9), shows a general agreement between satellite and *in situ* observations, at least in terms of general blooming areas and *in situ* hot spots with high *chl*. This is the case of the eastern (Ionian) coastline, where the highest *chl* values indicated by the imagery appear to be located in the Syracuse area and neighbouring waters, consistently with the chlorophyll-*a maxima* of the *in situ* measurements. In this area, a good correspondence can be observed in the spring record of the innermost coastal sites, as demonstrated by the *chl maximum* reached in April and the March/April bloom of *A. minutum* detected *in situ* (v). In contrast, with the exception of some small features appearing in late winter, no significant high *chl* events were evidenced by the satellite along the northern (Tyrrhenian) coastline and the Aeolian Islands area, where localized events of water discoloration due to *A. taylori* outbreaks were monitored in summer, as in previous years, on Vulcano Island (xiv).

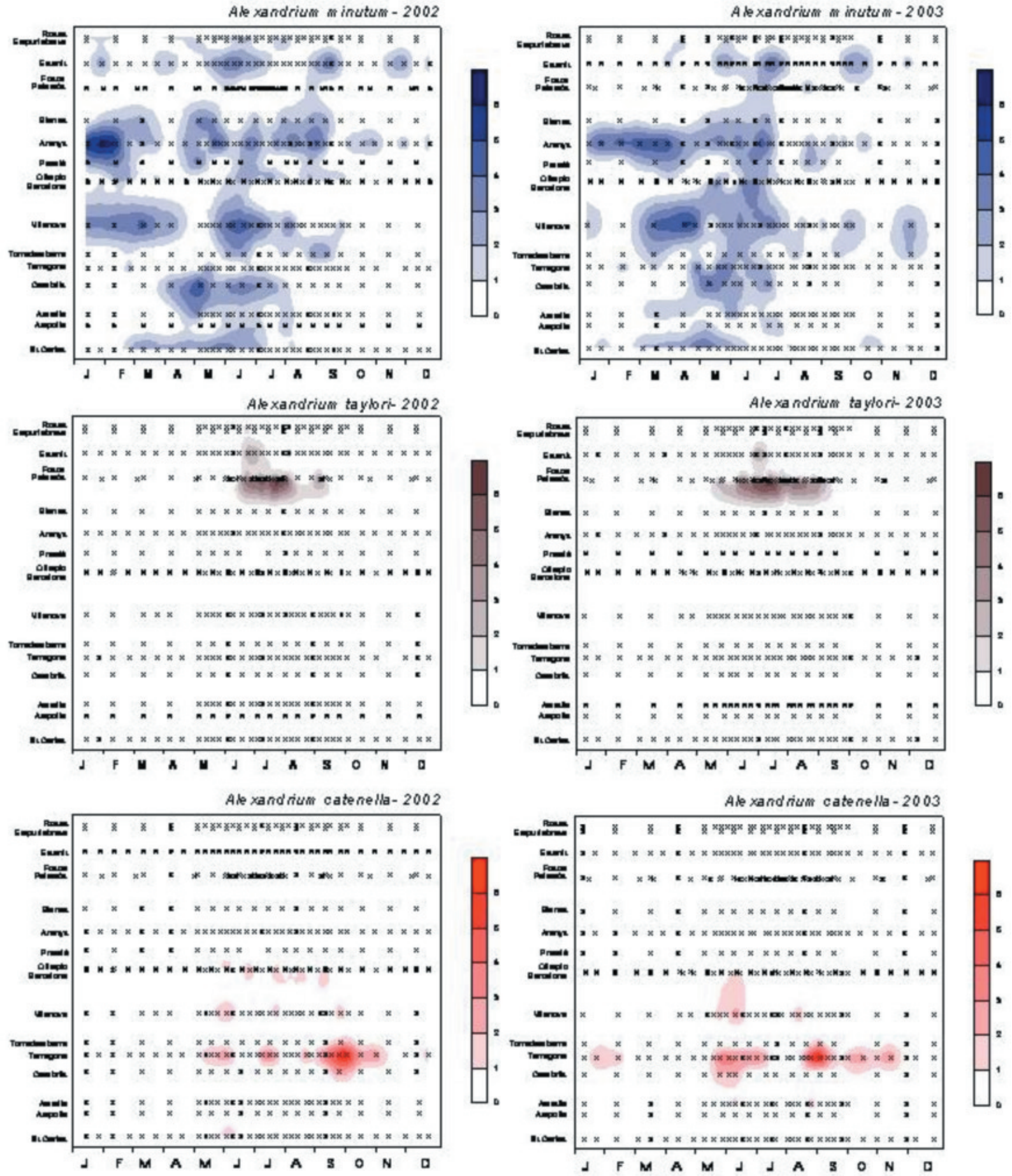

Figure 6. Alexandrium blooming record at coastal stations along the Catalan shoreline.

4 CONCLUSIONS

A comparison of satellite and *in situ* data was carried out to explore the phytoplankton field characteristics in a series of known hot spots for *Alexandrium* blooming, located along the Spanish and Italian coastlines (Catalonia, Sardinia and Sicily). The investigation considered blooms ranging from those of noxious species (*e.g. A. taylori*) that generate elevated biomasses, causing a deterioration of coastal water quality along popular beaches, to those of toxic species (*e.g. A. minutum and A. catenella*), that exhibited a rapid geographical spread during the past decade, mostly in harbours and shellfish farms, causing repeated sanitary alarms and substantial economic losses. In most cases, recurrent blooms have been described as localised phenomena, linked to increased nutrient availability and low water renewal, due to human presence/impact on site (*e.g.* crowded beaches or

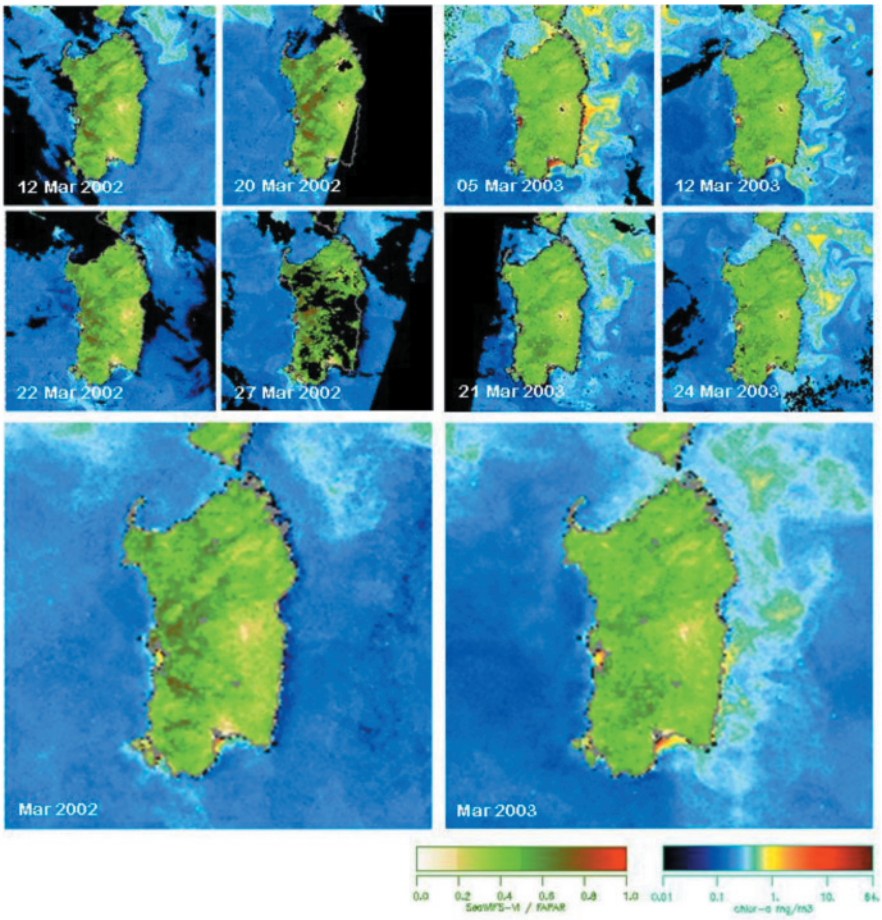

Figure 7. SeaWiFS-derived chl daily values (smaller images) and monthly means (larger Images) around Sardinia, for March 2002 (left) and March 2003 (right). Colour coding: *chl* in [mg m^{-3}] over water areas, dimensionless vegetation index (Fraction of Absorbed Photosynthetically Active Radiation, FAPAR) over land areas; missing data in black.

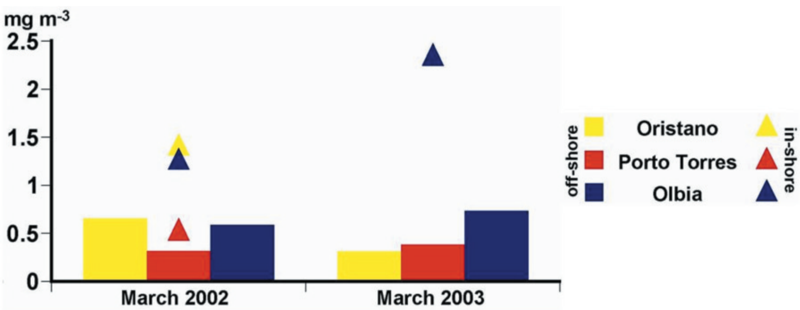

Figure 8. Total chlorophyll-a measured in March 2002 and March 200 at Sardinia coastal stations (Oristano, OR, Porto Torres, PT, and Olbia, OL) in offshore and inshore waters.

marinas), as well as to specific geographical and meteorological conditions (*e.g.* enclosed bays during summer, when hydrodynamic forcing is low).

The analysis of quasi-concurrent satellite images also indicates that this blooming might be linked to near-coastal factors, and only occasionally coincidental with the impact of mesoscale dynamical features such as offshore eddies or meanders. Hence, the present work suggests that, in the period considered, most *Alexandrium* blooms are local phenomena, with little or no connection

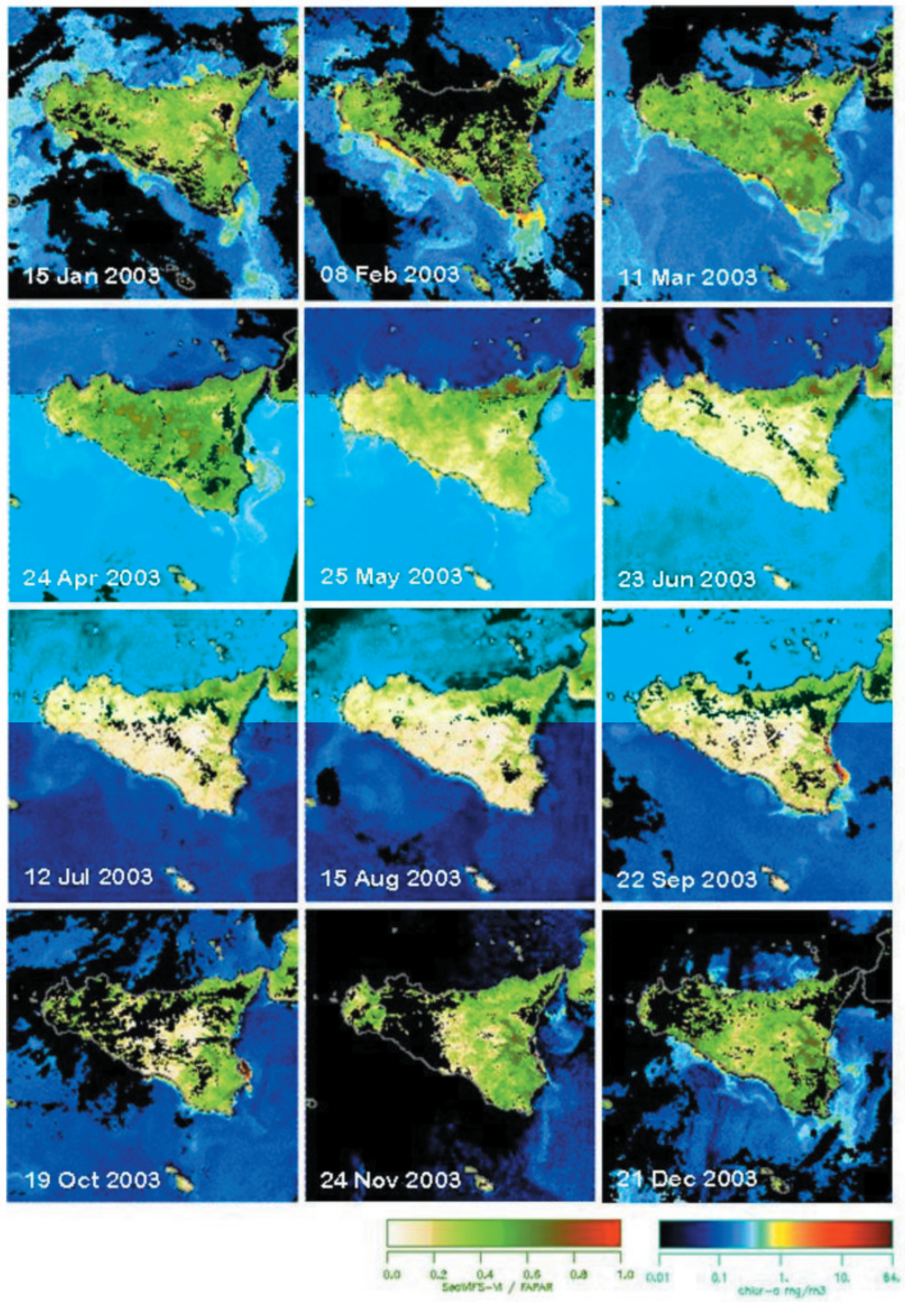

Figure 9. SeaWiFS-derived *chl* around Sicily, daily images representing the 12 months of 2003. Colour coding: *chl* in [mg m^{-3}] over water areas, dimensionless vegetation index (Fraction of Absorbed Photosynthetically Active Radiation, FAPAR) over land areas; missing data in black.

to regional events (except perhaps for the 2003 late-winter, early-spring bloom in the whole north-western Mediterranean). The isolated blooms detected at coastal stations in late-winter and early-spring coincide only occasionally with the regional type of blooming seen in the imagery. Later on in the year, in offshore waters – when thermal stratification develops and the surface layer may become nutrient depleted, with possible development of a deep chlorophyll maximum – these regional blooms fade away. On the contrary, the stabilization of inshore waters – where nutrient concentration may be quite constant, for the entire annual cycle, in fact – continues to favor the development of dinoflagellate blooms (xv). Thus, in summer, many coastal blooms can occur, but not necessarily at scales accessible to the kind of satellite observations available here.

The impression emerging from the present attempt to reconcile satellite and *in situ* assessments of algal blooms, due to the very different nature of the measurements in each case, is that of comparing phenomena occurring at uncorrelated space and time scales. The *in situ* data describe phenomena at much smaller scales and in shorter times than those appearing in the satellite data, which perform integrated measurements over larger areas and longer periods. Consequently, there appears to be hardly any correlation between the blooming periods/areas seen in the satellite data and *in situ* data. This would be an interesting preliminary result: it would essentially mean that the processes – the forcing functions – shaping the local (harmful) algal blooms and the regional blooms are different, or overlap only marginally. What matters locally seems to hardly have any effect at scales even slightly bigger (hence environmental impact, environmental sampling networks to monitor that impact, as well as remedies to that impact, can and must be addressed at the local level). Furthermore, large-scale phenomena, which matter at the basin level, may have a widespread impact, but can be easily overwhelmed, locally, by much-smaller-scale processes.

In other words, the lack of correlation between satellite and *in situ* data is due to the patchiness of the "local" measurements (say at scales between 1 and 100 m, in any case well below the 1000 m order of magnitude for picture elements in satellite observations), which is simply not seen from space. In addition, since "regional" measurements also present a certain degree of patchiness (say at scales between 1 and 100 km, this time), we might have to conclude, ultimately, that this is the result of different forcing functions, acting at different space/time scales. Thus, local measurements cannot be taken as representative of "larger scale" phenomena, while the satellite data might be useful to place local events into a regional contest, but not to explore the dynamics of "smaller scale" phenomena, which require direct, *in situ* monitoring.

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