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Using remote sensing as a support to the implementation of the European Marine Strategy Framework Directive in SW Portugal

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ABSTRACT

The exclusive economic zones (EEZ) of coastal countries are coming under increasing pressure from various economic sectors such as fishing, aquaculture, shipping and energy production. In Europe, there is a policy to expand the maritime economic sector without damaging the environment by ensuring that these activities comply with legally binding Directives, such as the Marine Strategy Framework Directive (MSFD). However, monitoring an extensive maritime area is a logistical and economic challenge. Remote sensing is considered one of the most cost effective methods for providing the spatial and temporal environmental data that will be necessary for the effective implementation of the MSFD. However, there is still a concern about the uncertainties associated with remote sensed products. This study has tested how a specific satellite product can contribute to the monitoring of a MSFD Descriptor for "good environmental status" (GES). The results show that the quality of the remote sensing product Algal Pigment Index 1 (API 1) from the MEdium Resolution Imaging Spectrometer (MERIS) sensor of the European Space Agency for ocean colour products can be effectively validated with *in situ* data from three stations off the SW Iberian Peninsula. The validation results show good agreement between the MERIS API 1 and the *in situ* data for the two more offshore stations, with a higher coefficient of determination (R^2) of 0.79, and with lower uncertainties for the average relative percentage difference (RPD) of 24.6% and 27.9% and a root mean square error (RMSE) of 0.40 and 0.38 for Stations B and C, respectively. Near to the coast, Station A has the lowest R^2 of 0.63 and the highest uncertainties with an RPD of 112.9% and a RMSE of 1.00. It is also the station most affected by adjacency effects from the land: when the Improved Contrast between Ocean and Land processor (ICOL) is applied the R^2 increases to 0.77 and there is a 30% reduction in the uncertainties estimated by RPD. The MERIS API 1 product decreases from inshore to offshore, with higher values occurring mainly between early spring and the end of the summer, and with lower values during winter. By using the satellite images for API 1, it is possible to detect and track the development of algal blooms in coastal and marine waters, demonstrating the usefulness of remote sensing for supporting the implementation of the MSFD with respect to Descriptor 5: Eutrophication. It is probable that remote sensing will also prove to be useful for monitoring other Descriptors of the MSFD.

1. Introduction

Maritime and coastal activities are expanding rapidly in the world increasing the pressures on the marine and coastal ecosystems (Bertram et al., 2014; Bertram and Rehdanz, 2013). Economic sectors such as fishing, aquaculture, maritime transport, energy production of oil and gas, intensive agriculture together with high population density in the coastal areas are the major economic drivers (Bellas, 2014; O´Higgins and Gilbert, 2014). In recent years, these economic activities provide a number of goods and services that are used directly or indirectly by humans. The sectoral drivers increase the competing usages and pressures on the marine and coastal ecosystems (Borja et al., 2013; Bertram and Rehdanz, 2013).

The objective of the EU Marine Strategy Framework Directive

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Table 1
(a) The qualitative descriptors for determining good environmental status for the Marine Strategy Framework Directive (MSFD). The descriptors highlighted in grey could potentially be monitored by remote sensing. (b) List of the indicators for the Descriptor 5: Eutrophication. The indicators highlighted in grey could potentially be monitored by remote sensing and in bold are the indicators that are assessed in this paper.

MSFD Descriptors
Descriptor 1: Biological diversity
Descriptor 2: Non-indigenous species
Descriptor 3: Commercial fish
Descriptor 4: Foof webs
Descriptor 5: Eutrophication
Descriptor 6: Sea-floor integrity
Descriptor 7: Hydrographical conditions
Descriptor 8: Contaminants and pollution effects
Descriptor 9: Contaminants in fish and other seafood
Descriptor 10: Marine litter
Descriptor 11: Underwater noise/energy

Descriptor	**Criteria**	**Indicator**
Descriptor 5: Eutrophication	5.1. Nutrients levels	5.1.1 Nutrients concentration in the water column
		5.1.2 Nutrient ratios
	5.2. Direct effects of nutrient enrichment	**5.2.1 Chlorophyll concentration in the water column**
		5.2.2 Water transparency related to increase in suspended algae, where relevant
		5.2.3 Abundance of opportunistic macroalgae
		5.2.4 Species shift in floristic composition such as diatom to flagellate ratio, benthic to pelagic shifts, as well as bloom events of nuisance/toxic algal blooms (*e.g.* cyanobacteria) caused by human activities
	5.3. Indirect effects of nutrient enrichment	5.3.1 Abundance of perennial seaweeds and seagrasses adversely impacted by decrease in water transparency
		5.3.2 Dissolved oxygen, *i.e.* changes due to increased organic matter decomposition and size of the area concerned

(MSFD) is to enable the sustainable use of marine goods and services and to ensure that the marine environment is safeguarded for the use of future generations (European Commission, 2008). The MSFD establishes a comprehensive structure within which Member States are required to develop and implement cost effective measures to protect and preserve the marine environment necessary to achieve or maintain "good environmental status" (GES) according to 11 key Descriptors by the year 2020 (European Commission, 2008). However, monitoring an extensive maritime area is a logistical and economic challenge, (European Commission, 2008), particularly, for a small country like Portugal with limited resources but, also, with an extensive exclusive economic zone (EEZ). Remote sensing offers the opportunity to assess a large amount of data with both a high spatial and temporal resolution (Pieralice et al., 2014). Table 1a shows which of the 11 Descriptors of the MSFD might be assessed from remote sensing data. For each Descriptor, there are series of Criteria and Indicators that enable assessment of GES. As these Criteria and Indicators are numerous, Table 1b lists only those for Descriptor 5: eutrophication. There is a range of earth observation satellites with different sensors (Johannessen et al., 2000) and it is necessary to identify which satellite products could contribute data to a MSFD Descriptor, by focusing on Indicator(s) for specific Criteria. For example, the key Descriptor 5: Eutrophication could be monitored by remote sensing of the "chlorophyll concentration in the water column" (Indicator 5.2.1) which responds to fluctuations in "nutrients level" (Criterion 5.1). Chlorophyll is considered a proxy for phytoplankton biomass (Boyce et al., 2010) and can be estimated by satellite sensors for ocean colour by measuring light coming from the sea and subsequently retrieving the chlorophyll concentrations with ocean colour algorithms (IOCCG et al., 2008).The objective of this paper is to test how a specific satellite product can contribute to the assessment of GES for a MSFD Descriptor.

The site selected for this demonstration is located off Sagres in SW Iberia (Fig. 1a and b) where there has been a project for the European Space Agency (ESA) to validate the ocean colour products of the MEdium Resolution Imaging Spectrometer (MERIS) located on the ENVISAT satellite with *in situ* measurements (Cristina et al., 2009, 2014; Goela et al., 2013, 2014). The product is Algal Pigment Index 1 (API 1) that corresponds to the total concentration of chlorophyll *a* and its degradation products, and should be useful for assessing Descriptor 5: Eutrophication. API 1 has been selected for this study as it is similar to the standard algorithms used in other satellite missions *e.g.* the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor aboard NASA's Aqua and Terra satellites. The OC4Me is the semi-analytical algorithm developed for MERIS for estimating the API 1 (Morel and Antoine, 2007). The algorithm includes four wavelengths at 443, 490, 510 and 560 nm providing three ratios of spectral reflectances that are used to construct the Maximum Band Ratio (MBR) for the OC4Me algorithm (Morel et al., 2007). Thus, API 1 data is more readily comparable between different ocean colour satellite missions than Algal Pigment Index 2 (API 2), where the latter is specific to the MERIS sensor and the algorithm includes the optical properties of phytoplankton pigments, total suspended matter and yellow substances (Doerffer and Schiller, 2007).

Earlier studies (Goela et al., 2013; Loureiro et al., 2005) in this region have suggested that these waters are essentially dominated by phytoplankton as there are no significant terrestrial inputs supplying suspended matter. Although the potential advantages of remote sensing data for monitoring GES are evident, uncertainties associated with this data have to be understood (Hooker and McClain, 2000). Thus, the validation or "sea truthing" of API 1 with *in situ* data is essential to understand and quantify the quality and accuracy of this data product, including verification of models and derived parameters (Bailey and Werdell, 2006; Cui et al., 2014; Mélin et al., 2007; Smith et al., 2013; Sørensen et al., 2007).

In summary, this paper presents how MERIS API 1 can be related to the chlorophyll concentration in the water column as an Indicator for the MSFD Descriptor 5, and how this application might be relevant to the other Descriptors of the MSFD.

1.1. Study area

In the context of the MSFD, the Sagres site is part the North-

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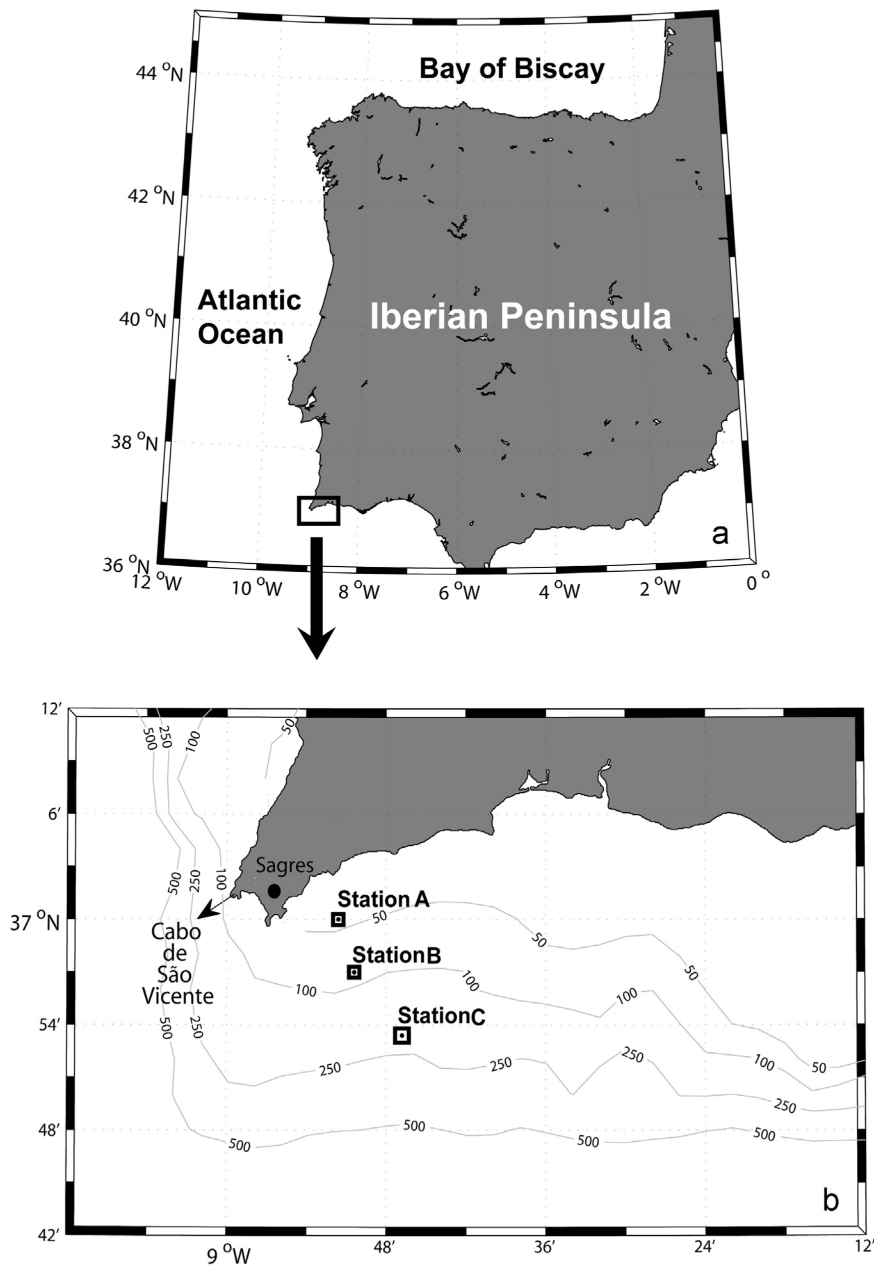

Fig. 1. Map of Iberian Peninsula (a) with the inset showing locations of Stations A, B and C off the coast of Sagres (b).

East Atlantic Ocean marine region and of the Bay of Biscay and Iberian Coast sub-region (European Commission, 2008). Sagres is also one of the intercalibration sites for the North-East Atlantic Ocean section of the Water Framework Directive (WFD) and is included in the Southwest Alentejo and Costa Vicentina Natural Park (Loureiro et al., 2008). The Sagres coast has a narrow continental shelf that descends rapidly to depths of over 1000 m at the continental slope. The *in situ* stations selected for validation measurements off Sagres are at 2, 10, and 18 km offshore and at respective depths of 40, 100, and 160 m along a north to south transect, perpendicular to the south coast of Sagres (Fig. 1b) (Cristina et al., 2014).

Sagres is close to Cabo São Vicente, at the intersection of the west and south coast of the Iberian Peninsula, and is dominated by the interaction of two weather regimes (Relvas and Barton, 2002). The first occurs during early spring to late summer, when the west coast is subject to northerly winds that promote upwelling events that in some cases flow counterclockwise around the Cabo de São Vicente, and flow eastwards along the southern coastal shelf, including the study site (Loureiro et al., 2005; Ramos et al., 2013; Relvas and Barton, 2002). The second regime occurs along the south coast and is characterised by the presence of a warmer and more saline coastal countercurrent over the continental shelf that develops whenever there is a relaxation of the wind that sustains upwelling (Cardeira et al., 2013; Relvas and Barton, 2002; 2005).

There are no permanent rivers in this area (Loureiro et al., 2011), and so upwelling events constitute the main source of nutrients in these coastal waters, a phenomenon known as natural eutrophication (Loureiro et al., 2008). The temporal variation of this phenomenon regulates the inputs of nutrient in these waters. The subsequent microalgal growth and resulting phytoplankton biomass sustain the production of the ecosystem (Loureiro et al., 2005). The upwelling events are dominated by fast growing diatoms, whereas small flagellate forms are more prominent during periods of relaxation (Goela et al., 2013, 2014; Loureiro et al., 2008).

2. Methods

In order to understand how the API 1 from the MERIS sensor was derived and compared with *in situ* data from Sagres, a short summary is provided in sections 2.1, 2.2, and 2.3 with a much more detailed description available in Cristina et al. (2014) and the references therein. MERIS was operational between March 2002 and April 2012. The sensor measured the solar radiation reflected by the earth, at a ground spatial resolution of 300 m, in 15 spectral bands, programmable in width and position, in the visible and near infra-red wavelengths (Rast et al., 1999).

2.1. Satellite data from MERIS

MERIS Level 2 Full Resolution (FR) and Reduced Resolution (RR) satellite images, with a spatial resolution of 290 m × 260 m and 1.2 km × 1.04 km, respectively, were used and analysed with the Basic ERS and ENVISAT (A) ATSR and MERIS Toolbox (BEAM version 4.9; www.brockmann-consult.de/cms/web/beam/). Based on the coordinates of the stations from each field campaign at Sagres, 3 × 3 macro pixels were extracted from the MERIS Level 2 products. The retrieval of level 2 data was evaluated with the standard MERIS processor (MEGS 8.1) as well as the Improved Contrast between Ocean and Land processor (ICOL, version 2.7.4) that was introduced to the MERIS processing chain to correct for errors arising from the adjacency effects from land (Santer and Schmechtig, 2000). The retrieval of level 2 data was evaluated against *in situ* data, both without and with ICOL. A matchup between satellite and *in situ* data was only accepted when: (i) *in situ* measurements coincided with the MERIS overpass; (ii) there were clear sky conditions; (iii) there were good sea conditions; and (iv) the satellite data was filtered for contamination (non-flagged) pixels (*e.g.* high glint, ice haze, high solar zenith, pcd_1_13 and pcd_15).

2.2. In situ measurements

Radiometric parameters and concentrations of optically active water constituents were estimated between September 2008 and March 2012. The measurements were consistent with the MERIS validation protocols (Doerffer, 2002; Barker, 2011). The measurements were timed to coincide with the MERIS overpass, within 30 min at Station A, and within 1.5 h at Station B and C. The clear skies and flexible access to boats at Sagres enabled approximately 300 matches between MERIS products and *in situ* data for the three stations, which corresponded to 26 days over the period of sampling. The radiometric measurements were made with a Tethered Attenuation Coefficient Chain Sensor (TACCS) manufactured by Satlantic and the results were presented in Cristina et al. (2009, 2014).

Coincident with the radiometric measurements, water samples were taken at each station with a Niskin bottle at three depths, (0 m, ½ Secchi depth, and 1 Secchi depth). The *in situ* variables measured at these three stations were the total concentration of chlorophyll a (TChl*a*) and its degradation products, the total suspended matter (TSM) and the absorption of yellow substance (YS). This paper will focus only on TChl*a*, which was determined by High Performance Liquid Chromatography (HPLC). The method and the analysis of this variable is explained in more detail in Goela et al. (2013, 2014).

As part of an effort to improve the quality of the comparison between API 1 and *in situ* TChl*a*, all the *in situ* data were optically weighted by using the protocol described in Smith et al. (2013) for the assessment of MERIS optical products in the shelf waters of the KwaZulu-Natal Bight, South Africa. The depth integration required for this protocol was obtained at Sagres, from the water samples collected at the three different depths at each station. The optically weighted TChl*a* (C_f) was calculated from Eq. (1) and Eq. (2) where: $C(z)$ is the TChl*a* at depth z; K_d and Z_{90} are the vertical attenuation coefficient and the penetration depth, respectively.

$$C_f = \frac{\int_0^{z90(\lambda)} C(z)f(z)dz}{\int_0^{z90(\lambda)} f(z)dz} \quad (1)$$

$f(z)$ is given by

$$f(z) = exp\left(-2\int_0^{z} Kd(\lambda, z')dz'\right) \quad (2)$$

2.3. Statistical analysis for the "matchup" analysis

MERIS RR satellite images were used for the time series between September 2008 and March 2012. For the matchup days, the satellite data used was from the MERIS FR satellite images. The statistics used to assess the results from the matchups and quantify the level of agreement between satellite Level 2 products (y_i) and *in situ* measurements (x_i) include: (i) the mean ratio (MR) in Eq. (3); (ii) the average absolute percentage difference (APD) in Eq. (4); (iii) the average of relative percentage difference (RPD) in Eq. (5); (iv) the root mean square error (RMSE) in Eq. (6); and (v) the intercept, slope and the coefficient of determination (R^2). The matchup index is i and the number of matchups is N:

$$MR = \frac{1}{N}\sum_{i=1}^{N}\frac{y_i}{x_i} \quad (3)$$

$$APD = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{|y_i - x_i|}{x_i}\right) \times 100\% \quad (4)$$

$$RPD = \frac{1}{N}\sum_{i=1}^{N}\frac{y_i - x_i}{x_i} \times 100\% \quad (5)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - x_i)^2} \quad (6)$$

3. Results

3.1. MERIS Algal Pigment one (API 1) validation

The comparison between the MERIS API 1 and the equivalent *in situ* measurements of C_f between October 2008 and March 2012 at all three stations are shown in Fig. 2 for both without and with ICOL processing. The R^2 for without ICOL improves from 0.63 at Station A, close to the coast, to 0.79 at Stations B and C further offshore. However, with ICOL processing there is an increase to 0.77 at Station A and a decrease to 0.73 and 0.78 at Stations B and C, respectively.

The statistics for *in situ* C_f measurements are shown in Table 2, where the mean for C_f declines from 1.16 μg l^{-1} at the coastal Station A through to 1.08 μg l^{-1} at Station B and 0.73 μg l^{-1} at Station C offshore. The maximum values vary from 5.98 to 2.75 μg l^{-1} between the coastal and offshore stations, whilst the relative difference for the minimum values are much less at 0.10 and 0.08 μg l^{-1}. Higher mean and maximum values are found at Station A compared to Stations B and C which are further offshore. The mean and extreme values for MERIS API 1, both without and with ICOL, are in Tables 3 and 4, respectively. In general, there is a similar pattern to those observed for the *in situ* data for C_f.

However, the differences include: (i) a lower mean and maximum values at Station B compared to Station C for MERIS API 1 without ICOL; and (ii) a higher maximum value at Station C compared to Station B for MERIS API 1 with ICOL.

The statistics comparing *in situ* C_f with the equivalent MERIS API 1 without and with ICOL are shown in Table 5. At the three stations, the MERIS API 1 without and with ICOL are overestimated relative to the *in situ* C_f where the MR > 1 and the RPD > 0. At Station A, the MERIS API 1 with adjacency correction show the best agreement with *in situ* data, increasing the R^2 and decreasing the uncertainties. However, the same does not occur at the other two stations, where there is a better agreement between data without the ICOL processor. In general, R^2 increases offshore and the uncertainties decrease, with the exception of Station B for the case of the MERIS API 1 data without ICOL that shows better results than Station C.

As an example, MERIS satellite images are presented in Fig. 3. comparing the spatial distribution of MERIS API 1 off Sagres processed with the standard MEGS 8.1 processor and the same images combined also with the ICOL processor. These images demonstrate that the ICOL processor can reduce the number of invalid API 1 (black areas in the image) when compared to images without the ICOL processor.

3.2. MERIS Algal Pigment Index 1 product used as an MSFD indicator

The MERIS API 1 product corresponds to the total chlorophyll *a* concentration and is a proxy for phytoplankton biomass, thus providing the possibility of using this variable as an ecological indicator that could be monitored using satellite images. Fig. 4 shows MERIS RR satellite images of API 1 between 11 February and 20 March 2012. The images demonstrate the evolution of an algal bloom around the coast of the study area, which increases between 27 February and 12 March and then starts to decline around 20 of March. Fig. 5 shows transects of values for API 1 that extend perpendicular to the coast up to 24 km offshore and incorporate all three of the validation stations. The figure shows how the satellite values for this ecological indicator can vary at different distances from the shore on 11 February 2012 (Fig. 5a) and 12 March 2012 (Fig. 5b), which are respectively periods of relatively low and high concentrations of API 1.

Fig. 5 also shows the effect of ICOL processing on the MERIS API 1. During the period of relatively low values for API 1 (0.44 μg l^{-1}), the satellite data processed with and without the ICOL show relatively similar transects (Fig. 5a), although the satellite data processed with the ICOL shows a better agreement with the *in situ* API 1 at Station A, than the data processed without ICOL. The transects also demonstrate that the influence of ICOL declines beyond 8 km from the coast. During the period of relatively high values of API 1 (4.43 μg l^{-1} without ICOL and 4.64 μg l^{-1} with ICOL), the transects show higher variability in the API 1 concentrations, particularly, near the coast. However, in contrast to the low value API 1, the satellite API 1 shows relatively little influence from ICOL processing when compared with *in situ* C_f at the three stations.

At the study area, all the available MERIS Level 2 satellite images between September 2008 and March 2012 have been extracted, where the images are free from cloud cover and have been filtered for contamination. Fig. 6 shows the variability of API 1 throughout this period at the three stations, with the *in situ* data showing higher concentrations at Station A, declining at Station B and culminating in the lowest values at Station C. There are also seasonal differences with higher values occurring mainly between early spring until the end of the summer, and lower values occurring during the winter.

Table 2
Statistics of *in situ* optically weighted total concentration of chlorophyll *a* (C_f) measurements at Stations A, B and C in μg l^{-1}.

	N	Mean	Max	Min
Station A	27	1.16	5.98	0.10
Station B	26	1.08	5.57	0.09
Station C	24	0.73	2.75	0.08

Table 3
Statistics of MERIS API 1 (without ICOL) at Stations A, B and C in μg l^{-1}.

	N	Mean	Max	Min
Station A	21	1.89	5.51	0.58
Station B	20	0.95	3.06	0.14
Station C	22	1.00	4.05	0.10

Table 4
Statistics of MERIS API 1 (with ICOL) at Stations A, B and C in μg l^{-1}.

	N	Mean	Max	Min
Station A	18	2.36	10.20	0.61
Station B	22	1.29	3.97	0.13
Station C	22	1.00	4.23	0.01

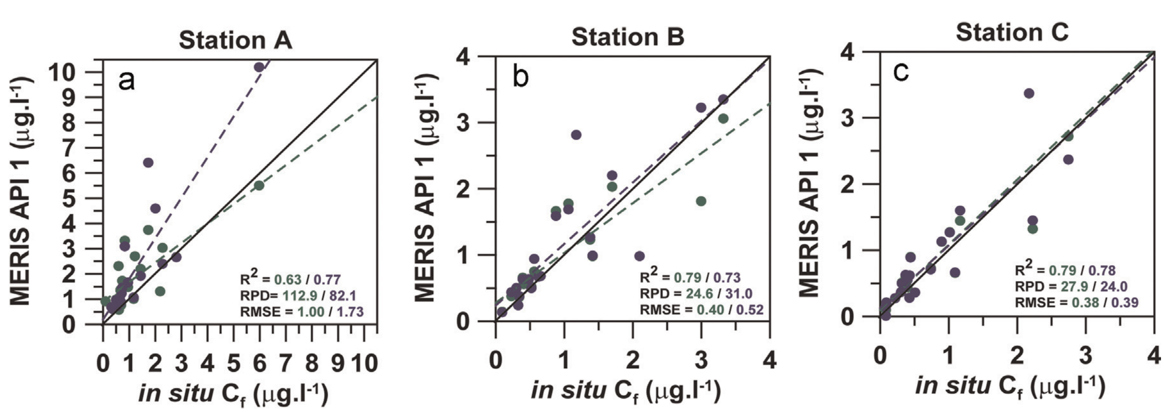

Fig. 2. Scatter plots of MERIS Algal Pigment Index 1 (API 1) versus *in situ* optically weighted total concentration of chlorophyll *a* (C_f) at Stations A, B and C. 1:1 relationship is represented by solid diagonal line, whilst the linear regressions are represented by the dashed lines. The green dots represent the MERIS API 1 without ICOL processor and the blue dots represent the MERIS API 1 with the ICOL processor. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
Statistical comparison between *in situ* optically weighted total concentration of chlorophyll a (C_f) and MERIS API 1 product from MEGS 8.1 without and with ICOL processor.

	Station A					Station B					Station C				
	R^2	MR	RPD (%)	APD (%)	RMSE	R^2	MR	RPD (%)	APD (%)	RMSE	R^2	MR	RPD (%)	APD (%)	RMSE
MERIS API 1 (without ICOL)	0.63	2.13	112.9	119.6	1.00	0.79	1.25	24.6	36.1	0.40	0.79	1.28	27.9	41.6	0.38
MERIS API 1 (with ICOL)	0.77	1.82	82.1	83.6	1.73	0.73	1.31	31.0	42.5	0.52	0.78	1.24	24.0	46.9	0.39

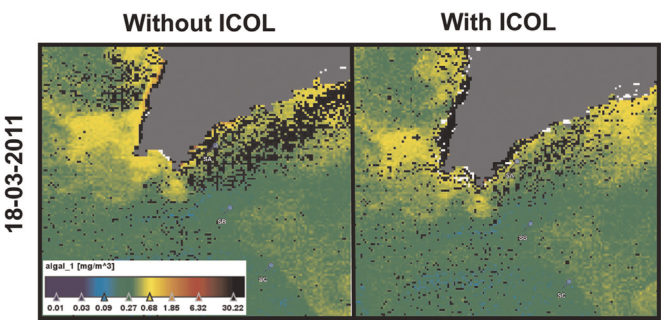

Fig. 3. MERIS Full Resolution satellite images of Algal Pigment Index 1 (API 1), without and with ICOL processor.

4. Discussion

The overarching objective of this study is to establish the uncertainties of using the MERIS API 1 as a potential proxy for the MSFD indicator TChl*a*, by comparing this satellite product with *in situ* data for TChl*a*. The results from this study have demonstrated that there is a good agreement between the satellite data and the *in situ* data (Fig. 2), working better at low rather that high chlorophyll concentrations, a fact that could be attributed to the patchiness during bloom events (*e.g.* Harvey et al., 2015). Moreover, the agreement improves at the more oceanic Stations B and C

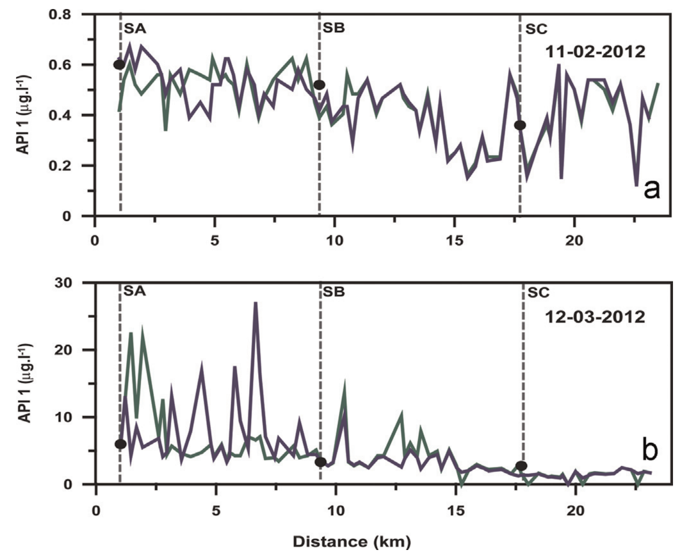

Fig. 5. Transects, extending perpendicular from the coast up to 24 km offshore, showing MERIS Algal Pigment Index 1 (API 1), without (green line) and with ICOL processor (blue line); the *in situ* optical weighted total concentration of chlorophyll a (C_f) is shown as full black circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

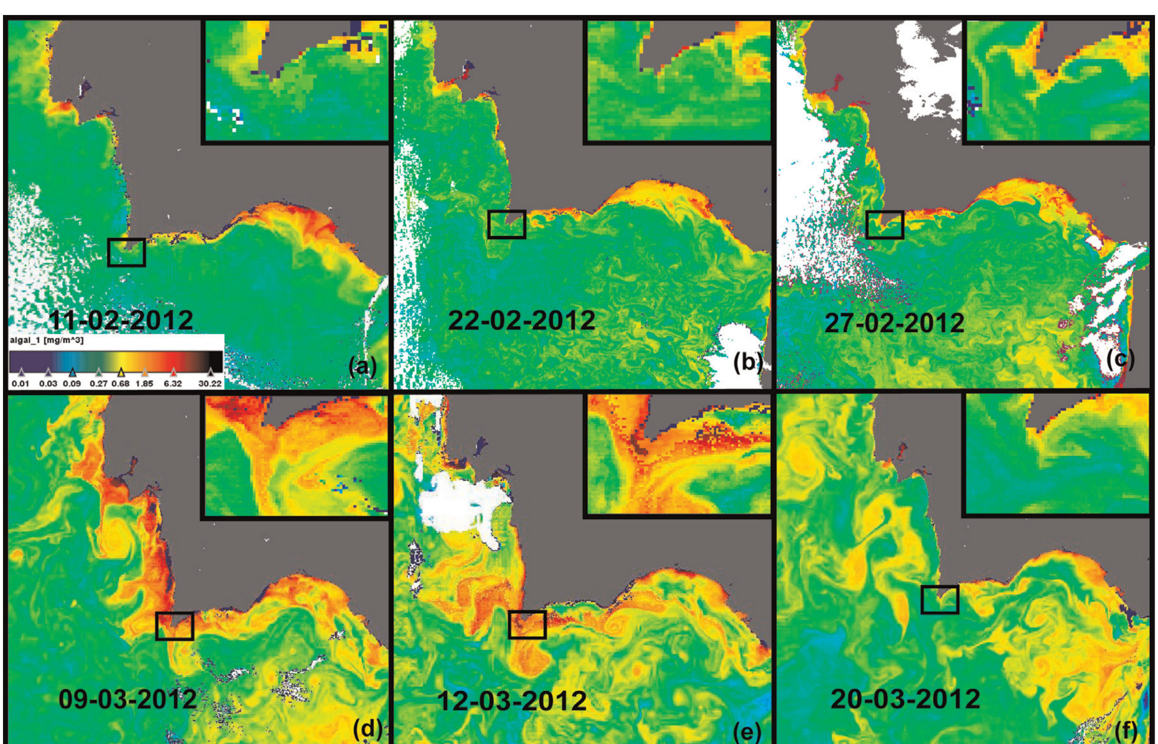

Fig. 4. MERIS Reduced Resolution satellite images of Algal Pigment Index 1 (API 1) showing the development of an algal bloom between February and March 2012 (adapted from Icely et al., 2013).

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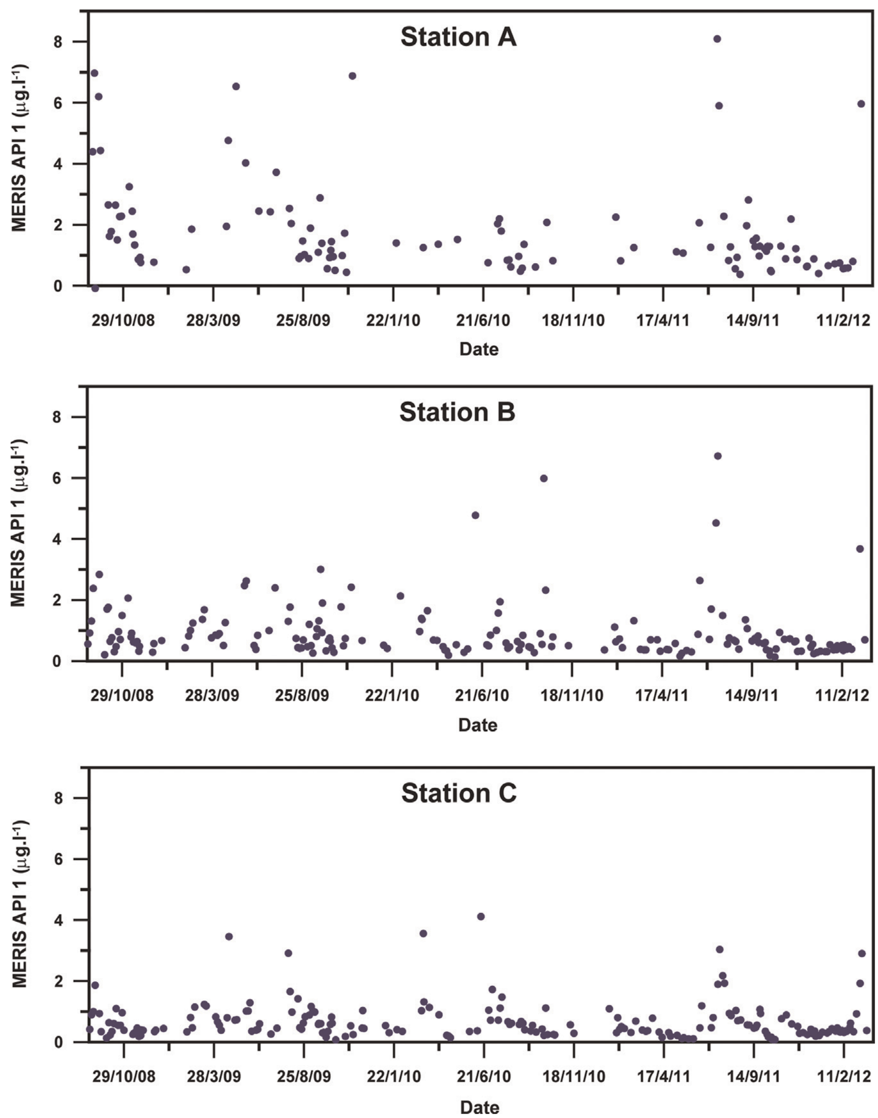

Fig. 6. MERIS Algal Pigment Index 1 (API 1) for all the available days free from cloud cover between September 2008 and March 2012.

(Fig. 2). However, even at the coastal Station A the agreement improves when the ICOL processor is applied. Indeed, this can be observed in the MERIS images when comparing without and with ICOL processing, where the black invalid pixels are substantially reduced by the ICOL processed image (Fig. 3). These results also show that MERIS API 1 does overestimate TChl*a* when compared with the *in situ* data, particularly at the coastal Station A. This is consistent with the findings of Antoine et al. (2008), Cui et al. (2010, 2014), Smith et al. (2013) and Harvey et al. (2015). The R^2 is similar to the results from Antoine et al. (2008) and Smith et al. (2013). Indeed, the uncertainties for Sagres results are consistent with the study of Smith et al. (2013), at the tip of the KwaZulu-Natal Bight in South Africa that has used the same processing procedures as the Sagres study with the MERIS standard MEGS 8 and the ICOL processors. Also, in common with the South African study, the application of the ICOL processor has reduced the extent of adjacency effects as demonstrated by improvements in the R^2 and a decrease in the uncertainties shown by the statistical analysis in Table 5. However, the adjacency effect is not the only correction required for processing satellite data near to the coast. The studies from Cristina et al. (2009, 2014) at Sagres reveal larger discrepancies in the blue wavelengths, when comparing MERIS with *in situ* water leaving reflectances. These discrepancies are attributed to problems with the atmospheric correction that are still to be addressed.

The validation studies that have taken place in this study area confirm that the satellite products from MERIS are of sufficient quality to provide a contribution to the monitoring of the coastal and marine waters off Sagres (Cristina et al., 2009, 2014). On the basis of this, it is feasible to monitor eutrophication (i.e Descriptor 5 of the MSFD), using API 1 as a proxy for the biological indicator TChl*a*. In the case of Descriptor 5, the chlorophyll *a* concentration in the water column, as well as bloom events of nuisance/toxic algal blooms, are the Indicators for the Criterion of the direct effects of nutrient enrichment (Ferreira et al., 2011). At Sagres, upwelling events cause natural eutrophication through the input of nutrients (Section 1.1); indeed, these events have demonstrated why Sagres is a good test site for monitoring eutrophication. MERIS Level 2 API 1 satellite imagery offshore from Sagres (Fig. 4) regularly show specific areas of increasing TChl*a* concentration near the coastal areas, and it has been possible to track and detect the extent of algal blooms in the coastal and marine waters with satellite images. This allows the possibility of identifying where and when the algal bloom starts and declines, demonstrating large-scale, real-time, and long-term monitoring. Kratzer et al. (2014) and Harvey et al. (2015) also used MERIS satellite images to

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monitor TChl*a* and the dynamics of cyanobacteria blooms in Swedish coastal areas in the Baltic Sea, but in this case, they have used the MERIS algal 2 product.

On the basis of the Sagres study, monitoring coastal and marine waters for the purpose of the MSFD by remote sensing could be scaled up for other regions of Portugal to cover one of the largest EEZs of the EU Member States in a cost effective manner. Although eutrophication is natural at Sagres, this is not necessarily the case for other maritime regions of the world, and monitoring by remote sensing would also be viable for cases where anthropogenic "human induced" eutrophication occurs in regions where sectoral drivers, such as agriculture, increase nutrient pressure. Well known examples are the Gulf of Mexico (Justić et al., 2002, 2005) and the Baltic Sea (Fleming-Lehtinen et al., 2015; Kratzer et al., 2014). As the MSFD focuses mainly on the human-induced eutrophication (European Commission, 2008), this use of remote sensing should be of interest to all EU member states that have to implement the MSFD by 2020 (European Commission, 2008).

Although the Sagres study has focused specifically on Indicator 5.2.1 "Chlorophyll concentration in the water column", it is probable that aspects of Indicator 5.2.4 "Species shift in floristic ratio, benthic to pelagic shifts, as well as bloom events of nuisance/toxic algal blooms (e.g cyanobacteria) caused by human activities" can also be addressed by the remote sensing approach. A number of recent studies have differentiated between phytoplankton functional types (PFTs) and phytoplankton size classes (PSCs) with remote sensing images (Brotas et al., 2013; Hirata et al., 2011; Nair et al., 2008). At Sagres, Goela et al. (2013, 2014) has identified PFTs and PSCs for the *in situ* samples presented in this paper.

In addition to the Descriptor 5 used in this study, it should be feasible to develop remote sensing approaches for monitoring Descriptors for 1 (Biological diversity), 7 (Hydrological conditions), 8 (Contaminant and pollutant effects), and 10 (Marine litter), and also follow the links between these Descriptors. For example, eutrophication damages the ecosystem structure causing loss of biodiversity, ecosystem degradation and harmful algal blooms (Ferreira et al., 2011). Another good example of the value of remote sensing is the capacity to relate commercial fish catches to algal biomass observed by remote sensing (IOCCG et al., 2009). Although it is evident that one of the substantial disadvantages of remote sensing is that it can only observe surface conditions, these are outweighed by the advantages deriving from the exceptional spatial and temporal range of data that can be provided by remote sensing (IOCCG, 2008).

Although the MERIS sensor has ceased to operate with the end of the Envisat mission in May 2012, there are other satellite missions with ocean colour sensors aboard that continue retrieving TChl*a*. Examples include the MODIS sensor aboard NASA's Aqua and Terra satellites (Esaias et al., 1998) and the Visible Infra-red Imaging Radiometer Suite (VIIRS) on NASA's Suomi National Polar-Orbiting Partnership (S-NPP) satellite mission (Hlaing et al., 2013). There are also the next generation of ocean colour sensors such as the Ocean Land Colour Instrument (OLCI) that is due to be launched on the ESA satellite Sentinel-3 as a replacement for the MERIS sensor to retrieve similar products (Donlon et al., 2012). These ocean colours sensors should continue to provide a wealth of data to assist with the implementation of the MSFD.

5. Conclusions

This study at Sagres demonstrates that monitoring by remote sensing is feasible for a Descriptor of Good Environmental Status (GES) for the Marine Strategy Framework Directive (MSFD) of the European Union. The satellite product tested is Algal Pigment Index 1 (API 1) derived from the MERIS sensor on the ESA Envisat satellite that corresponds to *the in situ* concentration of total chlorophyll *a*.

"Chlorophyll concentration in the water column" is one of the Indicators for the Criteria "Direct effects of nutrient enrichment" that is used to assess GES for the Descriptor 5: Eutrophication of the MSFD. Although API 1 can only assess TChl*a* at the surface, the large-scale, real-time, and long-term monitoring by remote sensing far outweighs this disadvantage.

The study at Sagres demonstrates the importance of sea-truthing and validation of API 1 so that the uncertainties associated with remote sensing data are fully understood. This improves the accuracy and the precision of the technique to retrieve good quality data that can be used by coastal and water managers for the management and for monitoring programs of coastal and oceanic waters.

Future work could focus on the use of remote sensing to evaluate other Indicators for Descriptor 5 such as identifying and differentiating between phytoplankton functional types and phytoplankton size classes. Indeed other remote sensing products such as total suspended matter, pigmented fraction of dissolved organic matter, as well as some indication of phytoplankton functional groups could contribute to monitoring GES in other Descriptors of the MSFD such as 1 for Biological diversity, 7 for Hydrographical conditions, 8 for Contaminants and pollution effects, and 10 for Marine Litter.

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