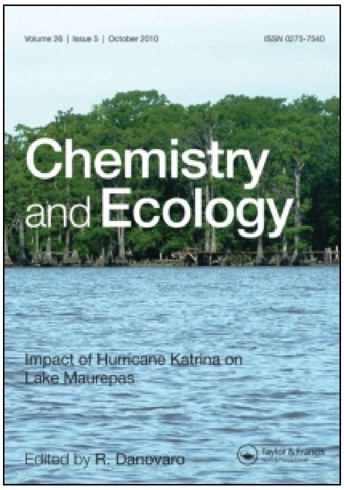

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A preliminary analysis of *in situ* and remotely sensed environmental variables in the coastal region of the Portofino Marine Protected Area

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A preliminary analysis of *in situ* and remotely sensed environmental variables in the coastal region of the Portofino Marine Protected Area

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Coastal marine environment is a complex system and its management requires adequate information. Marine Protected Areas (MPAs) are considered pilot sites useful to define innovative tools for the Integrated Coastal Zone Management (ICZM). Their management however requires acquaintance with the relationships between the protected site and the status of the coastal neighbouring areas in order to assess mutual effects and influences. There is the need of monitoring systems capable of highlighting physical and biological phenomena, and possible oceanographic anomalies at local scale, to assess possible existing differences between MPAs and their neighbouring unprotected zones. The present study proposes an integrated analysis of data sets coming from *in situ* and remote-sensing data to evaluate the reliability of satellite sensors for coastal zone monitoring and to better understand the short-term environmental dynamics on a coastal area centred on the Portofino MPA (Ligurian Sea).

Keywords: remote sensing; monitoring; Portofino MPA

1. Introduction

The study area encompasses the National Portofino MPA and the neighbouring stretches of coast (Tigullio gulf to the east and Paradise gulf to the west) (Figure 1a and b). This area is particularly relevant both for its environmental valence and for its tourist economical value.

The Portofino promontory, characterised by a very low population density, is placed just in the middle of one the most densely-populated stretches of coast of the North-western Mediterranean, characterised by many activities such as shipbuilding industries, mariculture, fishing and nautical and underwater tourism [1]. For these characteristics the Portofino MPA could be considered a pilot area to define tools useful to acquire the knowledge of the existing relationships between the protected site and the neighbouring coastal areas, in order to assess mutual effects and influences. Moreover, the MPA management body needs useful information to improve the

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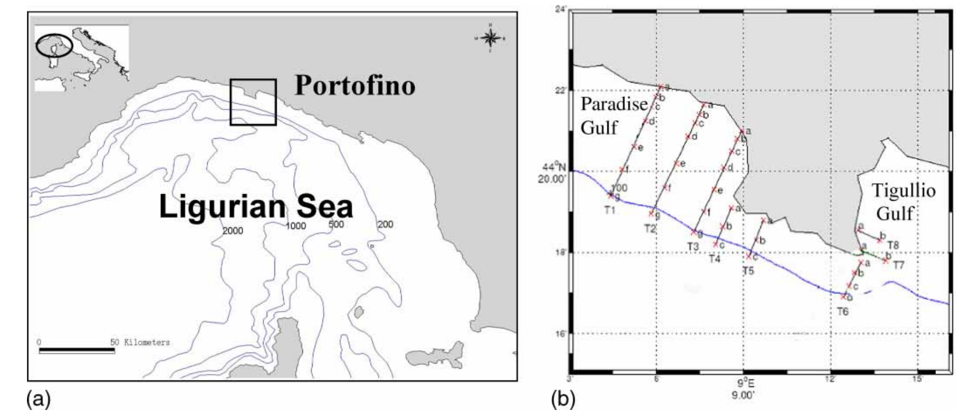

Figure 1. (a) The study area in the Ligurian Sea. (b) The Portofino Promontory and the sampling stations performed by the hydrographic cruises in November 2004.

marine environmental quality and to evaluate the efficacy of the management within the MPA's boundaries [2].

From an oceanographic point of view the Portofino MPA lies within the Ligurian current, which moves from east to west. The very narrow continental shelf, in correspondence with the Portofino promontory (Figure 1b), produces a tunnel effect of the coastal current, that significantly increases the dynamic of the area. Furthermore, for the same reason, the deep sea dynamic can easily interact with the coastal current. The water masses present in the area, besides being influenced by the presence of the coast, are deeply modified by the open sea conditions [3].

The present study proposes an integrated analysis of data sets coming from *in situ* and remote-sensing data to evaluate the reliability of satellite sensors for coastal zone monitoring and to better understand the short-term environmental dynamics on a coastal area centred on the pilot area of the Portofino MPA.

2. Materials and methods

2.1. *In situ sampling*

In 2004 a hydrographical cruise was carried out along the Portofino region on 17 November. *In situ* samplings were carried out along six transects perpendicular to the coast from 5 m to 100 m depth (approximately 35 stations) and covering an area of about 50 km^2 (Figure1b). The whole water column was investigated using a multiparametric probe (Idronaut Ocean Seven 301). The parameters measured were: sea temperature, salinity, dissolved oxygen, pH and chlorophyll (*chl*)-*a* concentration. *In situ* data were later interpolated in order to create Sea Surface Temperature (SST) at 0 m and *chl-a* maps at 0 m.

2.2. *Remotely sensed data and processing*

The methodological approach applied has foreseen the analysis of the geophysical parameter retrievable from satellite sensors such as SST skin and bio-optical parameters such as *chl*-like pigment concentration. SST skin was retrieved by means of the National Oceanic and Atmospheric Administration (NOAA)-Advanced Very High Resolution Radiometer (AVHRR) thermal sensor.

Chl-like pigment concentration was retrieved by the ESA (European Space Agency) Medium Resolution Imaging Spectrometer (MERIS) sensor.

NOAA-AVHRR map (on 17 November) at a spatial resolution of 1.1 km was downloaded from the German Remote Sensing Data Centre (DLR) [4], whereas MERIS images were kindly supplied by ESA. The algorithm used for retrieving SST skin is based on the brightness temperatures of AVHRR channels 4 and 5 (T4, T5) and it is described by McClain et al. [5]. As far as AVHRR data are concerned, only the 17 November 2004 map was not corrupted by clouds. On the contrary, both MERIS maps (16 and 17 November) were analysed.

Regarding the optical sensor, both MERIS Full Resolution (MER_FR) data at a spatial resolution of 300 m and MERIS Reduced Resolution (MER_RR) at 1100 m were analysed. Data were acquired at processing level 2 (L2) *chl* product (concentration of *ch*l-like pigment in mg m^{-3} of water). Two different types of ocean colour algorithms were developed by the ENVISAT project: algal_1 (alg-1) and algal_2 (alg-2) respectively.

Those calculate differently *chl*-like pigment concentration with respect to the different types of water considered. Alg-1 was developed for offshore waters (case 1 water according to Morel [6]) where only phytoplankton pigments and associated substances affect the water leaving radiance spectrum. Alg-1 is based on a semi-analytical model using two colour band ratio ($R_{(445)}/R_{(555)}$) for *chl* <2 mg m^{-3} [7]. On the other hand Alg-2 was developed for coastal waters (case 2 water), with multiple independent components, i.e. phytoplankton pigments, total suspended matter and yellow substance.

Alg-2 is based on an artificial Neural Network (aNN) inversion procedure. This relates directional water leaving radiance reflectance (R_{rs}) with the Inherent Optical Properties (IOPs) such as absorption and scattering coefficients or concentrations of different constituents present in coastal waters [8–10].

Both daily AVHRR and MERIS imagery were geo-registered and projected using the functionality of respectively ENVI (ITT Visual Information Solutions) [11] and BEAM (Brockmann Consult) [12] software. Images were re-mapped on a geographical projection (ellipsoid WGS-84). Two sub areas were extracted: the first covering the North-Western Mediterranean basin and in particular the Ligurian Sea, and the second smaller area encompassing Portofino MPA and the neighbouring stretches of coast (Figure 1a and b).

2.3. *Statistical analysis*

Correlation between SST skin satellite data and *in situ* collected data was not performed due to the high (0.01°C) precision of the SST skin data retrieved by the AVHRR sensor and also because of their reduced spatial resolution.

Geo-registered alg-1 and alg-2 *chl* (mg m^{-3}) data on 16 November (MER_FR) and 17 November (MER_RR) were extracted from the images, exported into text format and later imported into RGUI statistical free software [13].

In order to correlate *in situ* discrete *chl*-a data with the satellite *chl*-like pigment concentration, an interval of 0.002 degrees of latitude and longitude was chosen due to the reduced distance among the sampling stations. Thus a pixel square surrounding the discrete *in situ* sampling station without overlapping to the next one was considered. The comparison for MER_FR and *in situ chl*-a was performed by analysing all the sampling stations, whereas the relationship with MER_RR and *chl* -a was calculated by analysing only a reduced number of sampling stations due to the reduced spatial resolution of the former.

Relationships with *in situ* chlorophyll (averaged between 0 and 1 m) and chlorophyll estimated by alg-1 and alg-2 algorithms were quantified using linear regression analysis. The statistical significance (p value) of the most highly correlated variable was then determined as predictor of the best performing algorithm.

3. Results

Figure 2 shows the AVHRR SST skin map obtained from the data collected on the 17 November 2004. On the wider satellite imagery it is possible to notice a cold front located on the north western area of the Ligurian Sea with SST skin ranging between 16 and 17°C (Figure 2a). A warm thermal front moving west and reaching peaks of about 19°C contoured the Portofino Promontory (Figure 2b). In particular the Tigullio Gulf showed SST values around 18.2°C and offshore around 19.2°C whereas Paradise Gulf showed temperatures between 17.6 and 18.2°C (Figure 2b).

The interpolated *in situ* map on the 17 November 2004 shows warmer water far from the coast, also if the maximum gradient between coastal and deep temperature is very reduced (0.1–0.2°C) (Figure 3). The comparison with AVHRR map agrees to indicate warmer water far from the coast, while specific details are more difficult to compare.

Figure 4a and c show the chlorophyll content maps estimated by the alg-1 algorithm on the 16 (FR) and 17 November 2004 (RR) images respectively. The Ligurian Sea was interested by the start of a bloom moving westwards, visible on the image on the 17 November (Figure 4c). The highest *chl* values were recorded along Tigullio gulf and Paradise gulf (Figure 4d).

It is possible to note the inverse correspondence between satellite SST features and satellite *chl* features along the coast in the Portofino region images (Figures 2b and 4d).

Figure 5 shows the interpolated map of the *chl -a* surface concentration obtained *in situ*. The chlorophyll concentration evidences high values (0.45 mg m^{-3}), especially within the Paradise Gulf.

Table 1 shows the mean and standard deviations of the *chl*-a values calculated for each sampling station. In Tables 2 and 3 the stations used for the comparison between the *in situ* chlorophyll

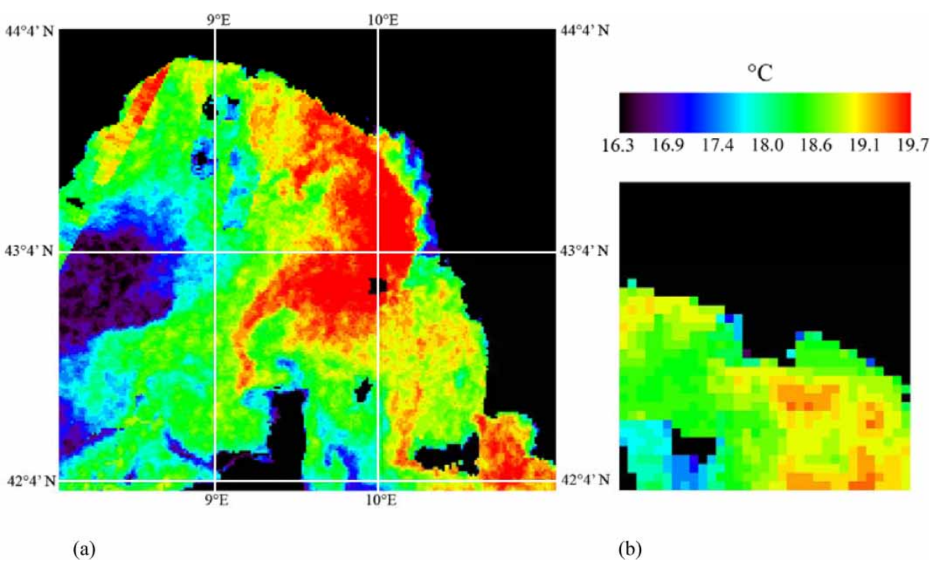

Figure 2. AVHRR SST skin maps highlighting Ligurian Sea and Portofino area respectively. (a) AVHRR SST skin map for 17 November 2004. (b) Portofino AVHRR SST skin map for 17 November 2004.

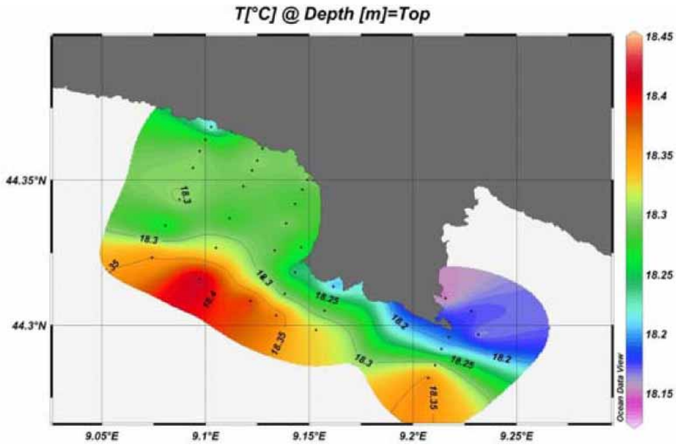

Figure 3. Interpolated SST surface maps retrieved from *in situ* data on the 17 November 2004.

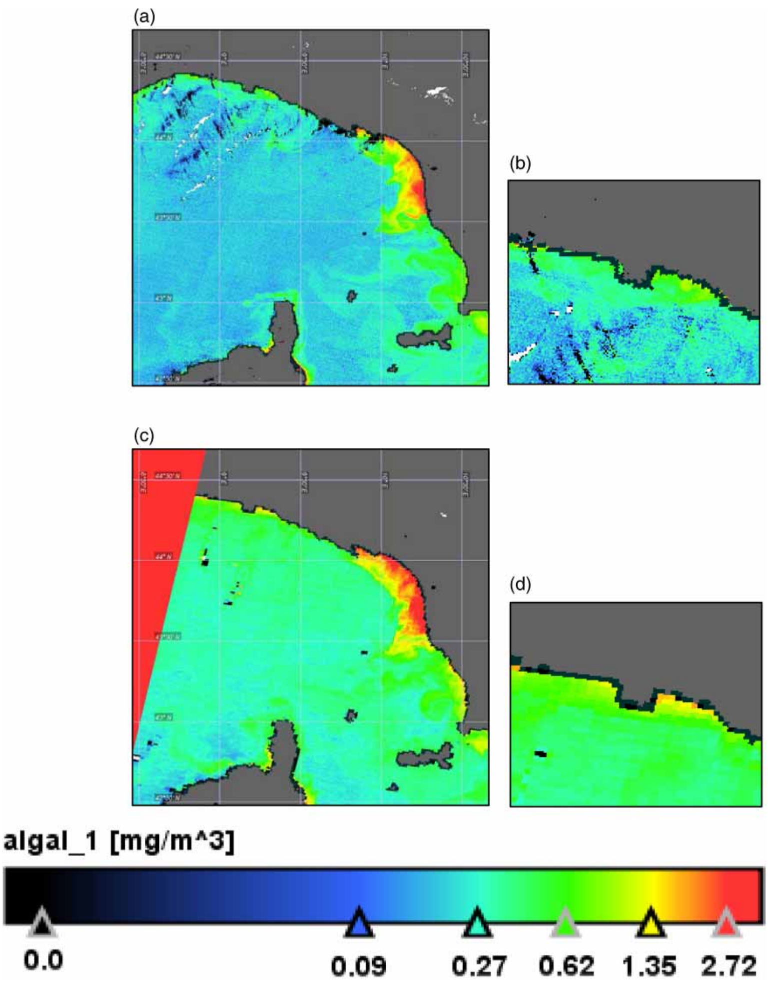

Figure 4. Chlorophyll maps calculated by alg-1 algorithm highlighting Ligurian Sea and Portofino area respectively. (a) Ligurian Sea MERIS Full resolution (FR) for 16 November 2004. (b) Portofino area MERIS FR for 16 November 2004. (c) Ligurian Sea MERIS Reduced Resolution (RR) for 17 November 2004. (d) Portofino area MERIS RR for 17 November 2004.

and MERIS alg-1 and 2 data for 16 and 17 November respectively are presented. The few points considered on 17 November are due to the reduced spatial resolution of the available image.

Linear regression calculated for *in situ chl*-a data with MERIS alg-1 on 17 November 2004 reported a slope of 0.26 and an intercept of 0.74. The model did not achieve significant levels ($p = 0.08$). The regression statistics calculated over the *in situ* data collected on the 17 November 2004 and the Alg-2 algorithm for the same day were not significant, showing a $R^2 = 0.27$ ($p = 0.24$). The inter-correlations between in situ *chl*-a and Alg-1 for 16 November 2004 gave significant linear relationship ($p = 0.01$, $R^2 = 0.17$) (Table 4).

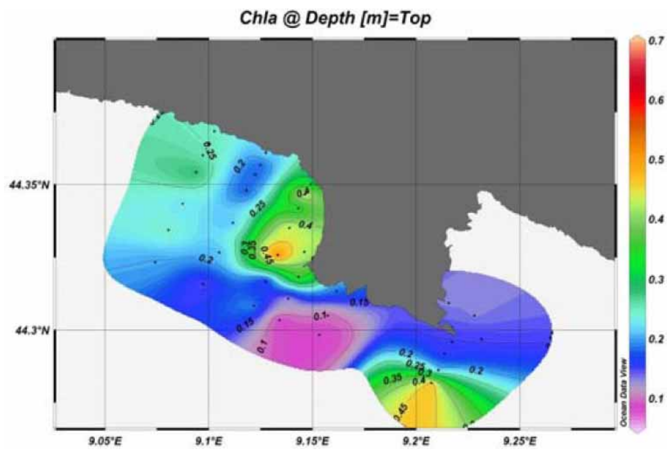

Figure 5. Surface chlorophyll-*a* concentration interpolated within the study area on the 17 November 2004.

Table 1. Mean and standard deviation (SD) of *chl -a* concentrations *in situ* sampling stations (0–1 m).

Code	Lat (N)	Lon (E)	$\bar{X}$ (0-1 m) (mg m^{-3})	N	SD
T1A	44.368	9.102	0.263	5	0.009
T1B	44.363	9.100	0.240	3	0.017
T1C	44.360	9.097	0.274	5	0.027
T1D	44.354	9.093	0.506	5	0.131
T1E	44.343	9.087	0.338	6	0.222
T1F	44.334	9.080	0.260	1	
T1G	44.323	9.074	0.260	3	0.122
T2A	44.360	9.127	0.510	4	0.429
T2B	44.356	9.125	0.515	4	0.193
T2C	44.353	9.122	0.150	5	0.017
T2D	44.347	9.118	0.148	4	0.015
T2E	44.336	9.111	0.440	3	0.520
T2F	44.326	9.105	0.186	8	0.013
T2G	44.315	9.097	0.137	3	0.006
T3A	44.350	9.149	0.248	5	0.236
T3B	44.346	9.146	0.513	3	0.155
T3C	44.341	9.143	0.393	6	0.255
T3D	44.335	9.138	0.794	8	0.274
T3E	44.325	9.133	0.708	4	0.101
T3F	44.316	9.127	0.170	4	0.012
T3G	44.308	9.121	0.442	5	0.346

(*continued*)

Table 1. Continued.

Code	Lat (N)	Lon (E)	$\bar{X}$ (0-1 m) (mg m^{-3})	N	SD
T4A	44.318	9.143	0.445	2	0.115
T4B	44.310	9.138	0.390	6	0.338
T4C	44.303	9.134	0.064	8	0.005
T5A	44.313	9.161	0.148	4	0.115
T5B	44.305	9.157	0.076	5	0.009
T5C	44.298	9.153	0.077	3	0.006
T6A	44.295	9.217	0.293	4	0.385
T6B	44.291	9.213	0.470	3	0.275
T6C	44.286	9.210	0.475	2	0.078
T6D	44.281	9.207	0.860	2	0.028
T7A	44.300	9.217	0.515	4	0.323
T7B	44.296	9.231	0.155	4	0.005
T8A	44.309	9.215	0.134	5	0.009
T8B	44.305	9.228	0.125	4	0.010

N = number of records

Table 2. Sampling stations considered for statistical analysis between *in situ* chlorophyll on 17 November 2004 and *chl* retrieved by alg-1 and alg-2 MER_FR image on 16 November 2004.

Stations	a	b	c	d	e	f	g
T1	X	X	X	X	X	X	X
T2	X	X	X	X	X	X	X
T3	X	X	X	X	X	X	X
T4	X	X	X				
T5	X	X	X				
T6	X	X	X	X			
T7	X	X					
T8	X	X					

Table 3. Sampling stations considered for statistical analysis between *in situ* chlorophyll on 17 November 2004 and *chl* retrieved by alg-1 and alg-2 MER_RR image on 17 November 2004.

Stations	a	b	c	d	e	f	g
T1					X		X
T2							
T3						X	X
T4							
T5			X				
T6		X		X			
T7							
T8							

4. Discussion

The above analyses demonstrate so far the reliability of satellite sensors also for coastal zone monitoring. SST skin data retrieved by thermal sensor (AVHRR) are particularly useful to monitor the regional scale phenomena and to encapsulate local scale processes. In this study we analysed both reduced and full resolution imagery obtained by MERIS sensor. RR at 1.1 km was particularly useful in characterising the oceanographic features occurring at a regional scale within the Ligurian basin. However, the FR at 300 m resulted the most useful at local scale to the inter-comparison

Table 4. Statistics of the linear regression for the relationship between *chl*- like pigment concentration and *in situ chl* -a on 16 and 17 November 2004. ANOVA on regression and determination coefficients are indicated.

Date	Independent variable	Dependent variable	Type of relationship	ANOVA	*p*	R2	Slope	Intercept
17/11/2004	*chl* -a	*chl*-like pigment concentration (alg-1)	Linear	$F(1, 5) = 4.40$	0.08	0.46	0.26	0.74
	chl -a	*chl*-like pigment concentration (alg-2)	Linear	$F(1, 5) = 1.82$	0.24	0.27	–	0.7
16/11/2004	*chl* -a	*chl*-like pigment concentration (alg-1)	Linear	$F(1, 33) = 6.79$	0.01	0.17	0.32	0.83
	chl -a	*chl*-like pigment concentration (alg-2)	Linear	$F(1, 33) = 0.96$	0.33	0.03	–	0.66

for *in situ* and satellite chlorophyll. This is clearly explainable with the reduced spatial extension of the study area.

Both MERIS algorithms (alg-1 and alg-2) were tested over the study area. Despite the relationship of *in situ* chlorophyll on the 17 November with satellite chlorophyll (alg-1) on the same date did not achieve statistically significant levels ($p = 0.08$), alg-1 algorithm showed a linear dependency with *in situ* chlorophyll. Moreover the number of points considered was low due to the reduced spatial resolution of the image considered. On the other hand alg-2 did not show a linear relationship with *in situ* chlorophyll data.

Inter-comparison between *in situ* chlorophyll and alg-1 for 16 November 2004 was significant.

Despite the reduced dataset used, statistical analysis confirmed that alg-1 algorithm should be used while monitoring the Portofino area. This could be explained by the presence along the study area of almost 'pelagic' waters due to the narrow continental shelf that characterises this stretch of coast. There is the tendency to a high dynamic exchange between coastal and pelagic water masses. By observing, on the satellite chlorophyll maps the mesoscale dynamic structures within the Ligurian basin, it is possible to note that, during the considered periods, these are similar to the mesoscale ones along the Portofino area. This tendancy should be verified further on; however it is evident that the offshore circulation appears to contour the Portofino promontory. There is not a transition region between coastal and pelagic zone. Moreover it is possible to hypothesise that the south-western (Paradise gulf) Portofino area hosts case-1 waters (offshore waters), whereas the waters along the eastern side are more influenced by the Entella river runoff, which flows into Tigullio gulf. However *in situ* data within this gulf were not available. In order to validate this last hypothesis further *in situ* sampling campaigns within Tigullio gulf are needed.

This study presents a preliminary approach to the integration of different data sets and methodologies to increase the use of satellite sensors for the continuous monitoring of coastal areas. The use of satellite imagery in addition to the instruments already used within the Portofino MPA waters revealed to be extremely useful in order to obtain more information on the main physical and biological phenomena. The experience acquired so far suggests a further improvement of the knowledge in this field to define standardised approaches useful to build-up a national monitoring system based on the coupling of data collected *in situ*, in specific pilot areas by means of profilers working in continuous, and those supplied by remote sensing. This kind of system could supply crucial information on the dynamics of the main environmental variables within the national coastal waters useful both to the Italian Ministry of the Environment and to the MPA managers, optimising the *in situ* sampling effort with the integration of specific information coming from satellite imagery.

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