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Ocean Science Discussions

Joint use of satellite and in-situ data for coastal monitoring

F. Gohin

DYNECO/PELAGOS, Centre Ifremer de Brest, BP 70, 29280 Plouzane, Brittany, France

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Correspondence to: F. Gohin (francis.gohin@ifremer.fr)

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Abstract

Sea surface Temperature, Chlorophyll and turbidity are three variables of the coastal environment commonly measured by monitoring networks. The observation networks are often based on coastal stations which do not provide a sufficient coverage to validate the model outputs or to be used in assimilation over the continental shelf. Conversely, the products derived from satellite reflectance show generally a decreasing quality shoreward and an accurate assessment of these data is required. In this text, we show that the satellite-derived chlorophyll products, obtained through a dedicated coastal algorithm, fulfil the first requirement of a monitoring system: the ability to represent correctly the mean annual cycle. The annual cycle, mean and percentile 90 of the chlorophyll concentration, derived from MERIS/ESA and MODIS/NASA, have been compared to in-situ observations at twenty six selected stations from the Mediterranean Sea to the North-Sea. Keeping in mind the validation, the forcing or the assimilation in hydrological, sediment-transport or ecological models, the non-algal Suspended Particulate Matter (SPM) is also a parameter which is expected from the satellite imagery. However, the monitoring networks measure essentially the turbidity and a consistency between chlorophyll, representative of the phytoplankton biomass, non-algal SPM, and turbidity is required. In this study, we derive the satellite turbidity from chlorophyll and non-algal SPM with a common formula applied to in-situ or satellite observations. The distribution of the satellite-derived turbidity shows the same main statistical characteristics that measured in-situ; which satisfies our first condition to monitor the long-term changes or the large-scale spatial variation over the continental shelf and along the shore. For the first time, maps of turbidity, so useful for the surveillance of the benthic habitats, are proposed operationally from space on areas as different as the Southern North-Sea or the Western Mediterranean Sea, with validation at coastal stations.

1 Introduction

Since the launch of SeaWiFS in September 1997, followed by MODIS/AQUA and MERIS in 2002, daily ocean colour images have been made available for monitoring the open and coastal waters. Amongst many algorithms developed to provide chlorophyll-*a* concentration in coastal waters, Ifremer's method is based on Look-Up-Tables, applied to the standard remote-sensing reflectance delivered by space Agencies (NASA and ESA) and specifically defined for the western European continental shelf (Gohin et al., 2002; Gohin et al., 2005). This method gives results similar to those of OC3-MODIS and OC4-MERIS in open ocean but with lower and more realistic levels in turbid waters. One of the advantages of the method is to provide consistent estimations of chlorophyll and non-algal SPM concentrations from MODIS or MERIS spectral reflectance, allowing the building-up of merged MERIS/MODIS products by optimal interpolation (Saulquin et al., 2010). The first application of the ocean colour products in coastal waters concerns the validation and calibration of regional biogeochemical models (Huret et al., 2007; Lacroix et al., 2007; Ménesguen and Gohin, 2006; Ménesguen et al., 2007). The assimilation in a biogeochemical model has also been performed with success in coastal seas, like the Gulf of Fos and the Rhône river plume in the Mediterranean waters (Fontana et al., 2010). Another class of application is the operational monitoring of the water quality which has been strongly supported by different national and European projects, like MarCoast (ESA funded) and ECOOP (E.U. funded). The "water quality" expression in these projects refers to the eutrophication risk, due to the enrichment in nutrients, or to the frequency and strength of HAB (Harmful Algal Blooms) events. The first risk is addressed explicitly by the European Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD) and the second by all the monitoring networks and rules established for the surveillance of the sea food quality.

HABs in the coastal waters around France are seldom visible from space, due to their low cell concentration, deep location (*dynophysis*) or occurrence in narrow estuaries (*Alexandrium*). The satellite imagery is also poorly efficient for the direct observation of toxic *Pseudo-nitzschia* which is a diatom able to bloom in high concentration with very variable toxicity (producing domoic acid, an amnesic neurotoxin). *Karenia mikimotoi* seems to be an exception as it may grow in very high concentration of cells in the western stratified part of the English Channel giving massive blooms visible from space (Van Houtte et al., 2006, Miller et al., 2006). These restrictions to the observation of HABs from space are balanced by an enhanced interest for the applications linked to the long term surveillance of the eutrophication risk requested by the WFD or the MSFD (Gohin et al., 2008). These applications require a joint use of the in-situ and satellite capacities of observations. The coastal in-situ networks in France are now well established and are more and more efficient (SOMLIT/CNRS and REPHY/Ifremer). They also benefit from the development of the coastal operational oceanography, in the frame of projects like Previmer (French national project). The harmonious development of observing systems from satellite and in-situ origins, together with modelling, is also one of the major goals of ECOOP. Three parameters useful for the coastal surveillance are currently observed from space: the sea surface temperature (SST), the chlorophyll-*a* (Chl) and the suspended particulate matter concentration (SPM). The SST and the chlorophyll concentration are also monitored in-situ and are basic measurements of the French coastal networks. However, the water clarity is much more often, and in an easier way, obtained from measurements of turbidity than from the concentration of suspended particulate matter. That is why we'll also present in this study the validation of the satellite-derived turbidity in complement to chlorophyll and SPM concentrations. To ensure consistency between the products, turbidity will be expressed from a combination of Chl and non-algal SPM. Considering that the light attenuation coefficient K_{PAR} can also be derived from Chl and non-algal SPM (Gohin et al., 2005), this will contribute to build up a consistent set of environmental data on our area.

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2 Methods

2.1 The in-situ data set

The in-situ data have been obtained from the REPHY phytoplankton network of Ifremer, including associated regional or national networks, and from the SOMLIT observation system managed by INSU (Institut National des Sciences de l'Univers). Twenty six stations along the shore have been selected for comparison with the satellite-derived products during the period 2003–2009. These stations have been selected for their capacity to represent different regional water conditions encountered in the French coastal waters. They can be considered as an extension of a previous data set of seven stations selected to validate SeaWiFS data for the surveillance required by the WFD (Gohin et al., 2008). These stations were also chosen because they have been frequently sampled in the recent years, through national or regional networks, as the SRN (Suivi Régional des Nutriments) and RHLN (Réseau Hydrologique du Littoral Normand) funded by the water agencies Artois-Picardie and Seine-Normandie. The locations of the selected stations are shown on Fig. 1. Two cross-shore transects, off Dunkerque and Boulogne and belonging to the SRN network, are also considered as they reveal the chlorophyll-*a* and turbidity cross-shore gradients in the productive waters of the eastern Channel and the southern North-Sea. These transects also provide very useful information for investigating the degradation of the quality of the satellite-derived products near the shore where pixels are often flagged (failure in the atmospheric correction, high radiance, etc...).

All these stations allow a direct comparison of satellite and in-situ observations except at Cabourg where the REPHY station is too close to the coast to be observed correctly by satellite. As this location, in the vicinity of the plume of the river Seine, is subject to eutrophication and high chlorophyll levels, it seemed useful to try to incorporate it into our selected stations despite the proximity of the coast. To that purpose, we consider a shift of three pixels (about 3.5 km) further north offshore to obtain a sufficient number of satellite samples for the comparisons (match-ups) and the monitoring. We

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have tested, through several short cruises dedicated to the study of the local pattern of chlorophyll, that there was no significant gradient at the Cabourg location and that this shift may be applied to the satellite data without creating any bias.

The concentration in chlorophyll-*a* was obtained by fluorometry or spectrophotometry. For spectrophotometric pigment analysis (Lorenzen, 1967; Aminot and Kerouel, 2004), samples of two litres of surface waters are prefiltered through 200 µm mesh nylon gauze and then filtered onto 47 µm GF/C fibre filters under low-pressure vacuum. The filters were ground into acetone–water solution (90/10, v/v) for pigment extraction and analysed by spectrophotometric method. The seawater volume filtered for the fluorimetric method (Neveux, 1976; Aminot and Kerouel, 2004) is lower than that used for the spectrophotometric method.

The concentration in SPM was only measured at the SRN (Dunkerque and Boulogne transects) and SOMLIT stations ("ROSCOFF_ASTAN", "MARSEILLE_FRIOUL", and "BANYULS_SOLA"). SPM is obtained through filtration onto 47 µm Whatman GF/F filters following the procedure described in Aminot and Chaussepied (1983). At the other stations (REPHY) the turbidity has been measured as an indicator of the water clarity.

The turbidity has been measured in-situ, using multiparameter portable field instruments or sondes (Hydrolab DS5, YSI 600 QS, YSI 6600, NKE MPx), or from water samples in laboratory, using a laboratory turbidimeter (HACH 2100N, HACH 2100N IS, HACH 2100A). These turbidimeters comply with ISO 7027 (FNU) or U.S.E.P.A. method 180.1 (NTU).

When the data are in NTU (Nephelometric turbidity Unit, U.S.E.P.A 180.1), they have been obtained from the measurement of a broad spectrum incident light in the wavelength range 400–680 nm, as one of a tungsten lamp, scattered at an angle of 90+/−30°. NTU is the unit of most of the REPHY data collected between 2003 and 2007 whereas the most recent observations are expressed in FNU (Formazin Nephelometric Unit, ISO 7027). In that case, they are obtained with an incident light in the range 860 +/−60 nm (LED) scattered at 90 +/−2.5°.

These reporting units are equivalent when measuring a calibration solution (for example, Formazin or polymer beads), but they can differ for environmental samples. There are four optical components in coastal waters, pure sea water, colored dissolved organic matter (or yellow substances), phytoplankton pigments and particles in suspension. The yellow substances are characterized by their absorption in low wavelengths. A high level of yellow substances will result in more absorption in the 400–680 nm radiation and, therefore, in less light exiting the turbidimeter and a lower value in NTU. This effect of the yellow substances on the measurements in NTU will not be visible in the data in FNU made at a longer wavelength. Therefore, in presence of yellow substances, the measurements in FNU are expected to be more related to SPM than those in NTU.

2.2 The satellite images and their processing

2.2.1 The satellite data

Daily standard remote-sensing reflectances of MODIS/Aqua, since January 2003, and MERIS, since January 2007, have been used in that study.

The MODIS Level-2 reflectance products (reprocessed in 2010, SeaDAS V6.2) have been downloaded from the OceanColor/GSFC (Goddard Space Flight Centre) WEB server in May 2010. MERIS data have been obtained from the rolling archive of the ENVISAT acquisition station of Kiruna (PDHS-K) in Near Real Time.

2.2.2 Processing the satellite reflectance for chlorophyll

The estimation of Chl is obtained by application of two Look-Up-Tables (LUT) to the spectral remote-sensing reflectance (Rrs) of MODIS and MERIS. The method, described in details in Gohin et al. (2002), is as empirical as the OC4/SeaWiFS algorithm of NASA (or OC3M-547 for MODIS and OC4E for MERIS) on which it is based but gives more realistic values over the continental shelf. In coastal waters, mineral

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SPM, absorption by CDOM (Coloured Dissolved Organic Matter) and errors in the atmospheric correction are the cause of frequent overestimations in the chlorophyll concentration by the standard procedures. Whereas OC4 makes use of the SeaWiFS and MERIS four channels ranging from 442 (Blue) to 559 nm (Green) and determines Chl from the maximum of the band ratios Rrs(Blue)/Rrs(Green) calculated from the three Blue Channels ranging from 442 to 510 nm available for SeaWiFS and MERIS, our algorithm considers also the reflectances at 412 nm and in the Green (547 nm for MODIS and 559 nm for MERIS). The Chl concentration is therefore determined from the triplet {Rrs(412), Rrs(Green), Maximum band ratio Rrs(Blue)/Rrs(Green)}. Rrs(412) accounts for the absorption by CDOM and the error in atmospheric correction, particularly significant at this low wavelength, and Rrs(Green) accounts for the effect of the backscattering by the Suspended Sediment not related to the phytoplankton. The algorithm is a 5-channel algorithm for MERIS (and SeaWiFS, not processed in this study) and a 4-channel one for MODIS. The method has been applied with success to the SeaWiFS data in the French coastal waters but also in the North-Sea and other turbid coastal waters (Huret et al., 2005) for years.

2.2.3 Processing the satellite reflectance for non-algal SPM

The procedure is based on the method described in Gohin et al. (2005). In this method we consider that the absorption by yellow substances can be neglected at wavelengths longer than 550 nm and propose a simple equation to express the reflectance (or the water-leaving radiance) from the absorption and backscattering coefficients of pure sea water, phytoplankton and non-algal Particles (NaP).

Firstly, we make the classical approximation in Eq. (1) that the absorption a and the backscattering coefficients b_b can be expressed from the concentration of phytoplankton, through Chl, and NaP (with coefficients from the literature):

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$$a = a_w + a_\phi + a_{\mathrm{NaP}} = a_w + a^*_\phi \times \mathrm{Chl} + a^*_{\mathrm{NaP}} \times \mathrm{NaP} \text{ and}$$

$$b_\mathrm{b} = b_{bw} + b_{b\phi} + b_{\mathrm{bNaP}} = b_{\mathrm{bw}} + b^*_{b\phi} \times \mathrm{Chl} + b^*_{\mathrm{NaP}} \times \mathrm{NaP} \quad (1)$$

Secondly, in Eq. (2), we define a linear relation between R*(550), a variable linked to the reflectance, and the satellite remote-sensing reflectance Rrs with coefficients α and β obtained by minimization from in-situ observations of Chl-*a* and NaP.

$$R^*(550) = b_\mathrm{b}/(a + b_\mathrm{b}) = \alpha + \beta\ \mathrm{Rrs}(550) \quad (2)$$

In Eq. (2), R*(550) is obtained from Chl and NaP through a and b_b (Eq. 1)

Thirdly, considering that the chlorophyll is known after application of the LUT to the satellite reflectance, we inverse R*(550) to get the last unknown which is the concentration of NaP.

Initially defined at 550 nm and validated on cruises on the continental shelf, the operational application of the method often showed low values in very turbid waters, leading sometimes to unrealistic features in the estuaries and the river plumes. That could be explained by increased errors in the atmospheric correction for very turbid waters and by the saturation effect due to the fact that the quantitative retrieval of SPM is no longer reliable beyond a certain concentration for a specified wavelength (Bowers et al., 1998). Nechad et al. (2010) suggest choosing a retrieval wavelength with sufficiently high pure water absorption, using longer red or near infrared wavelengths for water with higher SPM. That is why a second channel at 670 nm has been added to take into account the most turbid areas. Finally SPM (hereafter used for NaP) is defined from a switch of SPM(550) to SPM(670) depending on the SPM levels. If SPM(550) and SPM(670) are both inferior to 4 mg L^{-1} then SPM(550) is conserved otherwise SPM (670) is chosen. SPM is therefore obtained from the channel at 550 nm in relatively clear waters and from the channel at 670 nm in turbid waters. This method takes advantage of the relatively good sensitivity of the channel at 550 nm to the variation of SPM in clear waters and the better quality of the atmospheric correction at 670 nm as the atmospheric correction is obtained by extrapolation from the channels in the near infra-red, at about 760 and 860 nm.

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2.2.4 Processing the satellite reflectance for turbidity

As mentioned by Nechad et al. (2009) studies on the remote-sensing of turbidity in coastal waters are less numerous than those on SPM. However the turbidity is an optical property (volume scattering function at 90°) which is tightly related to the backscattering coefficient b_b. Nechad et al. (2009) propose an estimation of turbidity using a method based on a concept equivalent to Eq. (2). Doing so, they derive turbidity from MERIS (channels at 665 and 680 nm) with success in the very turbid waters of the Southern North-Sea.

However, to care for consistency between our different products, those observed in-situ or by satellite and those defined in the ecological models, we have chosen to derive turbidity from Chl and non-algal SPM. Chl and non-algal SPM are two variables used for validation or forcing of the ecological model (Huret et al., 2007) while turbidity is a parameter commonly measured.

Therefore, we express turbidity as a combination of non-algal SPM and Chl:

$$\text{turbidity} = \alpha(\text{SPM} + 0.234\,\text{Chl}^{0.57}) \quad (3)$$

where the term $0.234\,\text{Chl}^{0.57}$ represents the phytoplankton biomass linked to the Chl-*a* concentration (Gohin et al., 2005).

3 Results and discussion

3.1 Results for the MODIS and in-situ data

3.1.1 Validation of the chlorophyll concentration

There are two ways to validate the satellite products, one from direct comparisons based on satellite and in-situ match-ups and the second, more sophisticated but also more appropriate to the issues of the operational surveillance, from the consistency of

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the statistical properties (mean and percentile 90) of the annual cycles obtained from both data sets. The two ways have been explored in this study, with emphasis on the second one.

Figure 2 shows the scatterplot of the satellite versus in-situ chlorophyll. The match-up is considered for satellite and in-situ observations observed at the same pixel location and the same day. The coefficient r^2 obtained on the log-transformed Chl data is equal to 0.66. A significant part of the deviation can be explained by the intra-day variability of the chlorophyll concentration at the surface.

Figure 3 shows the annual cycles of Chl for some selected stations near the shores of the southern North-Sea to Brittany. These graphs can be separated into 3 classes corresponding to typical developments of the phytoplankton during the year. The curves at Dunkerque Points 3 and 4 show a characteristic spring peak of chlorophyll in mid-April. The Dunkerque's curves are unique in our data set and permit to identify this location as the nutrient-rich (high level) North-Sea offshore station. The stations of the Boulogne transect have a similar behaviour but the spring peaks is lower and later in the season. We can also notice that the spring peak is more marked at Boulogne Point 3 (offshore) than at Boulogne Point 2. The spring peak is relatively more intense for stations offshore where the main source of nutrients comes from the winter "reservoir" without significant supply from rivers in spring and summer. The station of Cabourg doesn't show such strong a spring peak but the levels reached are also very high (the highest of our selected stations). The shape of the phytoplankton curve at Cabourg can be described as a bell curve, characterising a station where a regular supply in nutrient is provided by a river, here the river Seine. Chausey and ROSCOFF_ASTAN, located in the Channel, show lower levels of Chl-*a* and a more regular productivity in waters strongly mixed by the turbulence due to the tidal current and waves.

Figures 4 and 5 show the annual cycle of chlorophyll at our selected stations along the Atlantic and Mediterranean coasts. The statistics during the productive season (from March to October) are also indicated on the figures.

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Figure 6 presents the satellite versus in-situ mean and percentile 90 of Chl at all the selected stations during the productive season.

3.1.2 Validation of the non-algal SPM concentration

The SPM validation will be carried out only on the 8 SOMLIT and SRN stations where SPM has been measured.

Our satellite-derived non-algal SPM is defined as the difference between Total SPM and the phytoplankton biomass derived from Chl-*a*. Therefore, what we define as non-algal SPM incorporates mainly mineral SPM but also organic SPM not related to the living phytoplankton (whose biomass is considered proportional to Chl), as organo-mineral aggregates (flocs) or organic matter from the river plumes. Although it may also include particles directly related to the phytoplankton in case of blooms of coccolithophorides, with their characteristic calcite skeleton, our SPM satellite product is dominated by mineral particles.

The annual cycles derived from the satellite data fits well those observed in-situ except at ROSCOFF_ASTAN (Fig. 7) where the in-situ concentration of SPM stays high in summer. The annual average and P90 of satellite SPM appear also logically lower in-situ for this station on Fig. 8. Despite the curious discrepancy at this station, with high SPM levels measured in-situ in summertime when lower concentrations are expected following the decrease in the resuspension induced by the waves in the English Channel (Velegrakis et al., 1999), the overall adjustment is excellent and the correlation coefficient is high. However we have only 8 stations and this enhances the interest for turbidity to test the aptitude of the ocean colour sensors to address the monitoring of the water clarity.

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3.1.3 Relation between turbidity, non-algal SPM and Chl-*a* and validation

Relation between in-situ turbidity measurements made in NTU and FNU

Most of our observations in turbidity have been measured in NTU. It is only recently (since 2008) that the measurements are made in FNU. For that reason we have to convert data in FNU to NTU to obtain a consistent data set. The relation:

$$\text{turbidity in FNU} = 1.267 \text{ turbidity in NTU} \tag{4}$$

has been obtained from a regression based on 69 pairs of turbidity measurements at different REPHY stations (Fig. 9).

Relation between in-situ turbidity and SPM

The term α in Eq. (3) is obtained by regression of turbidity on total SPM (TSPM) at the stations where both measurements are available (Fig. 10). These stations belong to the SRN network (Boulogne and Dunkerque transects) and are all located in the North of the studied area. The continuous line in Fig. 10 corresponds to the linear relation:

$$\text{turbidity} = 0.54 \text{ TSPM} \tag{5}$$

with turbidity in NTU and TSPM in g m^{-3}

Relations (3) and (5) can now be combined and applied to satellite SPM (with its two components, algal and non-algal) to derive satellite turbidity:

$$\text{turbidity} = 0.54 \left(\text{SPM} + 0.234 \text{ Chl}^{0.57}\right) \tag{6}$$

The annual cycles of satellite-derived and in-situ turbidity are very similar (Figs. 11 to 13). The stations where the differences are the highest are located in the Mediterranean Sea (like Toulon and Sud Bastia, see Fig. 13). In these very clear waters, the mean turbidity is also very low (Fig. 14) and the decreasing gradient from inshore to offshore waters in turbidity may be the cause of the large underestimation by the satellite data which may cover more offshore waters. We can also notice that when the number of satellite samples is high, like at Men er Roue (Fig. 12) where it reaches

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525, the satellite and in-situ curves are very close one to each other. A high number of samples from space means that the failures in the atmospheric correction don't occur significantly and that the location of the station is sufficiently far from the coast. It is a criterion of quality. At all those points where the number of satellite samples is superior to 200, the difference between the satellite and in-situ curves is very low.

Figure 15 presents an example of the maps produced to define the initial state of the French coastal environment for the MSFD. All the in-situ stations available around Normandy are shown on the figure. The selected stations, considered as representative, are from West eastwards: "Cabourg_Shifted", "Luc_1_mille", "Ouistreham_1_mille", "St_Aubin_les_Essarts", "Donville", "Chausey". Although some differences may appear locally, the satellite imagery considerably helps to improve the spatial coverage, allowing the extension of the surveillance to the continental shelf in full continuity with the observations of the coastal stations.

3.2 Results for MERIS

Results for MERIS will not be presented in detail at the stations as the patterns of the annual cycles are similar to those observed in-situ and from MODIS. Figure 16 shows the annual averages and P90 of MERIS-derived Chl, SPM, and turbidity compared to in-situ data (reference period is 2007–2009). In that case, the studied period covers only three years. The relation between satellite and in-situ measurements is excellent for the three parameters studied. The improvements compared to MODIS may be caused by several effects: the inherent quality of the MERIS sensor which has one more channel in the blue than MODIS, the in-situ data set which is more recent and expected of better quality, a better adjustment of the MERIS Look-Up-Table fitting a reduced set of data compared to MODIS, . . .

In fact, it is not so important to know at that stage if one sensor is better than the other, what is important for the operational surveillance is that both sensors give similar levels, allowing merging and improving the coverage in space and time (Saulquin et al., 2010).

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4 Conclusions

We have shown in this study that it was possible to handle and process simultaneously environmental data observed in-situ or from space for monitoring the coastal environment. To that purpose, many approximations have been made and simplistic formulations have been assumed. These approximations could be locally or regionally tuned to fit the complex environment of the coastal seas. For example, the simple relations proposed to convert turbidity from FNU to NTU or to derive turbidity from mineral and biological SPM is likely to be variable from one region to another. The satellite data have been processed mostly empirically and the Inherent Optical Properties (IOP) have only been evoked for estimating SPM. Therefore, much could be said on the approximations used in the processing of these data. For example, the relation between the backscattering coefficient and the SPM is supposed linear, whatever the size and the nature of the particles which may vary considerably on the continental shelf of Western Europe (Bowers et al., 2009). The variability of the turbulence leads to different sizes of particle alternatively aggregating trough flocculation, during calm weather, and breaking-up and disaggregating in spring tide or storms. Although the complex transformations of the particles may give them different shapes and sizes, Boss et al. (2009) have observed that the beam attenuation, an IOP, may remain fairly stable relatively to the SPM concentration. This is why the satellite data, processed through empirical methods give useful results, despite the numerous approximations made at the different stages of their processing, from top-of-atmosphere to marine reflectance, from marine reflectance to chlorophyll, SPM and turbidity. This may explain also why close estimations of SPM have been obtained in the plume of the Adour River, in the south of the Bay of Biscay, by Petus et al. (2010) using different empirical formulations (including ours) applied to MODIS reflectances at 1 km and 250 m resolutions. The new turbidity chain that has been defined in this study combines all the kinds of approximations that have just been mentioned. First of all, it could have been defined directly from the backscattering coefficient as, particularly when it is expressed in FNU, the notions are very close. However, we have decided, for ensuring consistency between all the variables, to derive turbidity from chlorophyll (for the phytoplankton part) and non-algal particles.

The new turbidity product defined in this study completes the data set of the environmental variables, Sea Surface Temperature, Chlorophyll, and Suspended Particulate Matter, already available from space for monitoring the coastal environment. We have also attached to those products selected coastal stations where they can be validated for many years onwards. Applications of these products will develop quickly now as they are provided under standard image formats, NetCDF, easy to use, or under the form of more elaborate syntheses, as the merged MERIS/MODIS daily interpolated products. Many requirements for the surveillance and the monitoring can be fulfilled by one or several of these new products.

Monthly averages of Chlorophyll, mineral SPM, and turbidity are presented in Appendix, A, B and C respectively. These maps, covering also the Irish Sea and most of the North-Sea, concern an area larger that the one considered in this study. They have to be validated and probably adjusted but, as they are, they are likely to bring new and valuable information.

Appendix A

Monthly Chlorophyll-*a* concentration over the 2003–2009 period

These monthly Chlorophyll-*a* maps derived from MODIS, as the SPM and turbidity maps, are obtained from the mean of the monthly averages calculated between 2003 and 2009. The reflectance data are considered only for solar zenithal angles inferior to 78°, therefore discarding data in the northern area from the end of November to the end of January.

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Appendix B

Monthly mineral SPM concentration over the 2003–2009 period

The term "Mineral SPM" is used for convenience but it corresponds more exactly to the Non-Algal Particles. It is essentially mineral suspended matter in the area but it can also come from organic particles not related to the phytoplankton bloom. The cells of some particular species may also be more scattering than the average and therefore be classified as mineral. The best example is provided by the coccoliths detached from the dead cells of the coccolithophorides whose calcium carbonate plates give to the surrounding waters a whitish aspect. However their blooms occur at characteristic time and location which make them easy to discriminate. They are very apparent on the SPM maps of May and June. Located initially in the Bay of Biscay they develop northwards, reaching western Ireland and northern Scotland in June in the vicinity of the continental shelf break.

Appendix C

Monthly turbidity in NTU over the 2003–2009 period (MODIS)

The turbidity maps are very similar to the mineral SPM maps. On the continental shelf, the phytoplankton contributes significantly to the turbidity only in case of strong (but episodic) blooms or in presence of coccolithophorides.

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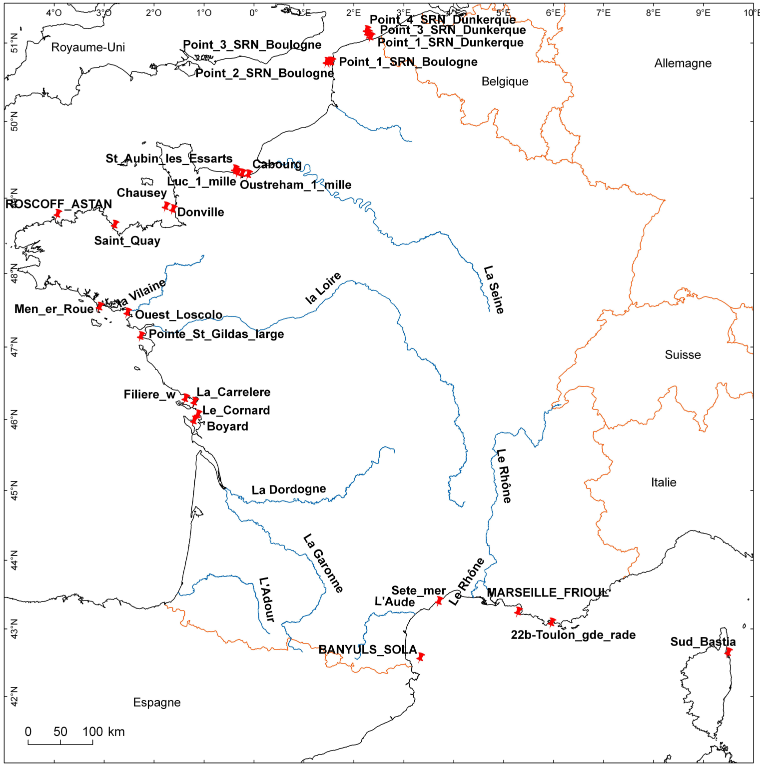

Fig. 1. The 26 stations selected for calibration The stations have the following codes, from North to South, in the networks: "Point_1_SRN_Dunkerque", "Point_3_SRN_Dunkerque", "Point_4_SRN_Dunkerque", "Point_2_SRN_Boulogne", "Point_3_SRN_Boulogne", "Cabourg_Shifted", "Luc_1_mille", "Ouistreham_1_mille", "St_Aubin_les_Essarts", "Donville", "Chausey", "les_Hebihens", "Saint_Quay", "ROSCOFF_ASTAN", "Men_er_Roue", "Ouest_Loscolo", "Pointe_St_Gildas_large", "Filiere_w", "La_Carrelere", "Le_Cornard", "Boyard", "BANYULS_SOLA", "Sete_mer", "MARSEILLE_FRIOUL", "22B_Toulon_gde_rade", "Sud_Bastia".

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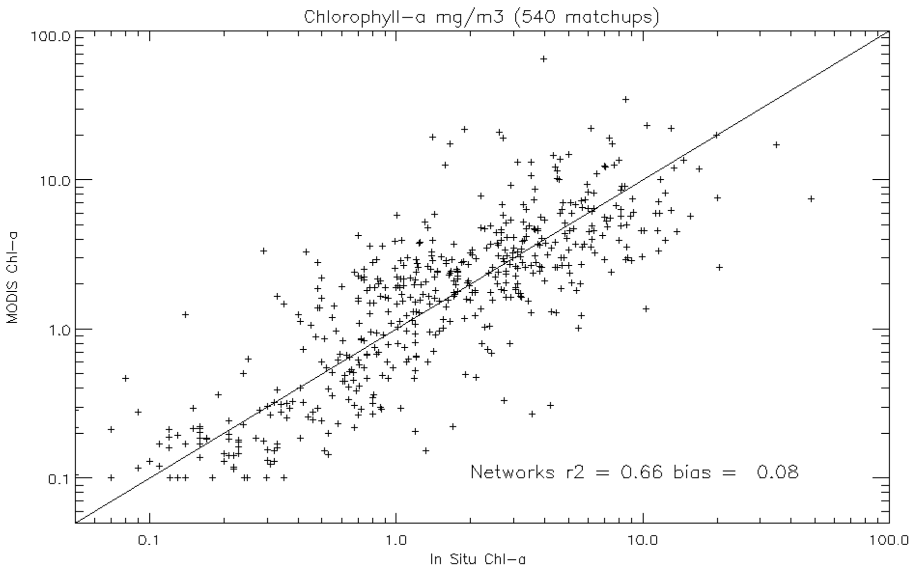

Fig. 2. MODIS-derived Chlorophyll versus in-situ observations at the selected stations.

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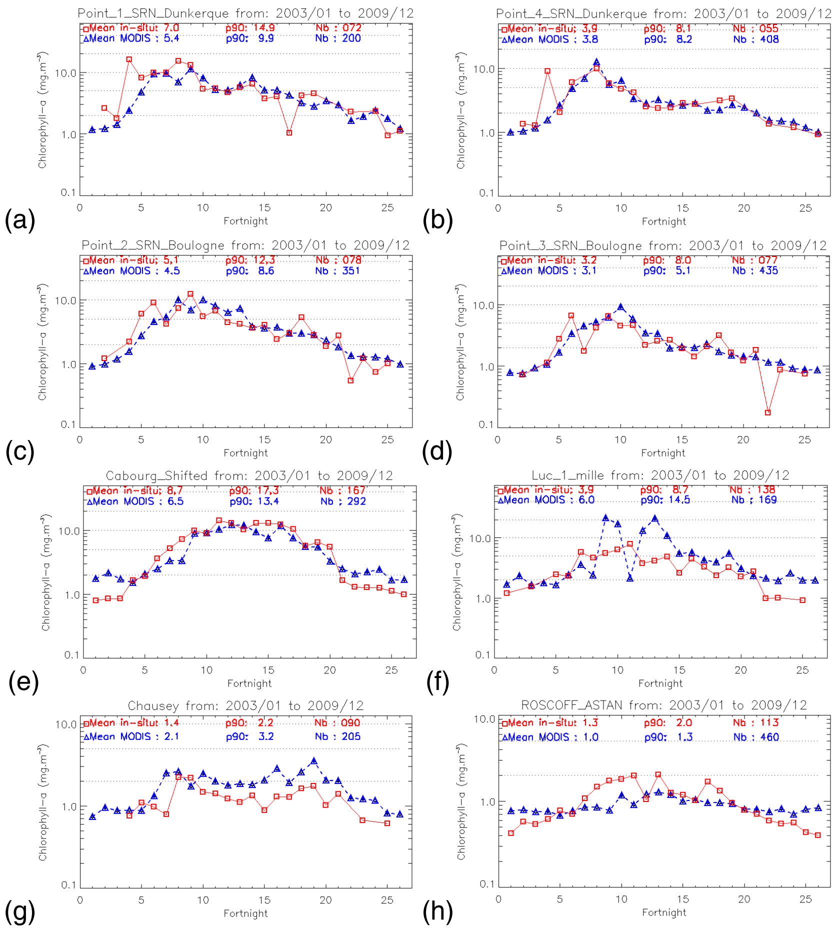

Fig. 3. The annual cycles of chlorophyll at some selected stations from the North-Sea to Northern Brittany. Statistics indicated on the graphs (Mean, p90, Nb samples available) concern the productive season (March to October). For the SRN transects off Dunkerque, Point 1 is coastal and Point 4 the furthest offshore. Same for Boulogne but Point 1 (too coastal) doesn't belong to our selected stations and Point 3 is the farthest offshore.

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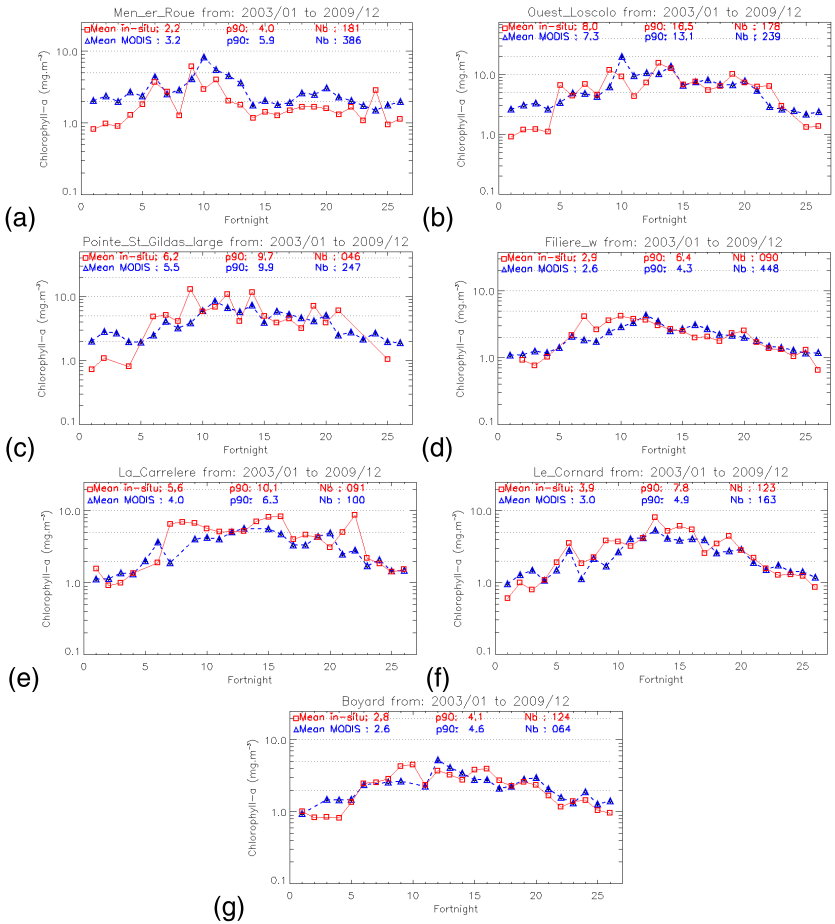

Fig. 4. The annual cycles of Chl at the selected stations of the Atlantic coast.

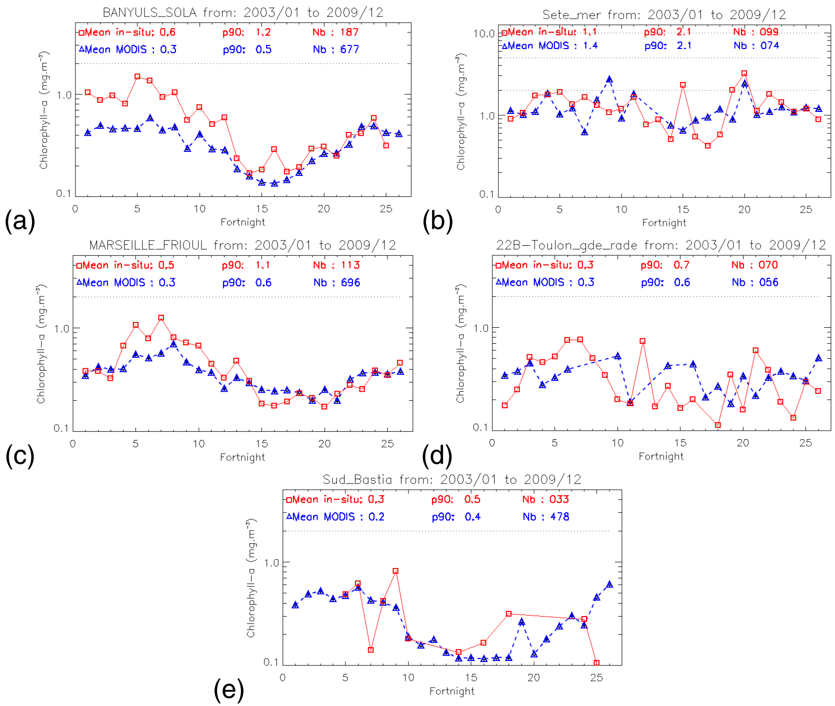

Fig. 5. The annual cycles of Chl at the selected stations of the Mediterranean coast.

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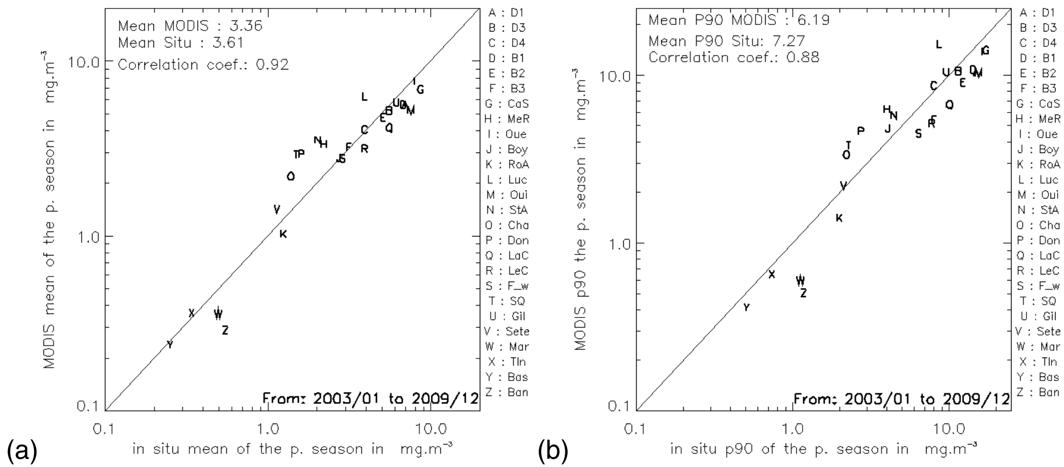

Fig. 6. Average **(a)** and P90 **(b)** of the MODIS and in-situ Chl for the productive season The stations are represented by two or three characters corresponding to the codes defined in Fig. 1. The lowest Chl means and P90s are obtained for Bas ("Sud_Bastia"), Tln ("22B_Toulon_gde_rade"), Mar ("MARSEILLE_FRIOUL") located in The Mediterranean Sea. The highest levels are observed at Oue ("Ouest_Loscolo") and CaS ("Cabourg_Shifted") in the vicinity of the Vilaine (Southern Brittany) and Seine rivers.

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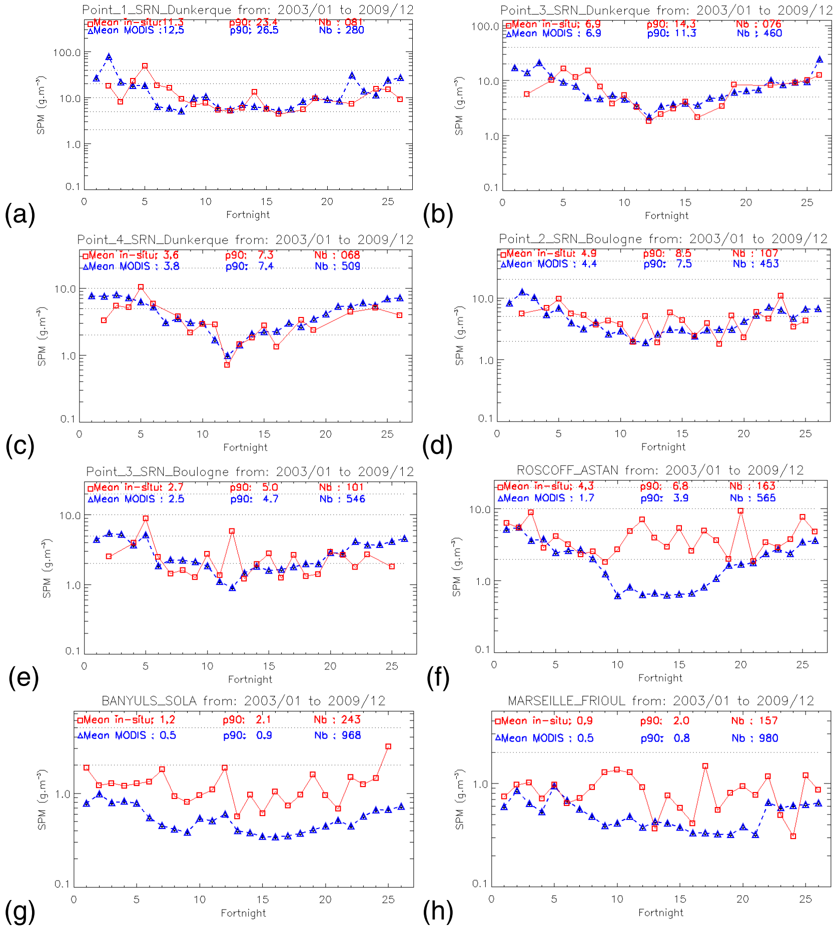

Fig. 7. The annual cycles of non-algal SPM at the 8 selected stations where it is measured. Statistics indicated on the graphs (Mean, p90, Nb samples available) concern the productive season (March to October).

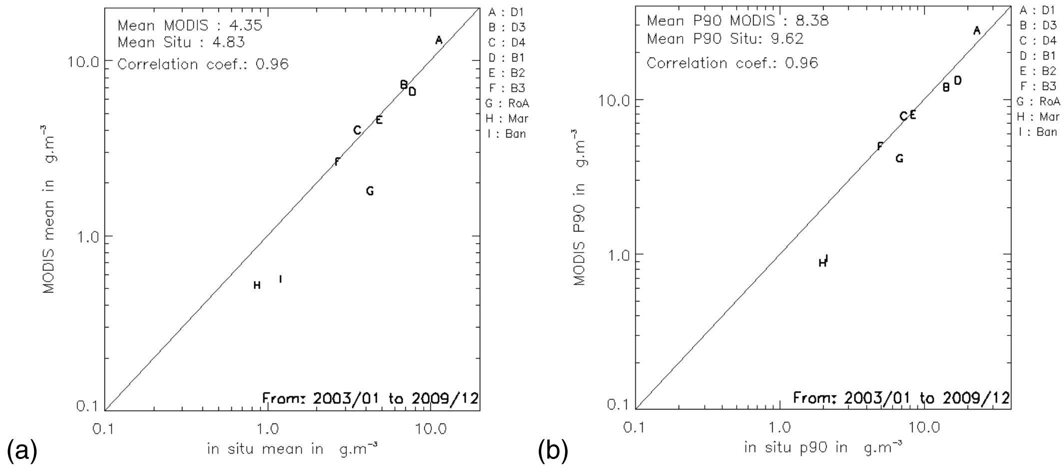

Fig. 8. Annual Average **(a)** and P90 **(b)** of the MODIS and in-situ SPM.

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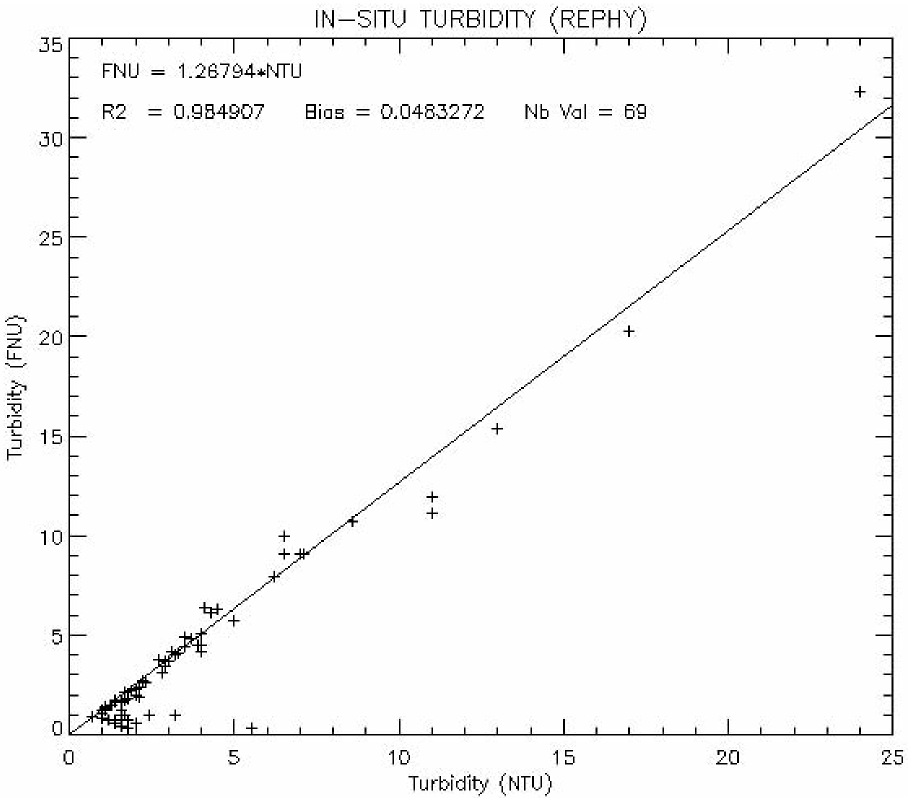

Fig. 9. turbidity in FNU versus turbidity in NTU.

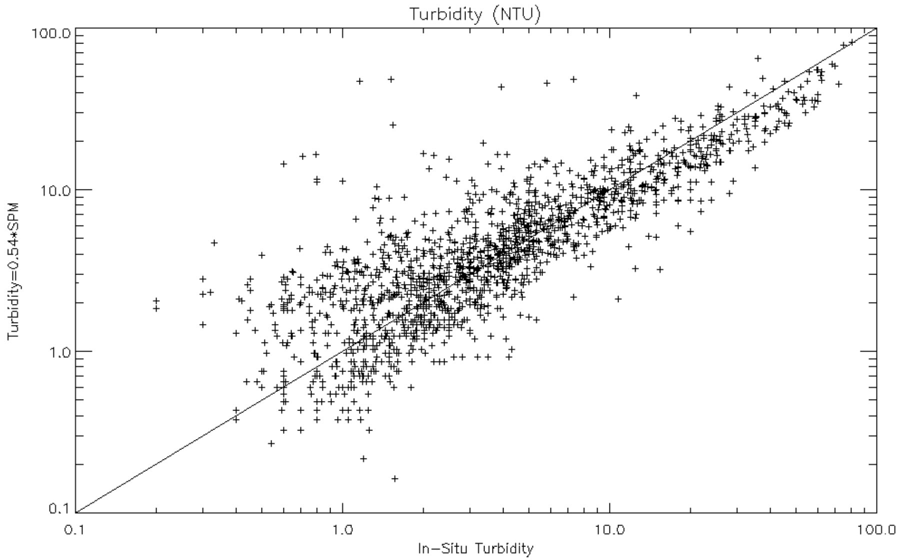

Fig. 10. The scatterplot of turbidity derived from total SPM by Eq. (5) versus observed turbidity (in-situ data collected at the Northern SRN stations).

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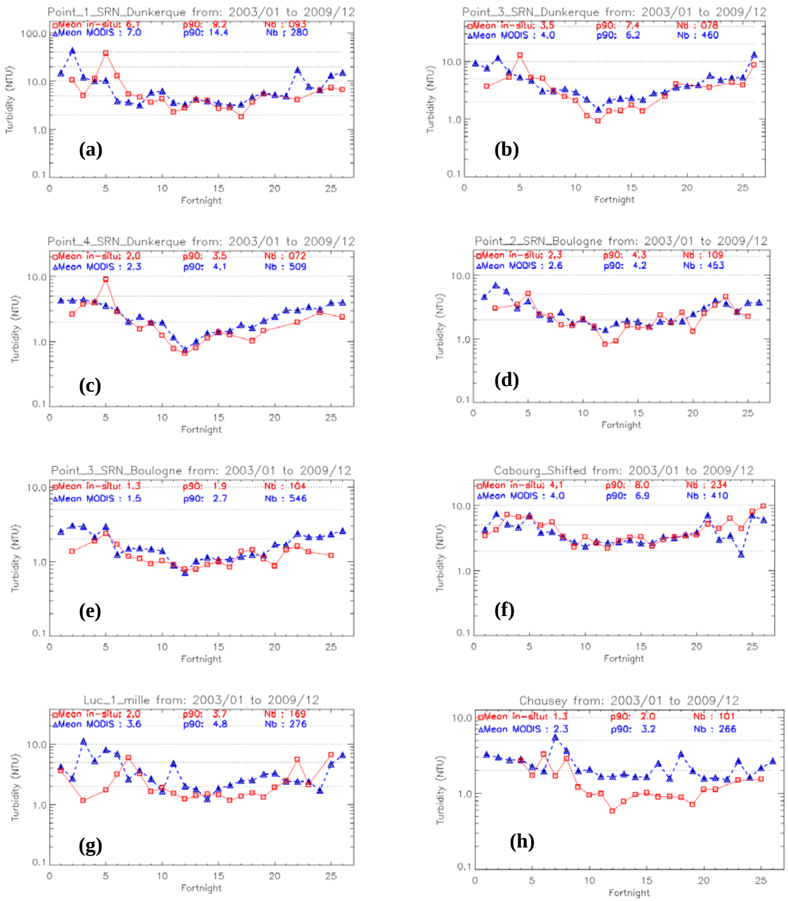

Fig. 11. The annual cycles of turbidity at some selected stations from the North-Sea to Northern Brittany. Statistics indicated on the graphs (Mean, p90, Nb samples available) concern the productive season (March to October).

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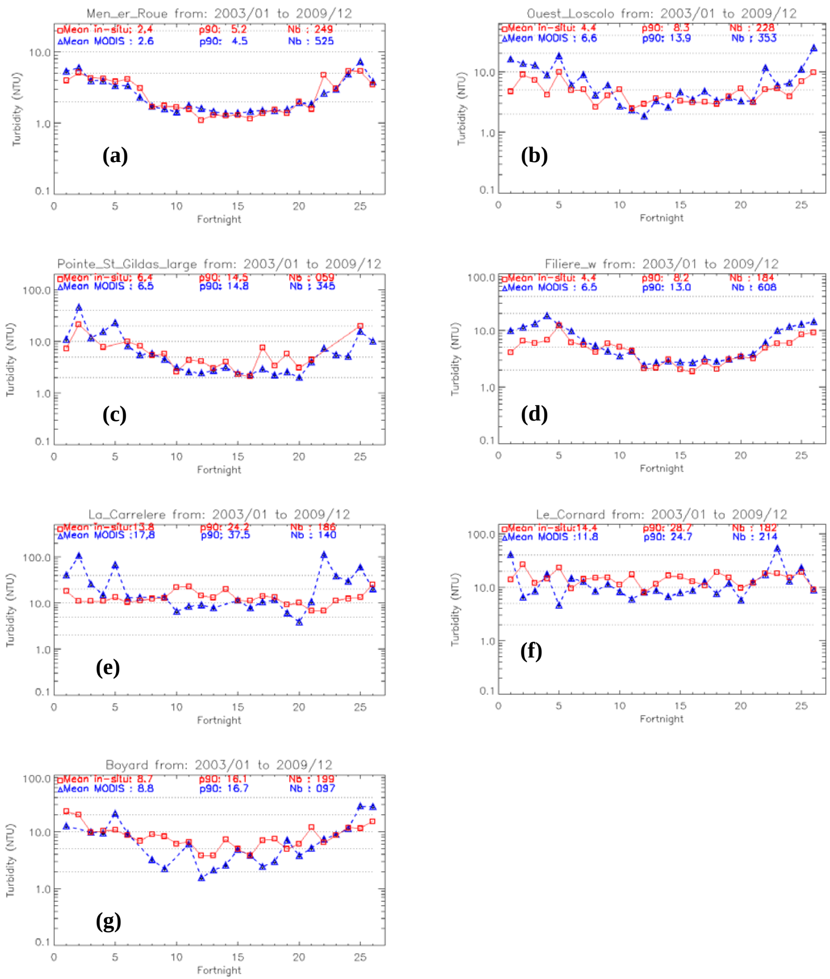

Fig. 12. The annual cycles of turbidity at the selected stations of the Atlantic coast.

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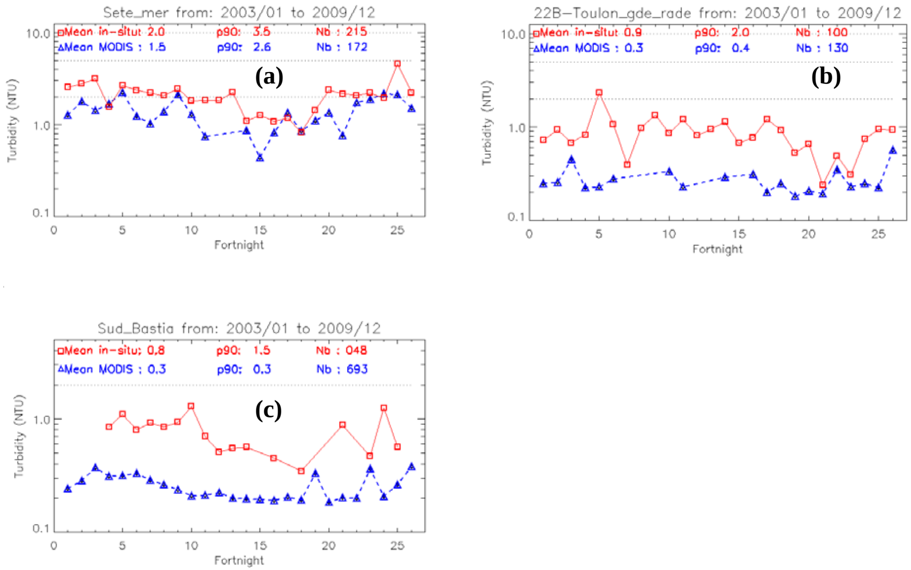

Fig. 13. The annual cycles of turbidity at the selected stations of the Mediterranean coast.

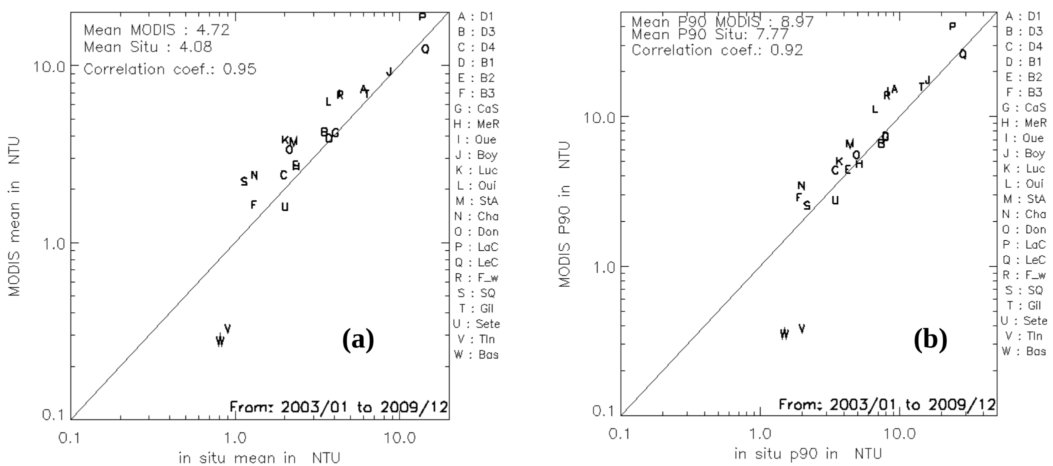

Fig. 14. Annual Average **(a)** and P90 **(b)** of the MODIS and in-situ turbidity.

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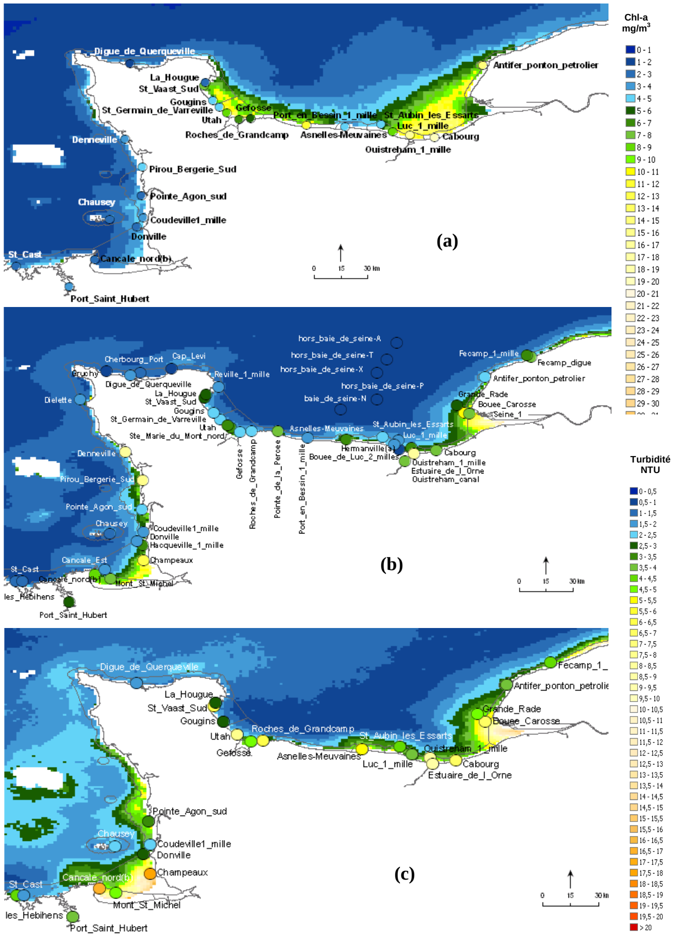

Fig. 15. Percentile 90 of the surface chlorophyll during the productive season **(a)** and mean turbidity during the productive season **(b)** and in winter **(c)** around Normandy. All the in-situ stations are reported on the maps, whatever the number of samples.

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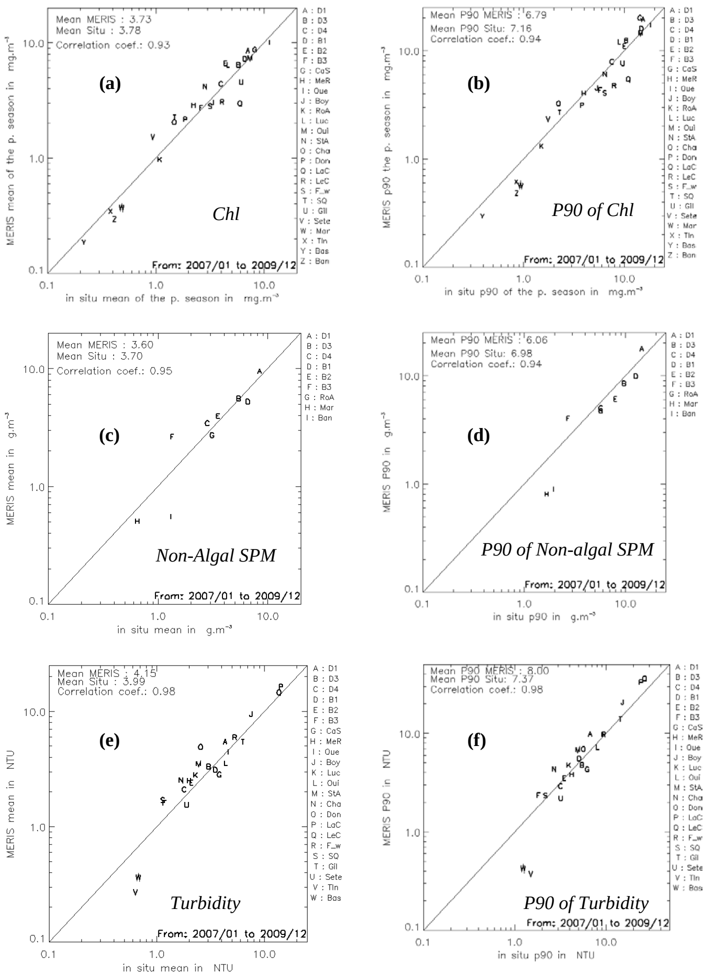

Fig. 16. Average and P90 of MERIS and in-situ Chl (productive period), non-algal SPM, and turbidity (annual).

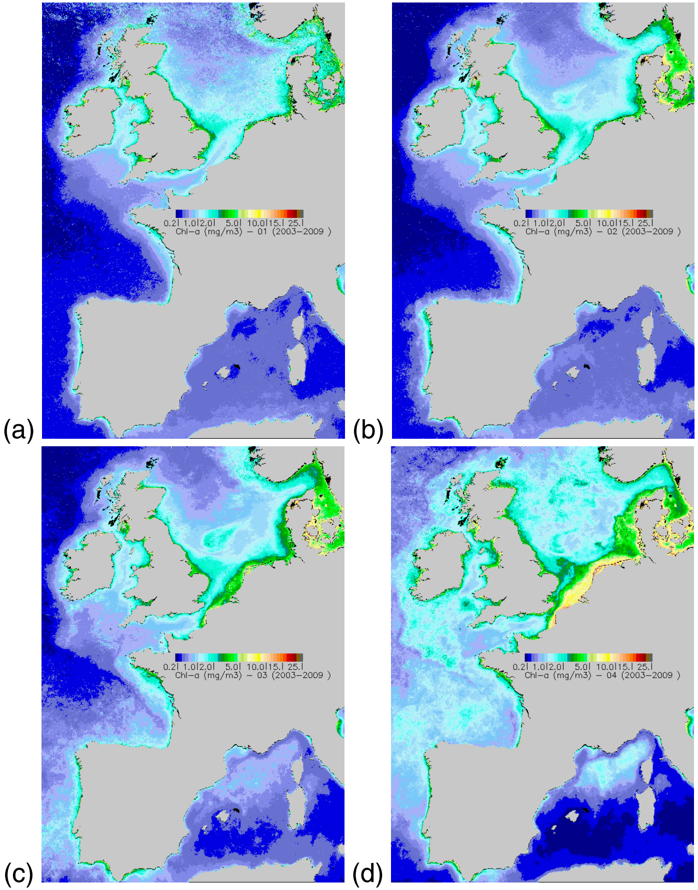

Fig. A1 Monthly Chlorophylle-*a* concentration for January **(a)**, February **(b)**, March **(c)** and April **(d)**.

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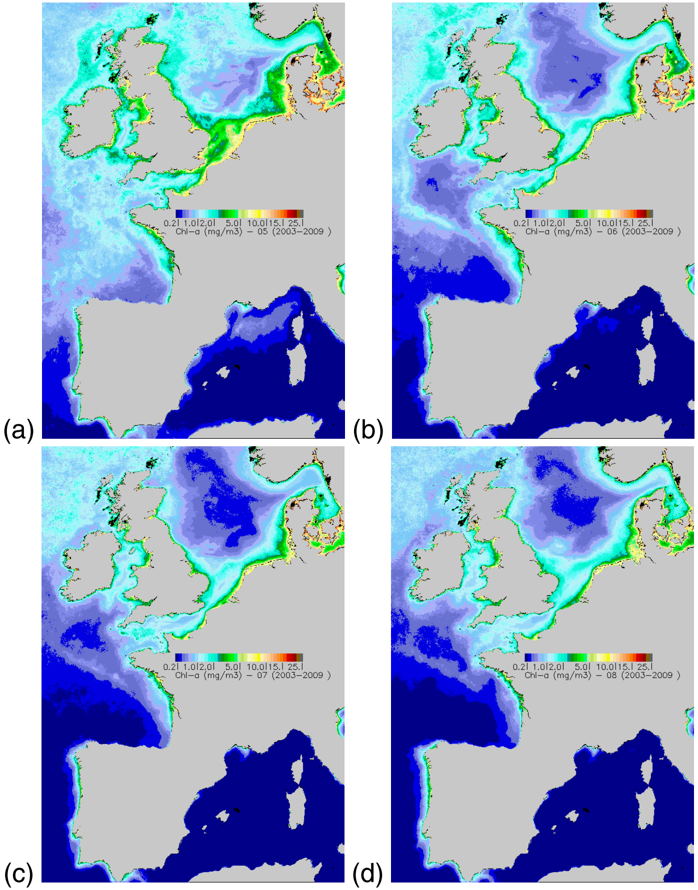

Fig. A2 Monthly Chlorophyll-*a* concentration in May **(a)**, June **(b)**, July **(c)** and August **(d)**.

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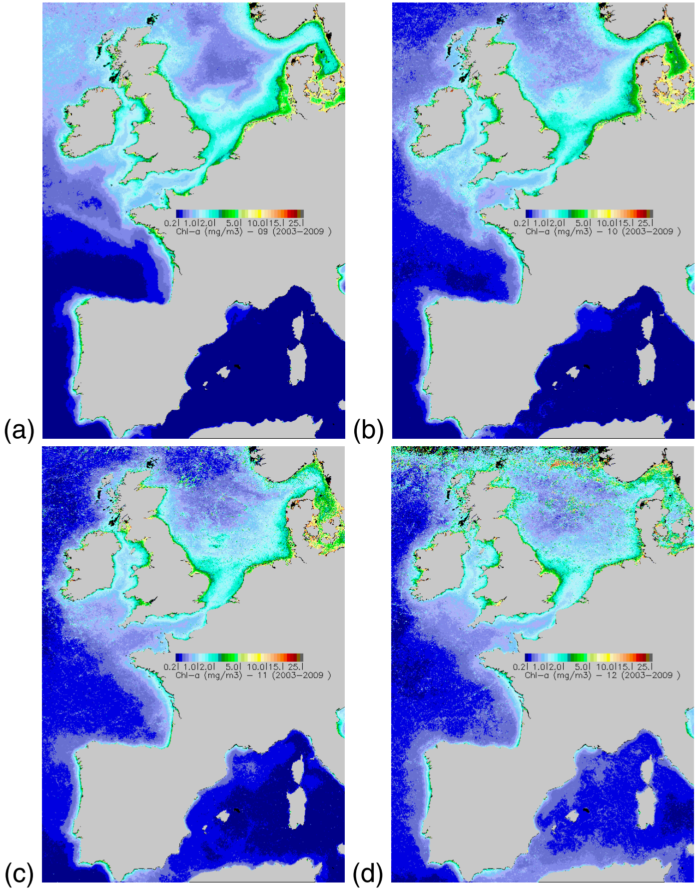

Fig. A3 Monthly Chlorophyll-*a* concentration in September **(a)**, October **(b)**, November **(c)** and December **(d)**.

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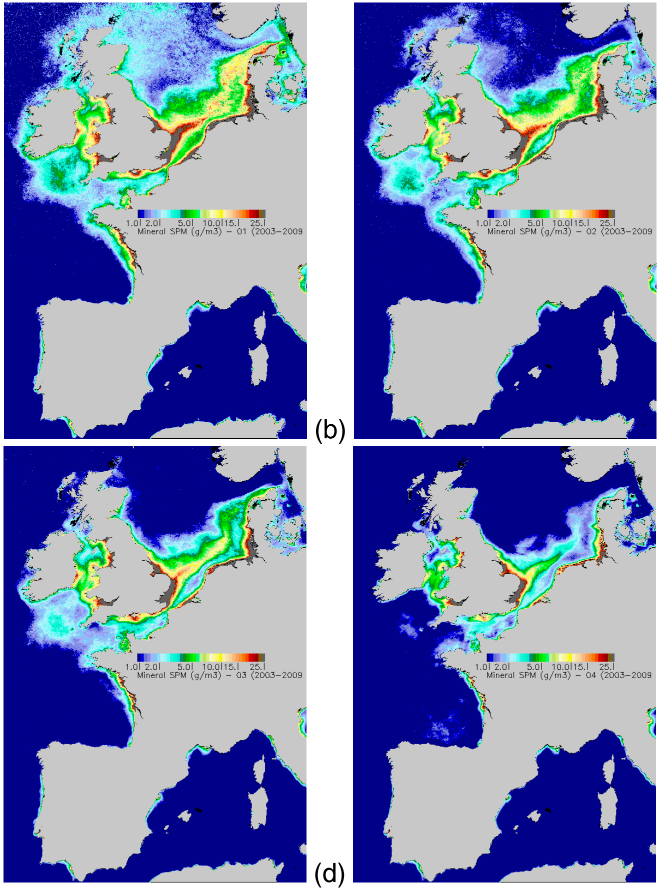

(a) (b) (c) (d)

Fig. B1 Monthly non-algal SPM for January **(a)**, February **(b)**, March **(c)** and April **(d)**.

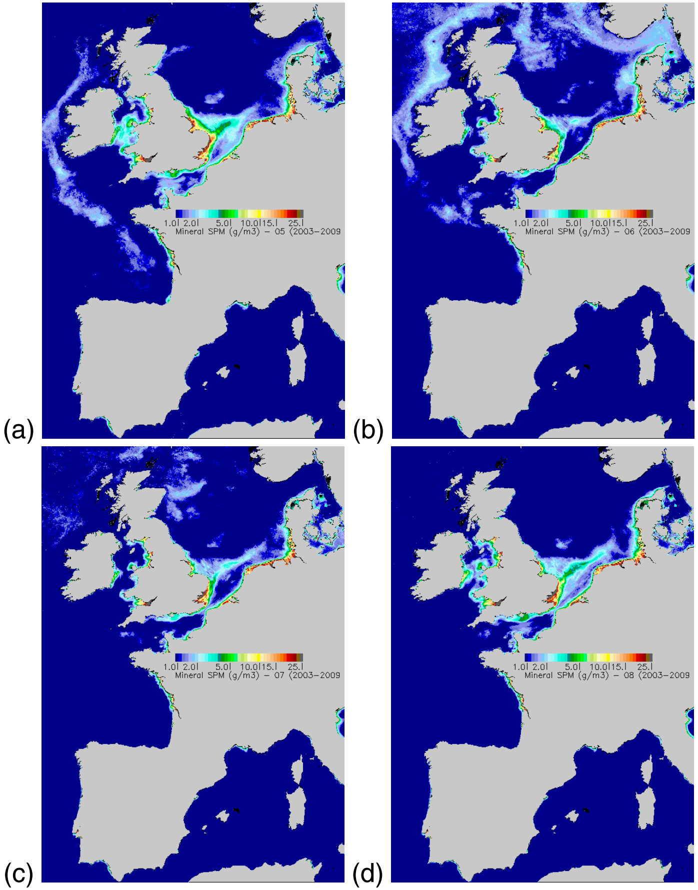

Fig. B2 Monthly non-algal SPM in May **(a)**, June **(b)**, July **(c)** and August **(d)**.

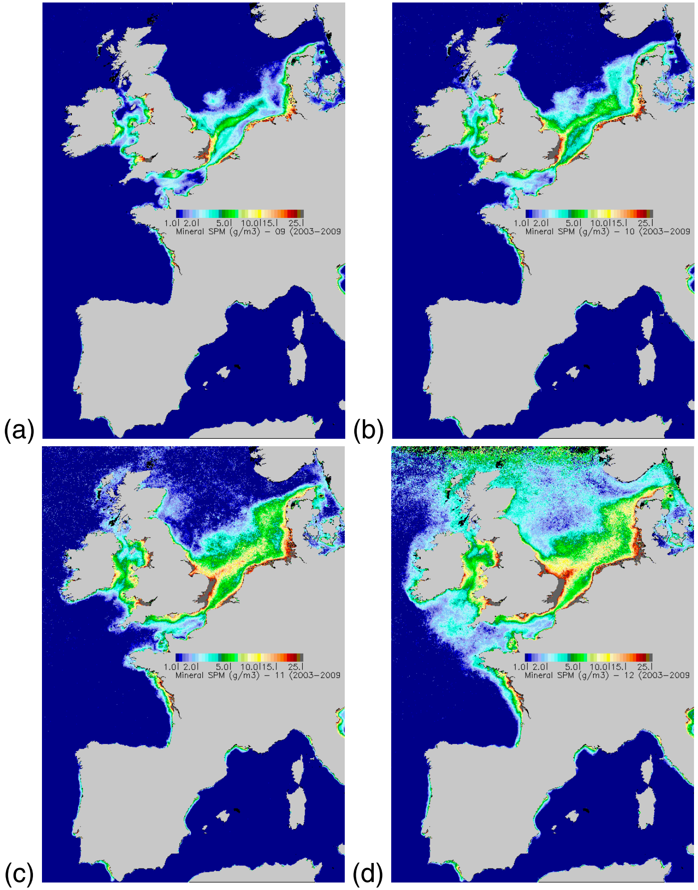

Fig. B3 Monthly non-algal SPM in September **(a)**, October **(b)**, November **(c)** and December **(d)**.

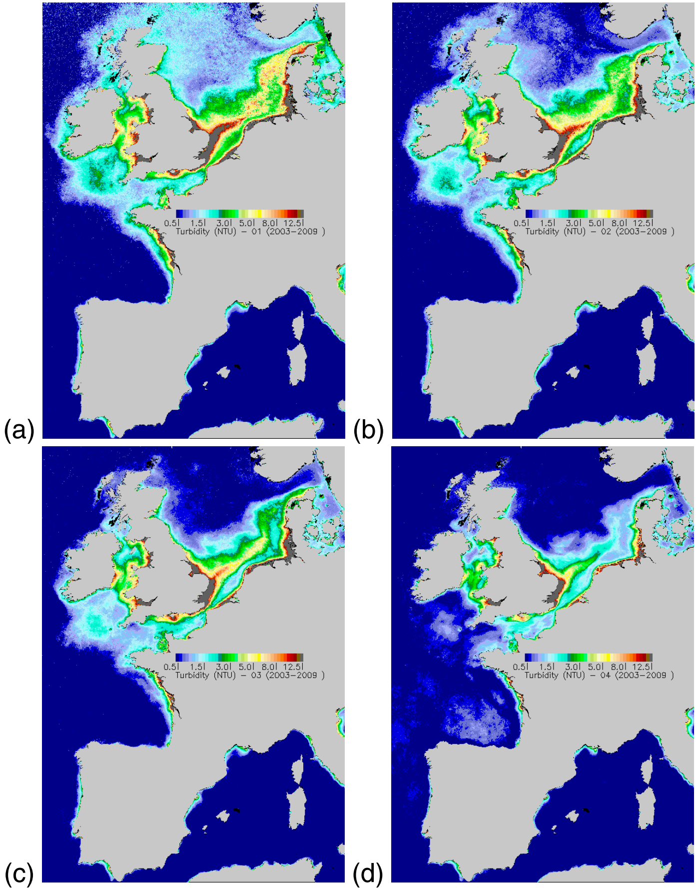

Fig. C1 Monthly turbidity for January **(a)**, February **(b)**, March **(c)** and April **(d)**.

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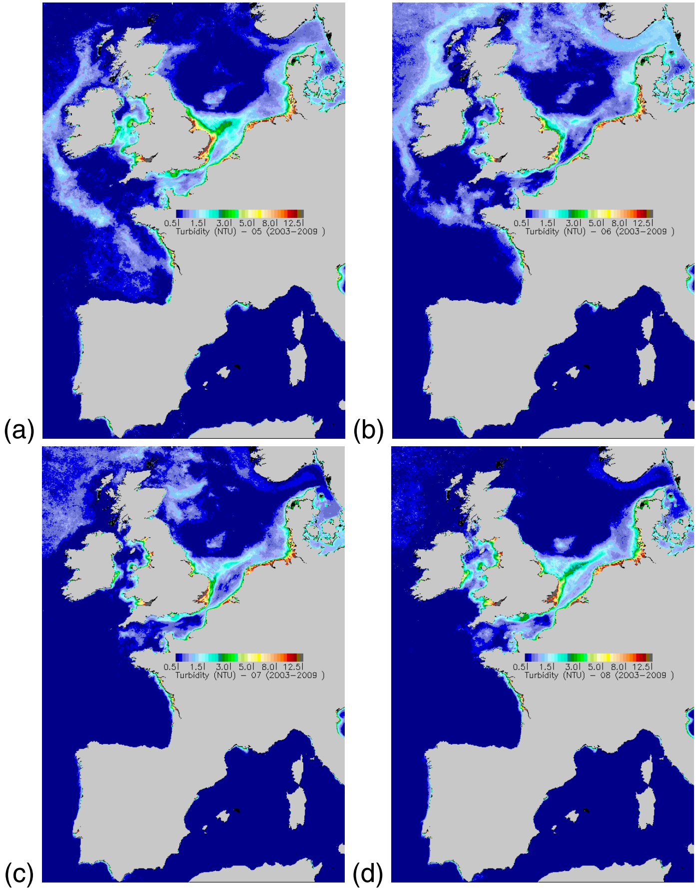

Fig. C2 Monthly turbidity in May **(a)**, June **(b)**, July **(c)** and August **(d)**.

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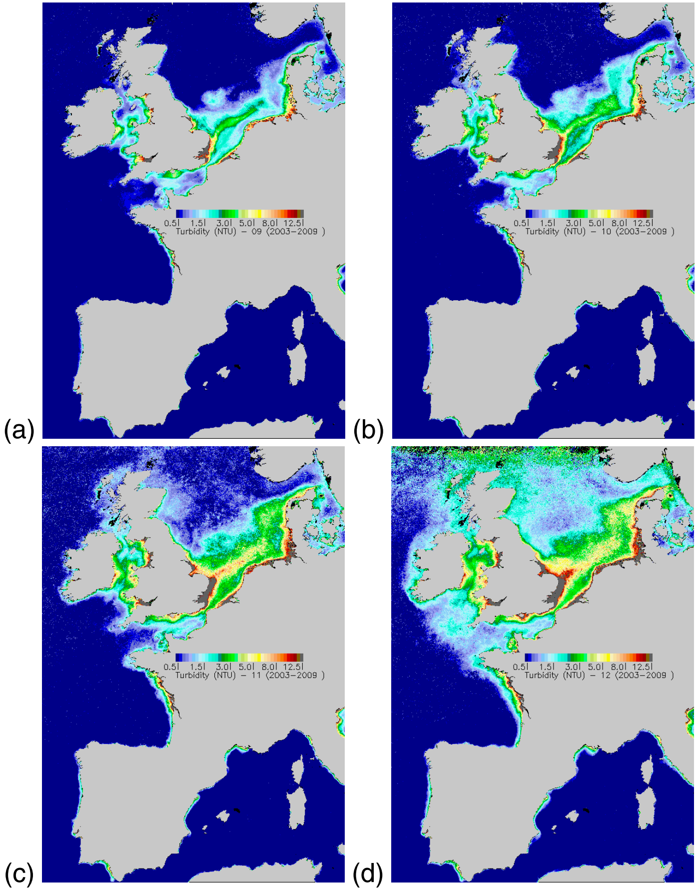

Fig. C3 Monthly turbidity in September **(a)**, October **(b)**, November **(c)** and December **(d)**.