CHLOROPHYLL AND TURBIDITY CONCENTRATIONS AS AN INDEX OF WATER QUALITY OF THE GULF OF GABES FROM MODIS IN 2009

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Soumis le 21 février 2011 ; accepté le 14 mars 2012 - © *Revue Télédétection*, 2012, vol. 11, n° 1, pp. 263-271

Abstract

Optical remote sensing was used to provide scientific information to support environmental management in the Gulf of Gabes located on the southeastern coast of Tunisia. This region is characterized by a shallow continental shelf with semi-diurnal tides. Since the early 1970s, industrial activity in this area may have contributed to the degradation of ecosystem biodiversity due to problems of eutrophication and the disappearance of benthic and planktonic species. Previous studies assessing the long term effects of anthropogenic and natural discharges on the Gulf of Gabes were based on regular seaborne measurements of total suspended matter, Secchi depth, turbidity, chlorophyll and temperature. However, these are often costly and difficult to obtain.

The objective of this study is to carry out an optical remote sensing analysis with supporting in situ measurements of chlorophyll to monitor water quality and the impact of industrial discharges in the Gulf of Gabes. To start with, data provided both by the optical sensor and by our in situ sampling methods is described. Then, semi-empirical algorithms (OC3, OC5) are presented which are used to process Moderate Resolution Imaging Spectrometer MODIS data for retrieval of chlorophyll (CHL) and a validated algorithm for TU. A comparison was made between the derived estimates CHL and TU and the concurrent bio-optical in situ measurements at stations representing the coast and open ocean and produced significant correlations. The results obtained therefore confirm the high sensitivity and useful spatial coverage of MODIS data to provide a significant tool to accurately assess water quality parameters.

Keywords : MODIS; chlorophyll; turbidity; Gulf of Gabes.

EXTRACTION DE LA CONCENTRATION DE LA CHLOROPHYLLE ET DE LA TURBIDITÉ COMME UN INDICE DE LA QUALITÉ DE L'EAU DANS LE GOLFE DE GABES DURANT L'ANNÉE 2009 À PARTIR DES DONNÉES MODIS.

Résumé

Les activités industrielles et de service, les déchets anthropiques et naturels et la pêche intensive ont contribué à la dégradation de la biodiversité de l'écosystème du golfe de Gabès. Cette situation a entraîné des problèmes d'eutrophisation et de disparition de certaines espèces benthiques et planctoniques, avec perte du couvert végétal de l'ordre de 90 %, conduisant à l'installation de biocénoses caractérisées par une faune et une flore de milieux envasés et dégradés. Deux campagnes de mesure en mer ont été effectuées pour mesurer la concentration de la chlorophylle, ainsi que la turbidité, la concentration de la matière en suspension, la transparence et la température de l'eau dans le golfe de Gabès. Les campagnes menées en juillet et en octobre 2009, ont été réalisées respectivement sur 30 et 28 stations. Les premières sont réparties dans l'ensemble du golfe et les secondes concernent 3 sites avec 11 stations dans chacune des régions du port de Gannouch et de Skhira et 6 stations dans la région de Sfax Kerkennah. Les résultats de ces deux campagnes de mesure ont servi de base pour une première validation des données satellitaires Moderate Resolution Imaging Spectrometer MODIS AQUA. La chlorophylle a été cartographiée à partir de deux algorithmes publiés (OC3 et OC5). L'exploitation des données satellitaires a permis de décrire la variabilité saisonnière et spatiale de la concentration de la chlorophylle et de la turbidité de la surface de l'eau. L'analyse et l'interprétation des cartes journalières et mensuelles de la concentration de la chlorophylle satellitaire, générées pour l'année 2009, montrent une cohérence par rapport aux données mesurées avec toutefois une forte surestimation des concentrations de la chlorophylle aux alentours des îles Kerkennah, Kneiss et Jerba pour OC3, une surestimation moindre par l'algorithme OC5 avec une corrélation de l'ordre de 80% qui montre donc des résultats beaucoup plus satisfaisants pour la bande littorale du golfe de Gabès.

Mots clé : MODIS, chlorophylle, turbidité, golfe de Gabès

1. INTRODUCTION

Services and industrial activities, anthropic and natural discharges and intensive fishing activities have contributed to the degradation of the ecosystem biodiversity in the Gulf of Gabes (Ben Mustapha *et al.,* 1999). Industrial activity which began in the seventies in the region of Gannouch notably deteriorated the environment. Studying primary production, temporal and spatial distribution of phytoplankton and water quality requires many costly seaborne measurements. Preliminary studies of Curan *et al.* (1987), Deschamps *et al.* (1987), Jaquet *et al.* (1999) and more recent research (Doxaran *et al.,* 2002, Ouillon *et al.,* 2008, Nechad *et al.,* 2010 and Dupouy *et al.,* 2010) have allowed to analyze coastal surface waters by means of satellite remote sensing and examined the empirical relationships between *in situ* reflectance and concentration of Total Suspended Matter (TSM), turbidity (TU), and chlorophyll (CHL). Many versions of algorithms have been developed depending firstly on the sensor type and secondly on the classification of waters proposed by Morel and Prieur (1977). In case 1 water, optical properties are dominated by CHL and associated degradation products. In coastal waters, classified as case 2, suspended particulate sediments and yellow substances of terrestrial origin, which are not co-varying with CHL, lead to a greater number of errors in estimating chlorophyll concentration (Carder *et al.,* 1991; Gohin *et al.,* 2002).

TSM can be estimated via the optical properties of suspended particles assuming, either directly or indirectly, a constant relationship between particle mass and particulate scattering. It is well known that, in reality, the relationship between particle mass and optical properties varies as a function of particle size and composition (refractive index). A family of TSM retrieval algorithms was described by Nechad *et al.* (2010) based on inversion of a theoretical model giving reflectance at a single wavelength as an increasing function of TSM. Such algorithms for the red bands (600-700 nm) of the Moderate Resolution Imaging Spectrometer (MODIS), Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Medium-Spectral Resolution, Imaging Spectrometer (MERIS) were used on the Gulf of Gabes (Katlane *et al*., 2011).

Chlorophyll is usually estimated from the ratio of blue to green water leaving radiance or from remote sensing reflectance Rrs using an empirical relationship and semi-analytical bio-optical models (Babin *et al.*, 2003 and Gordon *et al.*, 1988). Several versions of algorithms have been established to model CHL: OC2, OC3 and OC4 (O'Reilly *et al.*, 2000; Maritorena *et al.*, 2002) in order to find the best statistical relationship between *in situ* measurements and remote sensing reflectance (Log-Log regressions). The OC2 algorithm for the Coastal Zone Color Scanner (CZCS) uses the Blue/Green ratio Rrs(490)/Rrs(555). The OC4 algorithm (SeaWiFS) uses a single set of coefficients determined by the greatest ratio of Rrs(443)/Rrs(555), Rrs490)/Rrs(555) and Rrs(510)/Rrs(555) (O'Reilly *et al.*, 2000). The OC3 algorithm (MODIS-A) uses the maximum ratio Rrs(443)/Rrs(551) and Rrs(488)/Rrs(551). Finally, the latest published version is OC5 (Gohin *et al.*, 2002), which is a bio-optical empirical for MODIS, MERIS and SeaWifs data suited for case 2 French coastal waters. This algorithm tends to correct overestimation of chlorophyll in turbid waters by using a lookup table adapted to the French Northern Coastal waters based on thresholds of Rrs at 555 nm and 412 nm.

The objective of our study was to monitor water quality and the impact of industrial discharges on the chlorophyll surface concentration in the Gulf of Gabes with MODIS imagery. At first, our *in situ* sampling methods are described. Then, our 2009 data set provided from different sources, satellite, *in situ* optical sensors and laboratory analysis is presented. Chlorophyll and turbidity from MODIS data are retrieved by applying semi-empirical algorithms; information is then extracted, quality is controlled and data is validated. Then, CHL is mapped from both OC3 and OC5 algorithms for clear daily images from 2009 and data are extracted at station locations, while TU is mapped using a previously validated algorithm.

2. STUDY SITE

The Gulf of Gabes, part of the Pelagian Sea as described in Burollet *et al.* (1979), is located in southeastern Tunisia. It has a shallow continental shelf with a gentle slope extending 250 km offshore and ranging from 0.7 m up to 50 m in depth (figure 1). The hydrodynamics of this area are influenced by semi diurnal tides with maximum amplitude of 1.8 m in Gabes and a minimum of 0.3 m (Sammari *et al.,* 2006). The climatology of the studied area is influenced by the temperate, humid and hot Mediterranean air coming from the east, and also by the subtropical, dry, hot and sandy Saharan air coming from the southwest (Sogreah, 2002).

Intensive fishing, as well as natural and anthropogenic wastes, has contributed to the degradation of ecosystem biodiversity in the Gulf (Ben Mustafa *et al.,* 1999). Industrial activities causing heavy environmental deterioration began in the region of Gannouch in the seventies. The study done by Bjaoui *et al.* (2004) showed that phosphogypsum pollution, which comes from the production of phosphoric acid, covers over 60 km² of the area. From multitemporal TU maps produced from MODIS for 2009, areas around the islands (Kerkenah, Kneiss and Jerba) and at the industrial port of Gannouch, we showed that these areas are characterized by high values of turbidity, which can extend towards the center of the Gulf over distances of 70 km (Katlane *et al.,* 2011).

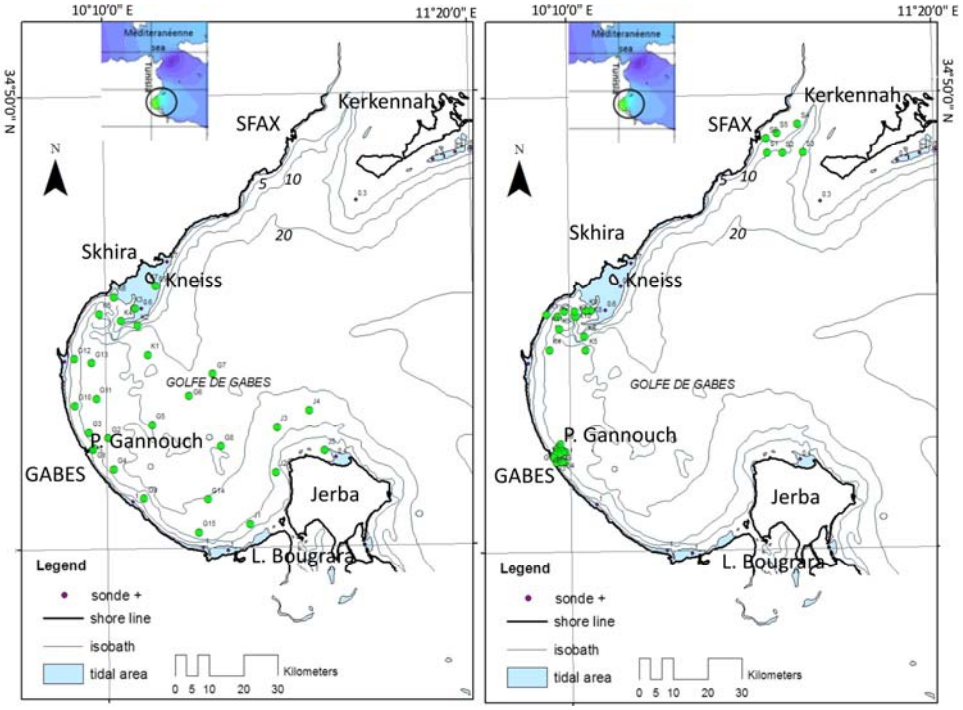


Figure 1 : Location of sampled stations, July 2009 on the left and October 2009 on the right. Green circles indicate the position of *in situ* measurements. Station numbers are indicated. *Localisation des stations de mesures : juillet 2009 à gauche et octobre 2009 à droite ; les cercles verts indiquent les positions des mesures in situ. Les noms des stations sont indiqués.*

3. METHODOLOGY

3.1 MODIS AQUA data

Satellite imagery from 2009 for the Gulf of Gabes from MODIS AQUA provided by the National Aeronautics and Space Administration (NASA), Ocean Biology Processing Group (OBPG) was used in this study. Level 2 (L2) satellite data products, available from http://oceancolor.gsfc.nasa.gov/ contain the geophysical value for each pixel, derived from Level-1B (L1B) radiance after radiometric calibration, atmospheric correction and bio-optical algorithms. Level 1 (L1B) calibrated radiance at 1Km resolution (MYDO21 km) was also downloaded from the Level 1 Atmosphere Archive and Distribution System (LAADS; ladsweb.nascom.nasa.gov/data/). These L1B data were used to support the L2 data to subjectively check the quality of the atmospheric correction implemented by NASA. Geometric correction was done with SeaDas on L2 geophysical products. MODIS L1B and chlorophyll L2 data using SeaDas and IDL software were processed and validated with *in situ* data. The flow chart shows the approach for processing and interpreting the data to generate chlorophyll maps (figure 2).

Chlorophyll was mapped using OC3, the semi-analytical algorithm for MODIS adapted to case 1 waters (O'Reilly *et al.,* 2000). The standard MODIS OC3 Chlorophyll algorithm uses the following formula:

$$[\,CHL_a = 10^{**}(a0 - a1*R + a2*R^2 + a3*R^3 - a4*R^4) \qquad (1)$$

where R (Ratio) is the greatest log ratio of Rrs(443)/Rrs(555), Rrs(490)/Rrs(555), and Rrs(510)/Rrs(555), and a0=0.283; a1=-2.753; a2=1.457; a3=0.659 and a4=-1.403.

Indeed, as the resuspension of the bottom sediments due to tidal effects and the phosphosgypsium wastes 4700 m3/h (Sogreah, 2002), the waters in the shallow coastal regions were classified as case 2 according to the classification established by Gordon and Morel (1983). This conclusion was made from TU maps issued from the algorithm applied to MODIS channel 667nm (Katlane *et al.*, 2011). Recall that values of TU in this paper was estimated using the bio-optical algorithm dedicated to coastal waters of Nechad *et al.* (2009) applied to MODIS remote sensing reflectance at band 667 nm (Rrs 667) and validated for the same area (Katlane *et al.*, 2011). For this reason, chlorophyll was mapped using OC5 (Gohin *et al.*, 2002) applied to L2 MODIS remote sensing reflectance at the 5 dedicated bands, and compared to OC3 to compare performance of both algorithms in case 2 waters of the Gulf.

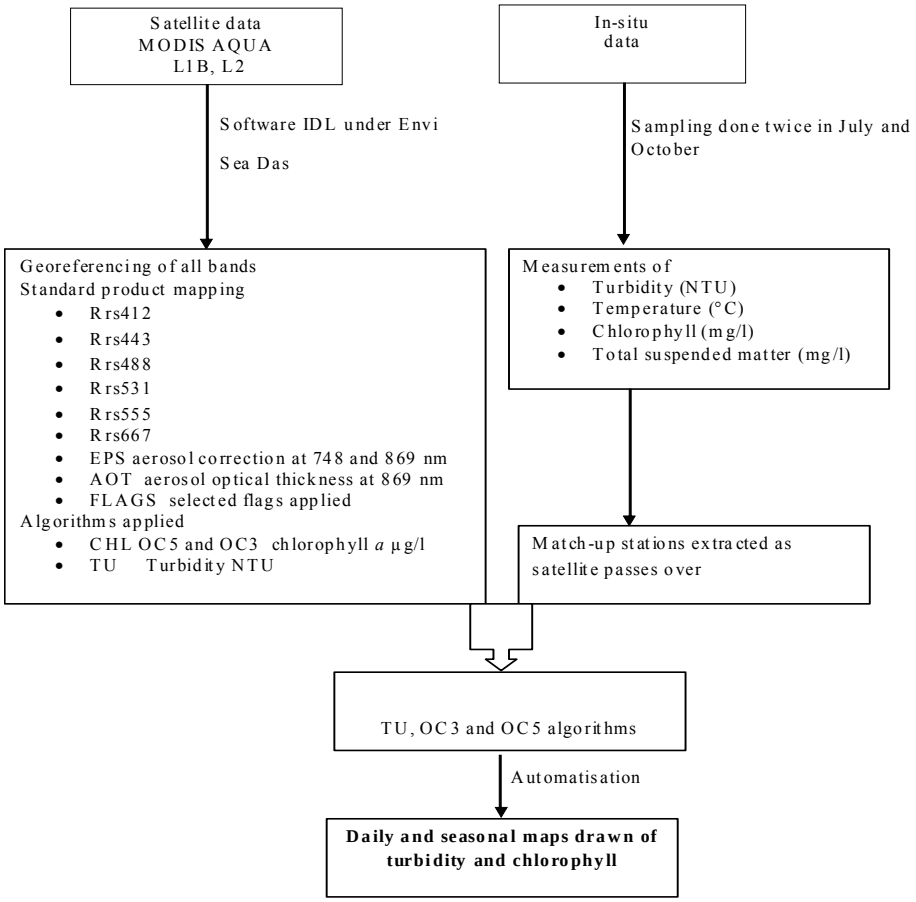


Figure 2 : Flow chart of the methodology adapted to map TU and CHL. *Organigramme de la démarche suivie pour l'interprétation des images niveau 2 MODIS, (L2) et la génération de cartes de la chlorophylle a et de la turbidité.*

3.2 *In situ* data

In situ data were collected from the 5th to the 7th of July 2009, and on the 6th, 8th and 19th of October 2009, concurrently with the satellite overpasses (Katlane *et al.,* 2011). Station locations are shown in figure 1. These seaborne measurements consist of chlorophyll *a* (µg/l or mg.m-3) shown at Table 1. Concurrent TU (NTU), water transparency (m^{-1}), TSM (mg/l), and temperature (°C) results are provided for the same stations in Katlane *et al.* (2011).

Chlorophyll *a* was measured by the spectrophotometric method in the GREEN LAB laboratory (Tunisia). Full details of the method can be found in REVAMP protocols (Tilestone, 2002) .Turbidity, suspended matter, and water transparency using a Secchi disk were measured as in Katlane *et al.* (2011).

Table 1 : Summary of measurement ranges; CHL: Chlorophyll concentration (µg/l) (see locations in figure 1). Minimum and maximum values for measurements taken in July and October 2009. *Résultats des mesures de la chlorophylle dans le golfe de Gabès; CHL : concentration en chlorophylle µg/l ; (voir stations figure 1). Minimum et maximum de mesures pour les deux dates juillet et octobre 2009.*

Locations	CHL (µg/l) min July	CHL (µg/l) max July	CHL (µg/l) min October	CHL (µg/l) max October
Port of Gannouch	0.7	1		-
Jerba	0.5	1.6		-
Kneiss	0.5	4.7	0.5	1.6
Lagune Bougrara	14	14		-
Sfax-Kerkennah	0.5	-	0.5	1.3

4. RESULTS AND DISCUSSION

The 2009 MODIS images were processed and only those without high sun glint, heavy cloud cover or atmospheric correction problems were kept for the validation study (59 scenes in 2009). The approach to product validation for CHL (2) was by "match-up", comparing the data value for a satellite pixel with an *in situ* measurement from a location within that pixel and acquired almost simultaneously. MODIS CHL data were extracted around match-up stations using a 3x3

box. In order to obtain relationships, only the pixels where *in situ* measurements were taken at the time of satellite overpass (+/-30 min) were considered, in order to avoid uncertainty from tidal effects (bottom sediment resuspension).

The scatter plots between *in situ* measurements and MODIS CHL derived from OC5 or OC3 (figure 3) show similar correlations (68 and 62%, respectively). OC5 allows a better retrieval of chlorophyll concentrations (CHLMODIS_OC5= 1.11 CHLin-situ) whereas OC3 overestimated chlorophyll (CHLMODIS_OC3= 2.78 CHLin-situ). The value at the top of the regression corresponds to a Kneiss mid-water station and was left in the regression. Examples of TU and CHL maps are given for the dates of July 5th, 2009 (figure 4) and October 8th, 2009 (figure 5). For CHL, the MODIS ocean color Standard NASA OC3 algorithm is known to overestimate chlorophyll in coastal waters of the Mediterranean area (Jaquet *et al.,* 1999 and Barale *et al.,* 2008). This overestimation is not as high with OC5 as shown by the July 5th image (figure 4b), or by the October 8th image (figure 5b), compared with images obtained with OC3 (figure 4c, figure 5c). This is especially true around Kerkennah, Kneiss and Jerba islands and Bougrara lagoon where remaining high CHLOC5 values are probably linked to shallow water and bottom reflection (as an example the highest value at Kneiss).

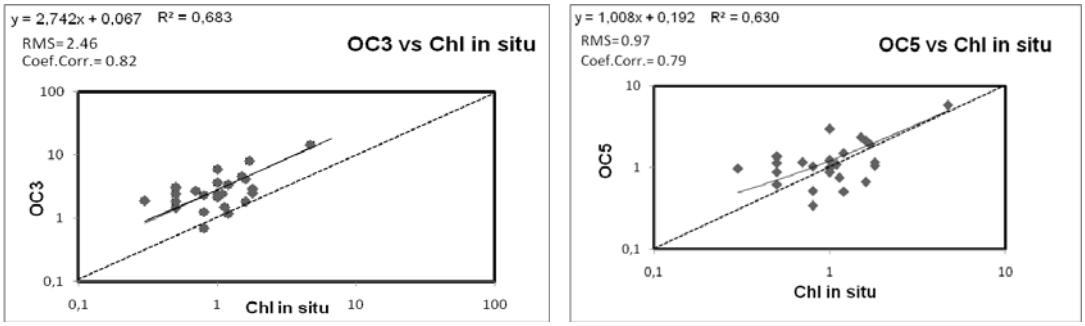


Figure 3 : Scatter plot of MODIS-derived CHL (µg/l) versus seaborne CHL (µg/l). On the left, CHL MODIS modeled from OC3; on the right, CHL MODIS modeled from OC5. *Relation entre CHLMODIS et CHL in situ (µg/l) in situ. A gauche, calculée à partir d' OC3, à droite calculée à partir d'OC5.*

The MODIS satellite images of CHL and TU show different distributions throughout the study area (figures 4 and 5). The TU maps derived for the 5th July and 8th October 2009 (figures 4a and 5a) as well as the other images processed in 2009 (Katlane *et al.,* 2011) show a maximum value of about 10 NTU around the Gulf islands and 7 NTU in the region of Gannouch, confirming that the coming out of turbidity is from the industrial port, and spread over the Gulf (c). Apart these maximum, the highest TU concentrations are located around the islands (Kerkennah, Kneiss and Jerba) and also in the industrial port of Gannouch.

The distribution of the chlorophyll according to the CHL OC5 images (figure 4b and 5b) shows a maximum of 20 mg/m^3 around Gulf islands and Bougrara lagune. However CHL OC5 chlorophyll in the southwest port of Gannouch is about 3 mg/m^3. This proves the performance of the OC5 algorithm applied, excepted around the Sfax region, and in the areas surrounding the Kerkennah, Jerba and Kneiss islands when TU and CHL OC5 record the highest values, when compared to deeper neighboring regions, especially the center of the Gulf of Gabes (c). Such high values remaining after the OC5 algorithm application are mainly due to the shallowness of the water causing enhanced bottom reflection.

The monthly distribution concentration of CHL for 2009 records its highest values in August, September and October, due to algal blooms during these months, as shown for the September 16th image around the Gulf islands and in the southwest port of Gannouch (figure 6). In fact, according to data from the National Network for Monitoring of Phytoplancton during the period of 1995-2005 (Fekki *et al.,* 2008, Bel Hassen *et al.,* 2008 and Bel Hassen *et al.,* 2009), different phytoplancton classes are found in the coastal area especially in the lagoon of Bougrara (Djerba island southwestern Gulf of Gabes) than near the Port of Gannouch and than in the central part of the Gulf of Gabes. The *in situ* observations show that the period from August to January, with peaks in September and January, seems to be favorable to algal blooms. This confirms qualitatively our data outcome from MODIS images.

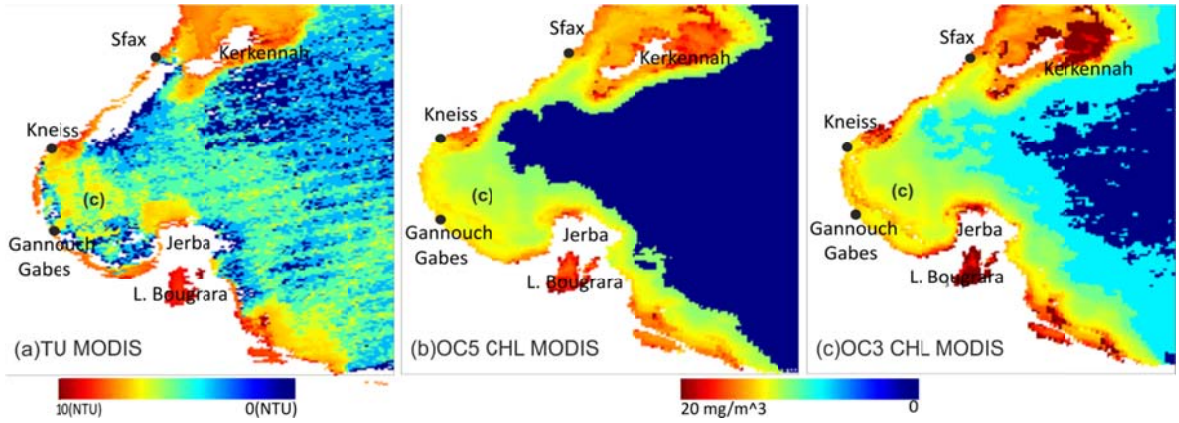


Figure 4 : MODIS imagery over the Gulf of Gabes on July 5th 2009 at 13:00 UTC (a) Turbidity TU(NTU), (b) CHL (mg/m^3) with OC5 and (c) CHL (mg/m^3) with OC3. Black points indicate the location of industrial discharges. *Distribution de la concentration de la chlorophylle CHL pour l'image du 05 juillet 2009 à 13:00 UTC(a) Turbidité (NTU), (b) CHL(mg/m^3) calculée avec OC5 et (c) CHL (mg/m^3) calculée avec OC3. Les points noirs indiquent la localisation des points de décharge industrielle.*

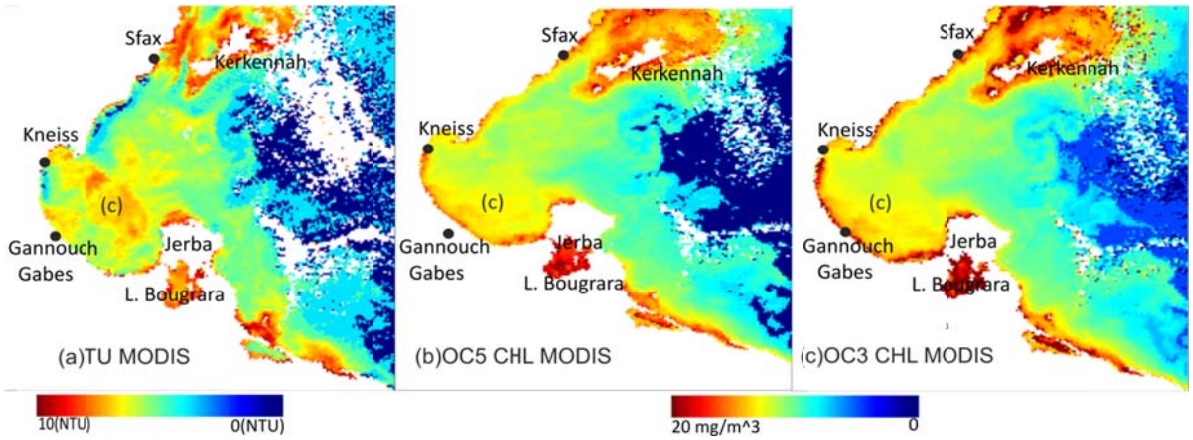


Figure 5 : MODIS imagery over the Gulf of Gabes on October 8th 2009 at 13:00 UTC (a) Turbidity TU(NTU), (b) CHL (mg/m^3) with OC5 and (c) CHL (mg/m^3) with OC3. Black points indicate the location of industrial discharges. *Distribution de la concentration de la chlorophylle CHL pour l'image du 08 octobre 2009 à 13:00 UTC(a) Turbidité (NTU), (b) CHL(mg/m^3) calculée avec OC5 et (c) CHL (mg/m^3) calculée avec OC3. Les points noirs indiquent la localisation des points de décharge industrielle.*

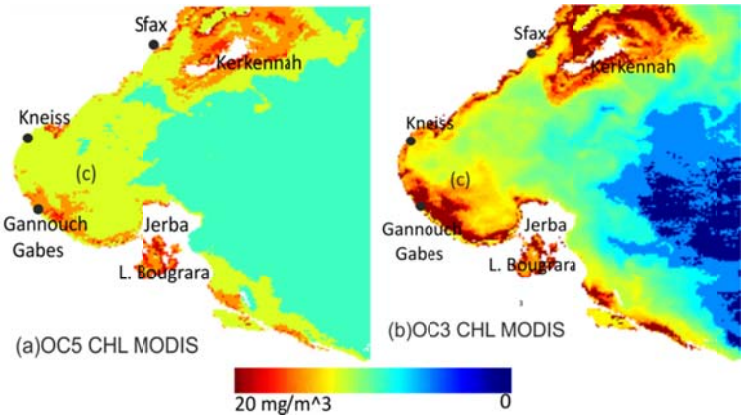


Figure 6 : MODIS imagery over the Gulf of Gabes on September 16th 2009 at 13:00 UTC (a) CHL (mg/m^3) with OC5 and (b) CHL (mg/m^3) with OC3. Black points indicate the location of industrial discharges. *Distribution de la concentration de la chlorophylle CHL pour l'image du 16 septembre 2009 à 13:00 UTC(a) Turbidité (NTU), (b) CHL(mg/m^3) calculée avec OC5 et (c) CHL (mg/m^3) calculée avec OC3. Les points noirs indiquent la localisation des points de décharge industrielle.*

The MODIS OC3 algorithm for chlorophyll *a*, based on the green/blue Rrs ratio, are known to overestimate values in coastal waters (Gitelson *et al.,* 1996). This overestimation is confirmed here in many places of the Gulf of Gabes. The overestimation is not as high for OC5 (figure 7) because this type of algorithm is developed for Case 2 waters and uses

not only the blue/green ratio but also the Rrs_412, which concerns CDOM and NAP absorptions, and Rrs_547, which reveals backscattering mainly due to suspended matter. Overestimation of chlorophyll values is mostly in the Gulf islands: Kerkennah, Kneiss and Jerba, and particulary around the Kneiss island, as this area is characterized by very shallow water, <1m, and an abundant benthic population. In these shallow waters, the performance of algorithms may be improved by selecting stations with a high TDT index, an index implying the knowledge of total chlorophyll (T), depth (D) and Turbidity (T) at each station (Dupouy *et al.,* 2010). Also it would be interesting to detect specifically Trichodesmium blooms are they often dominate phytoplankton and as their optical signature is rather specific (Dupouy *et al.,* 2008).

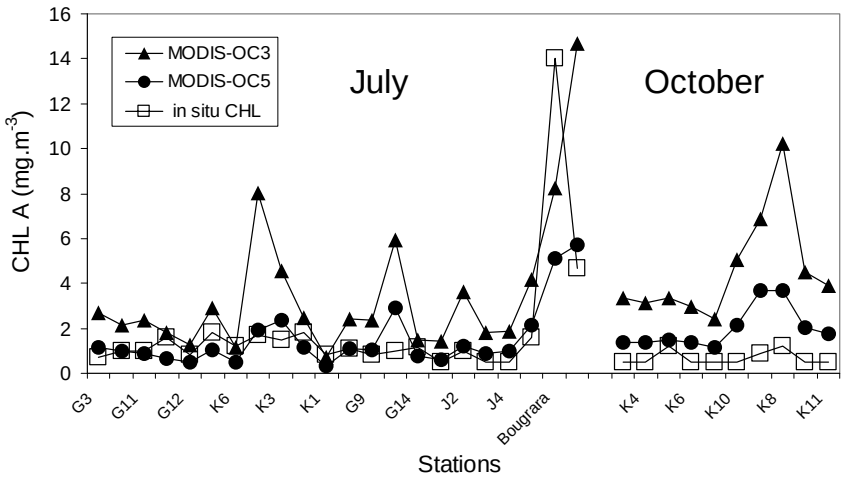


Figure 7 : Comparison of *in situ* CHLA data during sampling and of ocean color chlorophyll retrieved with the two algorithms MODIS OC3 and MODIS OC5 as a finction of stations in July and October 2009 (station names as on maps Figure 1). *Comparaison des résultats issus des mesures in situ et des deux algorithmes appliqués OC3 et OC5 en fonction des localités lors des deux campagne en mer juillet et octobre 2009 (noms des stations comme sur les cartes figure 1).*

5. CONCLUSIONS

Ocean satellite images can offer rapid concurrent and synoptic observations for deriving seawater constituents and the impact of industrial discharges. In this study, MODIS satellite data and various bio-optical algorithms were used for retrieving chlorophyll and spatial distributions were generated.

In order to map CHL distribution in the Gulf of Gabes, OC3 and OC5 algorithms were applied. The standard MODIS OC3 with a linear function (CHLMODIS_OC3= 2.78 CHLin-situ) as expected overestimated chlorophyll. The second algorithms OC5 (CHLMODIS_OC5= 1.11 CHLin-situ) allows a better retrieval of chlorophyll concentrations.

The analysis of all images for 2009 (CHLOC5 maps) allowed to divide the Gulf of Gabes into 3 different areas. At the center of the study area (C), TU and CHL derived from MODIS and *in situ* measurements show a good correlation. The second area was around the Port of Gannouch near the point of discharge (and where various effects from surface waste were observed from airborne imagery). The third area, is located around the Gulf islands where high CHLOC5 were recorded. These overestimates with an algorithm dedicated to coastal waters are possibly due to the tide, irregular depth and bottom reflection.

CHL OC5 maps described a high variability of chlorophyll distribution over the year, with a maximum during the bloom season (September). This is in accordance with recent *in situ* phytoplankton analyses showing that first blooms develop at the center of the gulf (July), and later (August- September) at the north of Jerba island, with different phytoplankton groups involved (Feki *et al.,* 2008 and Bel Hassan *et al.,* 2008, 2009).

This work showed that it is crucial to calibrate and adjust CHL algorithms to avoid overestimating ocean color data by satellite. Therefore, it will be necessary to measure water leaving reflectance and associated TU and CHL measurements, especially in coastal areas and around the Gulf islands. The next step will be to correct the imagery from bathymetric effects and to analyze the inter-annual variability from the MODIS satellite series, by using this future optical data set.

Acknowledgments

This study was funded by the Unit of Structure and Geologic Model of the University of Sciences of Tunisia. The authors would like to acknowledge the NASA ocean colors product distribution teams at The Goddard Space Flight Center GSFC for the distribution of MODIS products. We would also like to thank Jérome Lefèvre for the MODIS-

Data basis, Marc Despinoy at the Center IRD of Nouméa, New Caledonia, and Guillaume Wattelez for their help within the framework of the IRD/French "Validation HYperspectral SATellite data" project, Programme National de Télédétection Spatiale, The remote sensing team of MUMM are thanked for the help provided with the processing IDL of MODIS imagery.

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