Optical Remote Sensing of turbidity and Total Suspended Matter in the Gulf of Gabès

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Abstract

Optical remote sensing is used to provide scientific information to support environmental management in the Gulf of Gabès located in the southern east coast of Tunisia. It is a shallow continental shelf with semi-diurnal tides with average amplitude of 2m. Industrial activities in this area since the early 1970s may have contributed to the degradation of the biodiversity of the ecosystem with eutrophication problems, and disappearance of benthic and planktonic species. To assess the long-term effect of anthropogenic and natural discharges on the Gulf of Gabès, the optical environment in the coastal waters is assessed from in situ measurements of total suspended matter concentration (TSM), Secchi depth and turbidity (TU). The relationships between TU and TSM are highly correlated in the study area (correlation coefficient of 95.2%). Remote sensing data from the Moderate resolution imaging spectrometer MODIS AQUA is used to map turbidity and total suspended matter using a semi empirical algorithm applied to the band at 667nm. These bio-optical algorithms performed well in the Belgian coastal waters. Here they are tested for the Gulf of Gabès when in situ measurement of turbidity present fairly good correlation value (r^2=68.9%).

Keywords: Remote Sensing, Turbidity, Total suspended matter, Gulf of Gabès.

1. Introduction

The objective of this study is to use the optical remote sensing technique and in situ measurements to estimate water quality and the impact of industrial discharges in the Gulf of Gabès.

The Gulf of Gabès, part of the Pelagian Sea as described in Burollet and al (1979), is located in the southern part of eastern Tunisia. It is a shallow continental shelf with a gentle slope out to 250m from the coast; (Fig.1). The hydrodynamics of this area are influenced by semi diurnal tides with maximum amplitude of 1.8m in Gabès and a minimum of 0.3m (Sammari and al, 2006). The climatology of the studied area is influenced by the temperate, humid and hot Mediterranean air coming from the east, but also by the subtropical, dry, hot and sandy Saharan air coming from the south-west (Sogreha 2002).

Intensive fishing activity and natural and anthropogenic wastes have contributed to the degradation of the biodiversity of the ecosystem in the Gulf (Ben Mustapha and al, 1999). In addition, industrial activities in the region of Gannouch began in the seventies involving very notable environmental deterioration. The study of Bjaoui and al. (2004) illustrate that the pollution by phosphogypsum, derived from production of phosphoric acid, spreads over 60Km² in the area.

Optical remote sensing can be used to detect suspended matter in the surface layer of water (Althuis, 1998). The ocean colors data and the development of semi empirical algorithms in case II water provide direct relationships between ratios of remote sensing reflectance or water leaving radiances. This offers the possibility to detect the components of water especially suspended matter (Morel and al 1983).

In fact, the mapping of the suspended matter in coastal waters using satellite and in situ data, gives information about the quality of water. In order to monitor water quality, several studies have been previously published concerning the extraction of TSM from ocean color and mapping data.

Nechad and al. (2010) have used and calibrated Moderate resolution imaging spectrometer (MODIS), Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Medium-Spectral Resolution, Imaging Spectrometer (MERIS) red bands (600-700µm) to retrieve TSM map of the North Sea. Also Muller and al. (2004) used MODIS terra 250m band 1 (620-670µm) to map TSM in the coastal regions of the North Gulf of Mexico. Ouillon and al. (2008) propose a global algorithm for tropical coastal waters based on one or three bands: turbidity is first calculated from remote sensing reflectance Rrs 681µm and then if turbidity <1 Nephelometric Turbidity Units (NTU) it is recalculated using Rrs 620µm× Rrs 681µm/ Rrs 412µm.

These above studies have shown satisfactory results when comparing in situ measurements with products extracted from satellite remote sensing.

In this study, in situ measurements of turbidity (TU) and MODIS-derived TSM and TU were compared and correlated. TU and TSM satellite maps were obtained using the algorithm that was originally calibrated for the turbid waters of the North Sea (Nechad and al. 2009, 2010). The comparison of these MODIS satellite data with the measurements taken in the Gulf of Gabès indicates a reasonable correlation between these two parameters.

2. DATA AND METHODS

2.1 MODIS Data

Satellite imagery of 2009 from MODIS AQUA, provided by the National Aeronautics and Space Administration (NASA), Ocean Biology Processing Group (OBPG) were used for this study.

The Level 2 (L2) satellite data products, extracted from http://oceancolor.gsfc.nasa.gov/ contain the geophysical value for each pixel, derived from the Level-1B (L1B) radiance after radiometric calibration, geometric correction, atmospheric correction and bio-optical algorithms.

The Level 1 (L1B) calibrated radiance at 1Km resolution (MYDO21Km) were downloaded from the Atmosphere Archive and Distribution System LAADS Web http://ladsweb.nascom.nasa.gov/data/. This L1B data are used to understand some features observed in L2 data and to check subjectively the quality of the atmospheric correction implemented by NASA.

TSM concentration and TU maps were obtained using respectively the algorithms (Nechad and al. 2010 and 2009), applied to MODIS remote sensing reflectance at band 667nm

(Rrs667). These bio-optical algorithms (1) and (2) perform well in the Belgian coastal waters. Here, they are tested for the Gulf of Gabès. The algorithms for TSM and TU are respectively:

$TSM=62.86 \times (\rho/0.1736-\rho))$ (1)

$TU=50.46 \times (\rho/0.1736-\rho))$ (2)

Where $\rho=\pi\times$ Rrs)667

The processing of MODIS L1B and L2 images was established using the ENVI 4.1 (IDL) software to carry out the following procedures:

1. georeferencing of all bands.
2. extraction of standard products especially the Aerosols Optical Thickness at 869nm (AOT 869), aerosol epsilon factor, the ratio of aerosol reflectance at 748nm and 896nm (EPS78).
3. application of algorithm (1) and (2) to map TSM and TU.
4. application of the L2 flags, to remove data contaminated by cloud/ice and poor atmospheric correction (both warning and failure flags are used).
5. mapping of TSM and TU for interpretation.

TU and TSM are mapped for all daily images during 2009 and their seasonal and annual means were calculated and mapped.

2.1.1 MODIS images availability

The daily images covering the area of interest are frequently affected by sun glint, which is more frequent during the summer period. For example, the images taken on 06/07/2009 at 12:45 UTC and on 07/07/2009 at 12:15 UTC do not contain any data.

The image of 19/10/2009 at 11:55 UTC was affected by cloud and the majority of pixels are flagged. Based on the work of (Doerffer R., 2010) it could be possible to make an atmospheric correction and use images affected by moderate sun glint. The procedure is an artificial neural network (NN), which was tried with a large set of simulated TOA reflectances for 12 of 15 MERIS bands. If this algorithm becomes operational for MODIS or SeaWIFS, we will have more satellite data for the study area.

2.2 In situ data

In case II (similar to the studied area) waters light could be considerably attenuated due to suspended matter, phytoplankton, and yellow substance (Morel and al. 1977). In situ data were collected from 5th July 2009 to 7th July 2009, and on 6th, 8th and 19th October 2009 (Fig.1) concurrently with the satellite overpasses. These seaborne measurements consist of TU (NTU), water transparency (m), TSM (mg/l), chlorophyll a (µg/l) and temperature (°C). A summary of data is given in Table 1.

Turbidity is measured using the portable Hach 2100P ISO turbidimeter. The instrument records turbidity that range from 0 to 1000 NTU with resolution of 0.01 NTU. Three replicate turbidity measurements are recorded for each water sample, before and after filtration for suspended matter and chlorophyll *a* concentration, to detect possible handling errors. The standard deviation over the six values is about 19% for the sampling campaign of July and 29% for the October campaign.

Water transparency is measured using a Secchi disk, a circular plate divided into alternating black and white quadrants and attached to a long measuring tape (Secchi A, 1866). TSM was measured gravimetrically: 3000ml-4000ml water was sampled near the surface and filtered on-board over pre-weighed pre-ashed GF/F filters and the filters were rinsed one time with milli-Q water. Full details of the method are found in REVAMP protocols in (Tilstone, G. and al, 2002). The filters were then dried and weighed in the laboratory of GREEN LAB (Tunisia).

3. Results and discussions

3.1 Preliminary validation dataset

Results for in situ TSM and TU show a good correlation with a linear function: TSM (mg/l)=1.000TU(NTU)+0.807 and a regression coefficient of R^2=0.952 (Fig.2) This is similar to the correlation between these parameters (correlation coefficient of 98.6%), obtained in the southern North Sea (SNS) (Nechad and al.2009)

Near the industrial discharges in the region of Gannouch, the turbidity recorded a high value, e.g. 3.88 NTU. The origin of such high TU and TSM is due probably to recent phosphogypsum wastes, which form an opaque film on the water surface. In fact, the extent of phosphogypsum is related to the water current and the bathymetry in the area, since it needs a period of time for its decantation or dissolution. The pollution spreads further and decreases progressively if the water is deep and the currents in the receiving area are weak. On the other hand, if the currents are strong and the receiving area shallow, the phosphogypsum falls quickly to the bottom and is trapped by cohesive binding (Bjaoui, 2004).

Images of 05 July 2009

Detailed results are first shown for a single image, that of 05.07.2009, which was acquired during excellent weather conditions, clear sky and low wind.

Figure 3 show maps of the L1B radiances taken at this date:

- at 841nm (Fig. 3.a): grey area indicates the dispersion of the aerosols from land to sea following direction of the wind. The black area indicate the surface of the water seen by satellite and having low concentration of aerosols.
- at 915nm (Fig. 3.b) contain information that might be affected by atmospheric water vapor
- at1230nm (Fig. 3.c): aerosols patterns follow the coast lines.
- the L1B RGB image (Fig. 3.d) shows 2 types of waters: clear waters in blue and green waters indicating high turbidity near the coast mainly around Kerkennah island, Skhira town and port of Gannouch along the coast.
- the aerosol optical thickness at 869nm (Fig. 3.e), AOT, does not exceed 0.142 and has high spatial variability. The maximum AOT is reached near the port of Gannouch. Moreover, the direction of the aerosols is the same as the wind direction recorded during the satellite overpass.

The remote sensing reflectance at 667 nm (Rrs 667) map (Fig. 3.f) shows patterns that are uncoupled from the atmospheric patterns listed above. These are related to the signal coming from the sub-surface water layer. The MODIS level 2 flags for cloud/ice (cldice) and land pixels are used to set up the cloud and land masks respectively. There were no pixels with bad atmospheric correction. Those affected by a warning flag (atmwarn) cover only sand banks over land.

The TU map derived for the 5th July 2009 (Fig.3g) as well as the other images processed for 2009 show a maximum value of about 10 NTU around the Kneiss, Kerkennah and Jerba islands. This could be caused by tidal resuspension and also the sea bottom reflection in very shallow and transparency water. The region of Gannouch and the centre of the Gulf show values which do not exceed 7 NTU.

To validate the algorithms (1) and (2) just 12 match-ups images are used. The majority of the images downloaded have been eliminated because of high-glint, cloud conditions or atmospheric correction problems. Figure 4 shows a scatter plot of MODIS TU product using the algorithm of (Nechad and al. 2009) versus in situ TU. Only the pixels where in situ measurements were taken at the time of satellite overpass (+/-30min) are considered, to avoid uncertainty from the tidal effects (bottom sediment resuspension).

The regression $TU^{MODIS} = 0.588 TU^{in\ situ} - 0.339$ (3) illustrates the positive relationship found between in situ and satellite measurement with a fairly good correlation (68.9%) covering the range [0.5-4NTU],(Fig.4)

In the North Sea, the TU and TSM modeled from MODIS are highly correlated (Nechad and al. 2009). In addition MODIS TSM derived using reflectance at 667nm, correlates (81.47%) with sea borne TSM measurements in 24 locations (Nechad and al 2010). Despite the fact that these waters are more turbid [0.5-85 NTU] than Gulf of Gabès water TSM and TU could be mapped using algorithm (1) and (2) in the studied area.

3.2 2009 Turbidity Map

The mean annual turbidity map for 2009 (Fig.5) was computed from 58 images; 20 in autumn (September, October and November), 10 in winter (December, January and February), 14 in spring (March, April and May) and 14 in summer (June, July and August). It shows four areas of high turbidity in the study area: around Kerkennah, Kneiss and Jerba islands and especially in the center of the Gulf. This distribution of maxima was observed for all TU maps during 2009 (Fig.6 a, b, c, d, e and f).

The standard deviation turbidity TU map showed the same average spatial turbidity distribution as in mean annual 2009. According to the MODIS satellite data, the Sfax region and the area surrounding the Kerkennah, Jerba and Kneiss islands show very high TU (10 NTU), when compared to neighboring regions especially the center of the Gulf of Gabès and the Port of Gannouhe [5-7 NTU].

4. Summary and recommendation

In order to map TU distribution in the Gulf of Gabès, an algorithm (2) was adapted for this region. MODIS derived TU and in situ matchups taken in July and October 2009 were collected and compared. Analysis of all images and the turbidity mean for 2009 show that the highest TU are located around the islands (Kerkenah, Kneiss and Jerba) and also in the industrial port of Gannouche. This extends also toward the center of the Gulf over a distance of 70 Km. In fact, high values of TU and TSM observed around the islands are probably due to shallow waters and bottom reflection. However, the values of TSM and TU measured in the port of Gannouche and in the center of the Gulf were validated by in situ measurement.

In situ data and the relationship established between the measured parameters were useful for the interpretation of satellite data especially around islands and near the industrials discharges This study demonstrated that the algorithm originally developed for the North Sea, are applied here for the Gulf of Gabès, shows acceptable results concerning the spatial distribution of TU and TSM for this area. To further validate and possibly recalibrate the local algorithms, a large amount of in situ data, especially turbidity, total suspended matter and chlorophyll, from different dates would be useful.

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Table 1. Summary of measurement ranges: TU: Turbidity (NTU); TSM: Total suspended matter (mg/l); CHL: Chlorophyll concentration (µg/l). (see locations in Fig.1).

Locations	TU (NTU) min, max	TSM (mg/l) min, max	CHL (µg/l) min, max	date	Number of stations
Port of Gannouch	1.88, 3.88	2.2, 5	0.5, 1	04/07/09 and 06/10/09	26
Jerba	0.5, 2.12	1.4, 2.8	<0.5, 1.6	06/07/09	5
Kneiss	0.2, 5.5	0.7, 6.1	<0.5, 4.7	05-07/07/09 and 09/10/09	18
Sfax-Kerkennah	1, 3.1	1.6, 3.9	<0.5, 1.3	19/10/09	6
Lagune Bougrara	-, 9.9	-, 30	-, 14	06/07/09	1

Figures legends

F01. Location of sampled stations, July 2009 in the left and October 2009 in the right. Green circle indicate the position of in situ measurement and purple triangle indicate the 12 match up stations.

F02. Relationship between optical in situ measurements: turbidity (NTU) and the concentration of total suspended matter (mg/l) in the Gulf of Gabès for data obtained during July and October 2009

F03. MODIS imagery over the Gulf of Gabès on July 5th 2009 at 13:00UTC:
L1B (a-c) at 841nm, 915nm, and 1230nm, (d) RGB image composite of 915nm, 620nm and 469nm, (e) aerosol optical thickness and the red arrows indicate the wind direction in Sfax 8m/s, in Gabès10m/s and in Jerba 10m/s, (f) Rrs667,with flags superimposed, and (g) turbidity (NTU). Black plus indicate the location of the in situ measurements taken that day.

F04. Scatter plot of MODIS-derived TU (NTU) versus seaborne TU (NTU) measurement at 12 locations superimposed to the linear regression curve.

F05. Turbidity mean annual for 2009 map in the left and turbidity standard deviation annual for 2009 map in the right.

F06:
(a) MODIS-derived TU map 7 January 2009 at 12:30 UTC**, (b)** MODIS-derived TU map 4 February 2009 at 12:55 UTC, **(c)** MODIS-derived TU map 9 may 2009 at 13:05 UTC, **(d)** MODIS-derived TU map 19 June 2009 at 13:00 UTC, **(e)** MODIS-derived TU map 18 September 2009 at 12:40 UTC, **(f)** MODIS-derived TU map 16 November 2009 at 12:20 UTC