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

Rim Katlane Essersi[1] , Bouchra Nechad[2] , Kevin Ruddick[2] and Fouad Zargouni[1]

[1] University of Sciences Mathematic, Physics and Naturals of Tunisia,
[2] Management Unit of the North Sea Mathematical Models (MUMM), Royal Belgian Institute for Natural Sciences (RBINS)
Correspondence to: R. Katlane Essersi mailto: katlanerim@yahoo.fr

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. This is a region with a shallow continental shelf subject to semi-diurnal tides with average amplitude of 2 m. 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). 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 667 nm. These bio-optical algorithms performed well in the Belgian coastal waters. Here they are tested for the Gulf of Gabès where there is reasonable correlation (R^2=68.9 %) between in situ and remote sensing measurements of turbidity.

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

1. Introduction

The objective of this study is to use optical remote sensing with some supporting 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 et al. (1979), is located in the southern part of eastern Tunisia. It has a shallow continental shelf with a gentle slope extending 250 km offshore ranging from 0.7 m up to 50 m in depth; (Fig.1). The hydrodynamics of this area are influenced by semi diurnal tides with maximum amplitude of 1.8 m in Gabès 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, also by the subtropical, dry, hot and sandy Saharan air coming from the south-west (Sogreah, 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 et al., 1999). The industrial activities in the region of Gannouch began in the seventies involving very notable environmental deterioration. The study of Bjaoui et al. (2004) has shown that the pollution by phosphogypsum, derived from production of phosphoric acid, spreads over 60 km² in the area.

Optical remote sensing can be used to detect suspended matter in the surface layer of water (Althuis, 1998) and hence monitor this aspect of water quality. Several authors (Curran et al., 1987; Novo et al., 1989; Ritchie et al., 1990 ; Tassan, 1994 and Doxaran et al., 2002) have analyzed surface waters by means of satellite remote sensing and demonstrated empirical relationships between reflectance and the concentration of Total Suspended Matter (TSM). A family of TSM retrieval algorithms is 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. (Nechad et al., 2010) used and calibrated 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) sensors and used them to retrieve TSM maps of the North Sea. Miller and McKee (2004) used MODIS terra 250 m band 1 (620-670 nm) to map TSM in the coastal regions of the North Gulf of Mexico. Ouillon et al. (2008) propose a global algorithm for tropical coastal waters based on one or three bands: turbidity is first calculated from remote sensing reflectance R*RS* 681 nm and then if turbidity <1 Nephelometric Turbidity Units (NTU) it is recalculated using R*RS* 620 nm× R*RS* 681nm/ R*RS* 412nm. Further studies have used near-infrared reflectance alone to assess variations in turbidity or sediment suspended concentration (Wass et al., 1997 and Sterckx et al., 2007). Near infrared reflectance may also be combined with red reflectance (Doxaran et al., 2002) for the retrieval of TSM. These 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 using MODIS remote sensing reflectance at band 667 nm (Nechad et al., 2009, 2010). Here, they are tested over the Gulf of Gabès.

A preliminary validation of these products is presented, based on in situ measurement and MODIS matchups, indicating 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 (MYDO21 km) were downloaded from the Level 1 and Atmosphere Archive and Distribution System (LAADS) Web http://ladsweb.nascom.nasa.gov/data/. This L1B data are used as support for the L2 data to check subjectively the quality of the atmospheric correction implemented by NASA.

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

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

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

Where $\rho = \pi \times R_{RS}\,667$

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 including the Aerosol Optical Thickness at 869 nm (AOT 869), and the aerosol epsilon factor, the ratio of aerosol reflectance at 748 nm and 869 nm (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. Many of the daily images covering the area of interest are affected by sun glint, which is more frequent during the summer period.

2.2 In situ data

Morel and Prieur (1977) classified marine waters in terms of variability of optical properties, and called these Cases 1 and 2 waters. In Case 2 waters the optical properties are influenced not only by phytoplankton and related particles, but also by other substances such as Colored Dissolved Organic Matter (CDOM) and suspended sediments, that can vary independently from phytoplankton. This study area corresponds to Case 2 waters (as do many coastal ones and inland seas).

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 ranges from 0 to 1000 NTU with resolution of 0.01 NTU and auto-ranging. 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 of 30 cm diameter divided into alternating black and white quadrants and attached to a long measuring tape.

The disk is mounted on a pole or line, and lowered slowly down in the water on the shaded side of the ship. The depth at which the pattern on the disk is no longer visible is taken as a measure of the transparency of the water.

TSM was measured gravimetrically: 3000 ml-4000 ml water was sampled near the surface and filtered on-board with pre-weighed pre-ashed GF/F filters at 450°C for 1 hr and rinsed with milli-Q water (including the filter rim). After the cruise the filters are dried and weighed for determination of dry weight in the laboratory of GREEN LAB (Tunisia). Full details of the method are found in REVAMP protocols in (Tilstone and Moore, 2002).

3. Results

3.1 Preliminary validation dataset

Results for in situ TSM and TU (Fig.2) show a good correlation with a linear function:

TSM (mg/l) =1.000TU (NTU)+0.807 with R^2=95.2%

This is similar to the correlation between these parameters obtained in the southern North Sea (SNS) (Nechad et al., 2009).

TSM (mg/l) =0.9TU (FNU)+0.7 with R^2=98.6%

The similarity of the slopes obtained for TSM/TU correlations in the North Sea and the Gulf of Gabès suggests that there is a similar relationship between marine particle mass and side-scattering between the two regions, giving a basis for use of the North Sea algorithms in the Gulf of Gabès despite the lack of reflectance measurements for regional recalibration.

Near the industrial discharges in the region of Gannouch, the turbidity and total suspended matter were the highest values recorded in this site, respectively 3.88 NTU and 5mg/l. The origin of this TU and TSM value may be due 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 et al., 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, clears sky and low wind.

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

- at 841 nm (Fig. 3.a): grey area indicates the dispersion of the aerosols from land to sea following direction of the wind. The black area indicates the surface of the water seen by satellite and having low concentration of aerosols.
- at 915 nm (Fig. 3.b): contains similar information but might also be affected by atmospheric water vapor
- at 1230 nm (Fig. 3.c): shows the area of highest aerosol concentration coast to the coast line.
- 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 869 nm (Fig. 3.e) AOT, does not exceed 0.142 and has high spatial variability. The maximum AOT is reached near the port of Gannouch. The direction of the aerosols is the same as the wind direction recorded during the satellite overpass.

The remote sensing reflectance at 667 nm (R_{RS} 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 are used to set up the cloud and land masks respectively. Due to the high reflectance of the sand the flags consider some pixels in the land as area covered by ice.

The TU map derived for the 5th July 2009 (Fig. 3.g) 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 but could also be contaminated by 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.

In order to test the relations (1) and (2) only 12 match-ups pixels were used. 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 (+/-30 min) are considered, to avoid uncertainty from the tidal effects (bottom sediment resuspension).

The regression illustrates the positive relationship found between in situ and satellite measurement.

$TU^{MODIS} = 0.588 TU^{in\ situ} - 0.339$ (3)

With a fairly good correlation (68.9 %) covering the range [0.5-4 NTU] (Fig.4).

In the North Sea, the TU and TSM modeled from MODIS are highly correlated. We use the same 667 nm band to retrieve both of them according to (Nechad et al., 2009). In addition MODIS TSM derived using reflectance at 667 nm, correlates (81.47%) with seaborne TSM measurements in 24 locations (Nechad et al., 2010). Despite the fact that these waters are more turbid [0.5-85 NTU] than Gulf of Gabès water, it seems that TSM and TU can also be mapped using algorithm (1) and (2) in the studied area.

3.2 2009 Turbidity Map

The 2009 MODIS images were processed and the majority of these have been eliminated because of high-glint, cloud conditions or atmospheric correction problems.

Only 58 images were used for the mean annual turbidity map for 2009 (Fig.5); 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). This annual mean 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 map shows the same general distribution as the annual mean annual. According to the MODIS satellite data, the Sfax region and the area surrounding the Kerkennah, Jerba and Kneiss islands show very high TU variability (10 NTU), when compared to neighboring regions especially the center of the Gulf of Gabès and the Port of Gannouhe [5-7 NTU].

4. Discussion and Summary

In order to map TU distribution in the Gulf of Gabès, an algorithm (2) was tested for this region. Firstly correlation between in situ measurements of turbidity (side-scattering) and TSM in the Gulf of Gabès showed a similar (to within 10-20%) relationship to that found in North Sea waters. This gives confidence in the similarity of mass-specific scattering properties in the two regions and hence applicability of the North Sea TU and TSM algorithms. Secondly, MODIS images were processed and the derived TU was compared with in situ matchups taken in July and October 2009 in the Gulf of Gabès, showing reasonable correlation between satellite-derived and in situ TU, albeit for a limited number of matchups.

Multitemporal maps were then produced. 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. This study represents the first large scale mapping of TSM and turbidity in this region, made possible thanks to the use of remote sensing method. In the literature, there are studies of remote sensing of chlorophyll over global Mediterranean area (Jaquet et al., 1999; Barale et al., 2008 and Bricaud et al., 2002) showing some possible bottom effect in the Gulf of Gabès. There are also lot of in situ measurements and modelling of the stratified waters in the Gulf of Gabès, salinity, temperature, chlorophyll, pigments, hydrocarbon, tides, (Sammari et al., 2006; Smaoui et al., 2006; Zaghden et al., 2005; Kchaou et al., 2009; Khemakhem et al., 2010 ; Bel Hassen et al., 2009 and Drira et al., 2009). However, this is the first study using optical mapping TSM.

To further validate and possibly recalibrate the local algorithms, additional in situ data, especially water leaving reflectance 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 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 841 nm, 915 nm, and 1230 nm, (d) RGB image composite of 915 nm, 620 nm and 469 nm, (e) AOT aerosol optical thickness and the red arrows indicate the wind direction in Sfax 8 m/s, in Gabès 10 m/s and in Jerba 10 m/s, (f) R*RS* 667, 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