Mapping water constituents concentrations in estuaries using MERIS full resolution satellite data

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1. INTRODUCTION

In coastal waters directly influenced by human activities and climate change, an operational oceanography is necessary to obtain a better understanding of the involved processes and rapidly provide adapted monitoring systems able to produce predictions and forecasts. For this reason, applied research activities are highly supported by the European Community.

The goal of ocean colour remote sensing measurements is to quantify and map the optically significant water constituents: phytoplankton (chlorophyll a (Chla)), coloured dissolved organic matter (CDOM) and non-algal suspended particulate matter (SPM). It consists in estimating these water constituents' concentrations from apparent optical properties (AOP) measurements (namely the irradiance reflectance, R, or remote sensing reflectance, Rrs, signals). This can be done if the inherent optical properties (IOP) of these constituents are sufficiently well documented. The information potentially delivered by ocean colour remote sensing is of first importance in highly dynamic coastal waters where terrigeneous substances are transported from the continent to the ocean. The supplied nutrients enhance the primary production whereas SPM and CDOM limit the solar light penetration within the water column. Pollutants due to anthropic activities can also influence and modify the ecosystems in a way that is detectable in the ocean colour signal (e.g. eutrophication). Transport of suspended sediments has a direct influence on the coastline changes (creation of mudbanks), hydrodynamic conditions (e.g. filling of navigation channels and resulting dredging activities) and biogeochemistry of the environment (e.g. creation of maximum turbidity zones / fluid mud layers systems). Ocean colour remote sensing can provide useful information for monitoring coastal waters, using the recently developed satellite and airborne optical sensors. Such sensors are nowadays adapted to the study of coastal waters, as they are improved in terms of spatial, radiometric and spectral resolutions.

Significant results have been obtained in oceanic waters using ocean colour remote sensing when estimating the phytoplankton biomass and associated primary production (e.g. [1], [2]). This has not yet been the case in turbid coastal waters where the following problems are encountered:

- The atmospheric correction of satellite and/or airborne data is complex. The assumption of a pure atmospheric signal in the near-infrared (NIR), made when determining the aerosol contribution over oceanic waters, is no longer valid above turbid waters and results in an under-estimation of the water-leaving signal in the visible range.
- The superposition of the spectral signatures of the different optically significant water constituents makes their discrimination difficult, especially because the IOP of the constituents are poorly documented.

Moreover, the information extracted from remote sensing data is limited in time and space by the occurrence of clouds and only reflects the composition of surface waters. It is therefore insufficient for monitoring the spatial daily dynamics of coastal / estuarine waters.

In order to understand and predict the dynamics of coastal waters, three-dimensional (3D) hydrodynamic and sediment transport models have recently been developed (e.g. [3], [4]). Hydrodynamic models include realistic tide, river regime, wind, and wave forcings, whereas sediment transport modelling often use approximate and empirical parameterisation to reproduce erosion, settling, deposition and damping processes. This is the reason why such models need to be calibrated and validated ([4], [5]). In-situ observations are relevant but expensive and thus insufficient in this matter. This lack of information may be complemented by satellite and/or airborne observations. The actual problem is to define an optimal use of this information coming from different sources, in terms of model calibration and validation. Simple comparisons between observations and model calculations (e.g. [5], [6], and [7]) are not satisfactory, as only providing a qualitative estimate of the model realism. It is necessary to directly integrate the observations into sediment transport models. Very few attempts exist in this domain [8].

The aims of this study are:

- To assess the integrity of recent ocean colour algorithms developed to quantify the SPM, CDOM and Chla concentrations in turbid estuarine using MERIS but also MODIS (Aqua and Terra) satellite data and CASI airborne data;

- To map routinely the SPM concentrations retrieved from remote sensing data in two selected estuaries and complement the information obtained with in-situ SPM measurements;
- To integrate the information obtained from in-situ and remote sensing data into a sediment transport model in order to develop an efficient monitoring tool that could be used to quantify sedimentary fluxes in estuarine/coastal waters.

2. OBJECTIVES AND METHODS

2.1 Objectives

The first objective is to assess recently developed ocean colour quantification algorithms. In various turbid coastal and estuarine waters, algorithms have been developed to quantify SPM (total, inorganic and organic) and CDOM concentrations from ocean colour remote sensing measurements ([9], [10], [11], and [12]). Preliminary results show the possibility to quantify Chla concentrations in such turbid waters ([12], [13]). These algorithms are based on robust quantification relationships established between the water constituents (SPM, CDOM) concentrations and the Rrs signal. Such relationships can be applied to satellite or airborne reflectance data corrected for atmospheric effects.
Before considering and using the concentrations retrieved from remote sensing measurements, the first objective is to assess the integrity of the developed quantification algorithms. This integrity depends first on the atmospheric correction of remote sensing data, then on the validity of the quantification relationships. In other words, it is necessary to know how accurately: - the water reflectance signal can be estimated from measurements recorded onboard satellites or planes; - the water constituents concentrations can be estimated from the obtained water reflectance.
The aims are: - to determine the atmosphere contribution to the total signal recorded onboard planes or satellites depending on the water turbidity; - to quantify the integrity of both atmospheric correction and quantification relationships. Depending on the selected optical sensor and atmospheric conditions (e.g. aerosol content, humidity, presence of clouds), a confidence level will be determined, to be considered before interpreting and using the retrieved concentrations.
The second objective is to develop an efficient and operational system for monitoring the SPM dynamics in coastal and estuarine waters. Routinely applied to satellite and airborne data, the developed quantification algorithms can provide information on surface SPM horizontal distributions at different spatial and temporal (tidal and seasonal cycles) scales. This information will contain gaps due to the occurrence of clouds and will be limited to surface waters. Such limitations may be crucial in highly dynamic environments where the water turbidity mainly depends on deposition and erosion processes occurring near the bottom. For this reason, remote sensing data must be complemented by in-situ measurements providing information on: - the continuous variations of SPM concentrations, representative of tidal and seasonal cycles; - the stratification of turbidity, i.e. the relationships between surface and bottom SPM concentrations and typical SPM vertical profiles.
The second objective is to generate such a relevant database (SPM in-situ and remote sensing observations) in a selected study area and propose an optimal use of it by integrating this information into a sediment transport model. The objective is to go further than simple comparisons between observations and model calculations. An operational data-integration method will be applied. It will first be used to assess the reliability and efficiency of the different sources of observations (in-situ and remote sensing) in terms of model calibration. It will then contribute in the valorisation of existing databases and highlight a new application for ocean colour remote sensing. The obtained results are expected to provide an improved and performing monitoring system for estuarine and coastal waters (e.g. sedimentary fluxes calculations, forecasts, fate of eventual pollutants and management of coastal areas).

2.2 Methods

Two estuarine environments are considered to develop the research programme:

- The Gironde estuary (France) as main study area
- The Tamar estuary (UK).

These two areas are associated with existing optical databases. In both cases, quantification relationships have been established for SPM (Gironde), SPM and CDOM (Tamar). Regular ocean colour satellite and airborne data that were recorded over the two study areas will be considered. In the Gironde estuary, an operational 3D hydrodynamic and sediment transport model (SiAM-3D) is available (details provided in section B2.2).
Field optical measurements will include existing data sets ([17], contract EVK3-CT-2002-50012) and regular data acquisition concurrently with satellite/plane overpasses. Theoretical AOP and IOP calculations may also be carried out with the Hydrolight (Mobley 1994) radiative transfer code. Numerous IOP measurements will be carried using in-situ absorption and attenuation sensors (ac-9).

Validation of quantification algorithms requires match-ups, i.e. simultaneous satellite (and/or airborne) and in-situ measurements. Such match-ups first provide a direct comparison between reflectance measurements recorded just above the water and within or at the top of the atmosphere. They also provide simultaneous measurements of the concentrations of the water constituents in order to validate the established quantification relationships.
In the Tamar estuary, match-ups with airborne (CASI) data in 2003 and 2004 (contract EVK3-CT-2002-50012) will be considered.
In the Gironde estuary, match-ups with satellite data will be conducted in 2005 and 2006. Four intensive field campaigns will be conducted to cover the different environmental conditions (high / low river flow periods and spring / neap tides).
Field measurements (will) systematically include:
• Water sample collections for analyses: - SPM concentration, organic content, mineralogy, grain-size distribution; - CDOM and Chla concentrations
• Hyper/multi-spectral Rrs and/or R reflectance; absorption (a), scattering (b) and backscattering (bb) coefficients of the different water constituents.
Direct comparisons between in-situ reflectance measurements and satellite/airborne data corrected for atmospheric effects will be used to assess the accuracy of different atmospheric correction methods: - previously applied ([9], [14]); - existing [15] and recently developed [16]. An improved correction method is currently developed at the Host Institution and may also be tested. At this stage, it will be possible to determine the most accurate atmospheric correction method and the corresponding error associated to the retrieved Rrs signal.
Based on the determined Rrs uncertainty, the error associated to the retrieved water constituents concentrations (in particular SPM) when applying the quantification relationships will be quantified. The results will be supported by direct comparisons with the measured in-situ concentrations. In the Gironde, continuous data recorded by four autonomous fixed stations equipped with turbidity sensors will greatly increase the number of match-ups.
IOP measurements, converted into specific absorption and backscattering coefficients (a* and bb*, respectively), i.e. coefficients per unit of water constituent concentration, will be integrated into the reflectance model currently developed (contract: EVK3-CT-2002-50012). In each study area, the tidal and seasonal IOP variability determines the long-term validity of the established quantification relationships.
In the Tamar estuary, airborne (CASI) and satellite (Chris-Proba) data recorded in 2003 and 2004 will be reprocessed to determine the percentage of error associated to the retrieved SPM, CDOM and Chla concentrations.

In the Gironde estuary, a relevant database will be generated to observe the tidal and seasonal SPM dynamics. This database will combine remote sensing and in-situ observations.
The quantification algorithms applied to remote sensing data will produce surface SPM concentration maps with associated integrity factors (percentage of error associated to the retrieved concentration). Ocean colour satellite data will be selected according to the cloud cover during one full year. SPM concentrations will be estimated using:
- MODIS and MERIS moderate resolution (1000 m) satellite data in the turbid plume and adjacent coastal waters. The objective is to process images recorded on a weekly basis to obtain information related to monthly and seasonal cycles.
- MODIS and MERIS full resolution (250 m and 300 m, respectively) in the mouth and downstream part of the estuary. Images will be processed on a monthly basis.
- High spatial resolution satellite sensors (Hyperion, ASTER) in the inside part of the estuary. SPOT-HRV and Landsat-ETM+ data may also be considered in order to obtain at least one image per month (spatial resolution around 25 m).
In addition, Airborne (CASI) data may be used to observe the tidal dynamics of surface SPM concentrations (project submitted in collaboration with the University of Plymouth).
In-situ measurements will document:
- The continuous variations of SPM concentrations in the estuary. This information will be provided by four fixed stations located in the central and upstream parts (SMEAG-EPIDOR programme). Surface and bottom SPM concentrations are measured every 20 minutes.
- The vertical stratification of SPM concentration and current velocity. Information from the four fixed stations will be complemented by regular (monthly) surveys (tidal variations of SPM and current velocity vertical profiles) in four other fixed stations representative of the different parts of the estuary (SOMLIT programme). SPM and current velocity vertical profiles will also be measured during the fieldworks planned in 2005/2006.
The database will therefore document the tidal and seasonal variations of SPM concentrations (surface and bottom) and the typical vertical profiles of turbidity and current velocity. It will permit to determine how ocean

colour remote sensing observations, limited to surface waters, are representative of the SPM dynamics in the estuary.

Remote sensing and in-situ observations of SPM concentrations) will be integrated into the computational grid of the sediment transport model. Each integrated data will be associated with a time (time of acquisition) and an integrity factor (measurement uncertainty).
In collaboration with modellers at the University Bordeaux 1 and ACRI-ST Company, a cost function representative of differences between observed and calculated SPM concentrations will be defined. This cost function will be close to the one defined by Vos et al. [8] and will take into account the integrity of the observations. It will be reduced by fitting the different model parameters in the empirical laws reproducing the settling, deposition and erosion processes (e.g. critical deposition and erosion shear stresses, settling velocity).
This study will first be conducted considering the continuous and regular in-situ observations. The objective will be to test the sensitivity of the model when separately integrating bottom and surface SPM concentrations. These tests will be carried out in collaboration with the University Bordeaux 1 where a PhD thesis aims at comparing bottom SPM concentrations measured in situ (autonomous fixed stations) and calculated by the SiAM3D model. Results will highlight the variability of the model parameters in the different parts of the study area.
Once operational, the integration technique will then be applied considering only the remote sensing observations. The first objective will be to assess the efficiency of ocean colour remote sensing, only providing surface SPM concentrations but covering in detail the whole study area, in terms of sediment transport model calibration.
The final step will to apply the full (in-situ and remote sensing) data integration method during one year. Results will be compared to previous long-term simulations ([3], [17], and [18]). At this stage, the integrated data-modelling approach is expected to provide more satisfactory results and be operational to calculate sedimentary fluxes.

3. FIRST RESULTS AND DISCUSSION

In the two selected study areas (Gironde, Tamar), robust SPM quantification relationships have been established ([9], [10], [11], [12]). These relationships based on Rrs ratios (between near-infrared (~850 nm) and visible (~550 or 650 nm) wavelengths) have been established from numerous in-situ hyperspectral Rrs measurements. They can be easily adapted to different ocean colour satellite sensors such as MERIS using the bands number 5, 7 and 13.
These relationships were applied to high spatial resolution (SPOT and Landsat, pixel size of respectively 20 and 30 m) satellite data from the Gironde estuary. The selected satellite data (7 images) were corrected for atmospheric effects using available meteorological data integrated into a radiative transfer code (6s, [19]) and the dark pixel method ([9], [14]). Results showed with great detail the seasonal movements of suspended sediments in the estuary.
Then, the relationships established in the Tamar estuary have been applied to CASI airborne data [13]. From CASI data recorded at different moments of a same tidal cycle, it was possible to observe tidal movements of surface suspended sediments in close agreement with in-situ observations.
The next step was to apply routinely the SPM quantification relationships established in the Gironde estuary to MERIS and MODIS full resolution (300 and 250 m, respectively) satellite data. First satisfactory results were obtained using MODIS-AQUA full resolution data (Fig. 1). Applying simple atmospheric corrections (using 1km atmospherically corrected data and the dark pixel method in the near-infrared), the SPM concentrations and SPM map retrieved from satellite data were in agreement with in-situ observations. MODIS-AQUA complemented by MODIS-TERRA full resolution data certainly represent a great potential to observe the dynamics of suspended sediments in estuaries. Similar and possibly better results are expected using MERIS multi-spectral data.

4. CONCLUSIONS

High spatial resolution satellite (SPOT, Landsat) and airborne (CASI) sensors proved to be efficient tools to observe the seasonal and tidal, respectively, movements of suspended sediments in estuaries. Encouraging first results were also obtained using MODIS-AQUA full resolution (250 m) data. Interesting results are now expected according to the specifications of MERIS full resolution data (300 m spatial resolution, multi-spectral).
But before processing routinely MERIS and MODIS satellite data to produce maps of suspended sediments in turbid estuarine waters, an effort has to be made concerning the atmospheric corrections of such data. Different techniques must be tested and compared to conclude. The use of a bright pixel correction method will require a detailed knowledge of the IOPs in the near-infrared spectral domain (700 – 900 nm).

These IOPs will first be investigated in several European estuarine waters in order to generate a large and representative dataset, and then investigated in detail (geographical, tidal and seasonal variations) in our main study area: the Gironde estuary.
This should result in the creation of a relevant SPM database that will be used to develop an operational monitoring system for estuarine and coastal waters.

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6. REFERENCES

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7. FIGURES

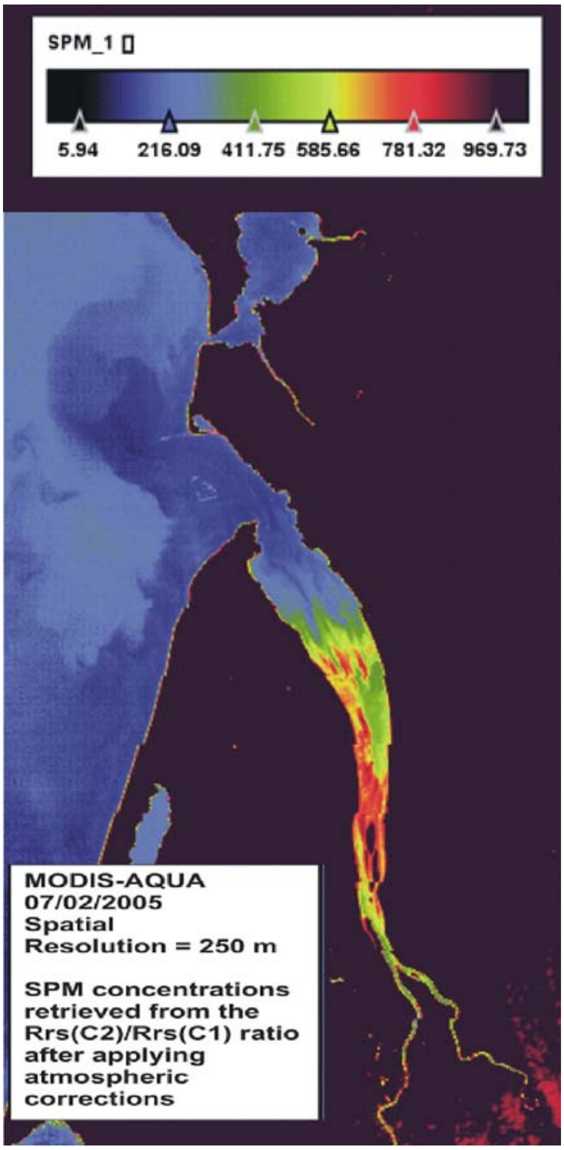

Figure 1. Example of SPM map obtained in the Gironde estuary from MODIS-Terra full resolution data (MODIS-Terra data recorded the 07/02/2005 with a spatial resolution of 250 m). Data were corrected for atmospheric effects before a quantification relationship was applied.