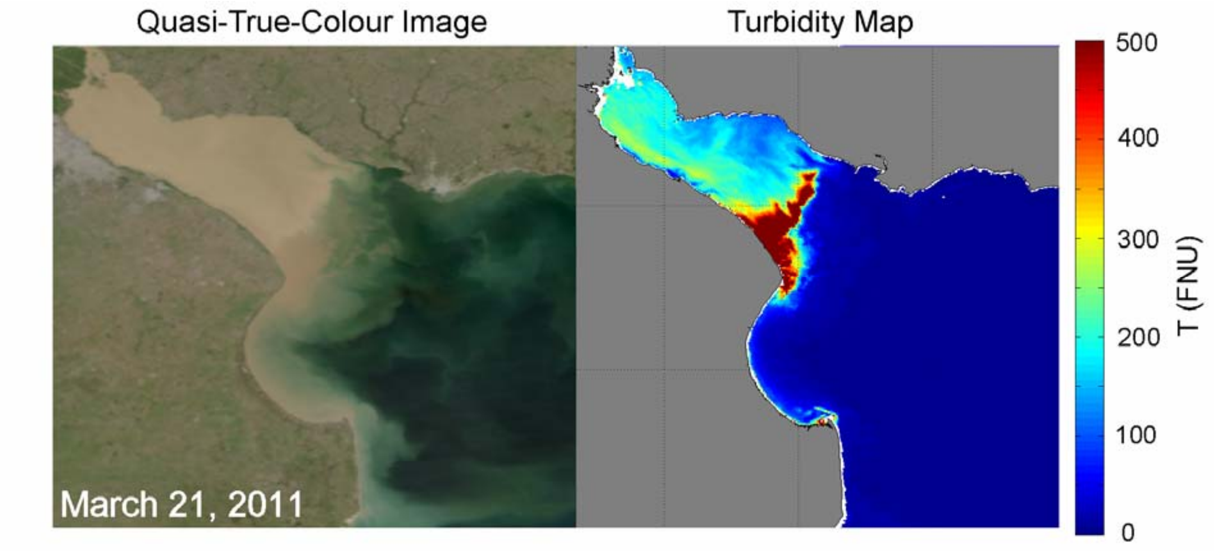
Satellite mapping of La Plata River plume (BELCOLOUR-ARG)



BELSPO Post-doc Fellowship
Final Report

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Visit period: October 2010 – October 2011

Introduction

The main objective of the BELCOLOUR-ARG project was to characterise the dynamics of La Plata river plume along the coasts of Argentina, Uruguay and Brazil by analysis of a multi-year archive of satellite maps of turbidity. This objective has been achieved by adapting and improving methodologies developed in the STEREO/BELCOLOUR-2 project for

- deriving marine reflectance from satellite optical remote sensing by atmospheric correction over turbid waters,
- deriving turbidity and Total Suspended Matter concentration from satellite-derived marine reflectance, and
- processing above water reflectance measurements for validation of the satellite-derived marine reflectances.

The methodologies developed were implemented in an automated satellite data processing chain and used to generate turbidity maps for La Plata region.

These methodologies, as well as the main results and conclusions are described in the following section.

Atmospheric correction over turbid waters (T1)

In order to select the optimal atmospheric correction algorithm to implement over La Plata region, three different correction approaches were applied to MODIS-Aqua level 1A (L1A) imagery (see flow chart in Figure 1):

1) The standard NIR atmospheric approach, which uses the 748 and 869 nm bands and corrections to account for NIR ocean contribution estimated from the 667 nm band.
2) The NIR-SWIR switching algorithm, which was applied using the 1240 and 2130 nm bands when T_{ind}>1.3 as in Shi & Wang (2007), and
3) An iterative approach of the SWIR atmospheric correction algorithm is used for the turbid waters, i.e. when T_{ind}>1.3, as proposed and implemented in Wang *et al.* (2011).

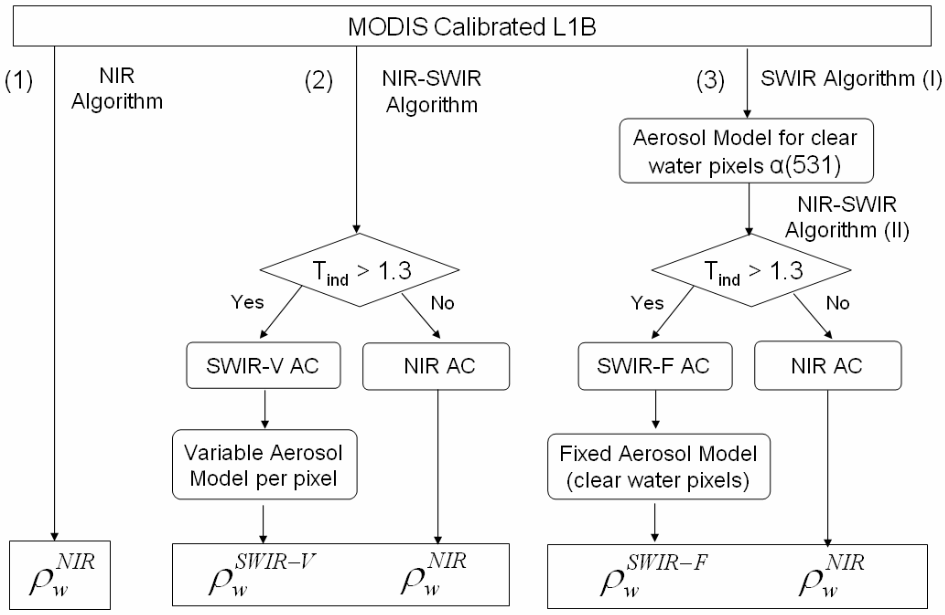


Figure 1. Flow chart of the different atmospheric correction (AC) approaches applied to MODIS-Aqua imagery and analyzed. Reproduced from Dogliotti et al (2011, ONW).

The third approach requires running the atmospheric correction twice; first the 1240 and 2130 nm SWIR bands are used to retrieve the aerosol model (Angström exponent) on a pixel-by pixel basis. Angström exponent at 531 nm, α(531), from a region of clear water pixels is used to determine the aerosol model since each model has a unique value of α(531). The mean value of α(531) from a region of relatively clear waters (30x30 pixels) located in the center of Samborombón bay is extracted from each scene. Then, a second run of the atmospheric correction is applied to the turbid waters using a fixed α(531) obtained from the clear water pixels and information on aerosol concentration is taken from 2130 nm band. This approach assumes a fixed aerosol model for the whole image and will be referred to hereafter as SWIR-F, while the standard SWIR approach which uses a variable aerosol model estimated in a pixel-by-pixel basis will be referred as SWIR-V.

<u>Results</u>

1) The application of the standard NASA (NIR) atmospheric correction systematically failed to retrieve water reflectance from the highly turbid waters of La Plata River estuary. The main reason is saturation of MODIS ocean bands. The retrieval of water reflectance is not possible due to saturation of the MODIS 667, 748 and 869 nm bands which are used in the NIR atmospheric correction. As a result the whole estuary is generally masked in the ocean bands, while negative values are retrieved in the high resolution (250 and 500 m) land bands mimicking the high turbid water plume.

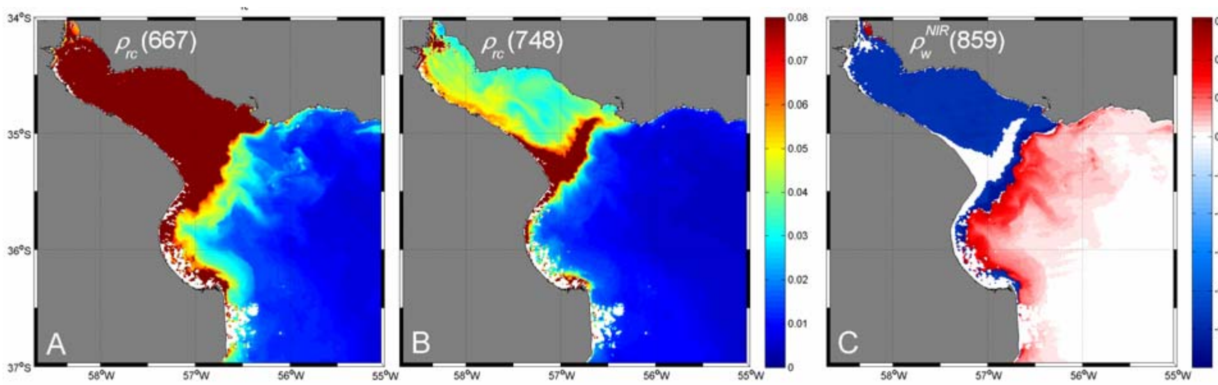


Figure 2. MODIS-Aqua Rayleigh-corrected reflectance at A) 667, B) 748 nm bands, and C) water reflectance at 859 nm band obtained using the standard NIR AC approach on Dec 20, 2010 over La Plata estuary region. Band saturation and clouds are shown in brown and white, respectively. Reproduced from Dogliotti et al (2011, ONW).

2) When the standard SWIR approach is used (SWIR-V), relatively high aerosol reflectance (ρ_a^{SWIR-V}) values can be observed where the maximum turbidity front is known to occur (Barra del Indio shoal, approx. 35.4°S, 57.0°W) and which is correlated to relative lower water reflectance (ρ_w^{SWIR-V}) (Figure 3 top row). This unphysical correlation between the atmospheric ρ_a(412) product and a marine feature is a consequence of the non negligible water reflectance in the 1240 nm SWIR band in the most turbid region. Invalidity of the SWIR black pixel assumption leads to an overestimation of ρ_a^{SWIR-V} and consequently to an underestimation of ρ_w^{SWIR-V}, with greatest underestimation in the blue bands.

3) When the iterative approach of the SWIR approach is used (SWIR-F), the spatial distribution of ρ_a^{SWIR-F} (412) and ρ_w^{SWIR-F} (412) show no correlation with the highly turbid front (Figure 3 bottom row) indicating a more realistic separation of top-of-atmosphere radiance into atmospheric and marine components.

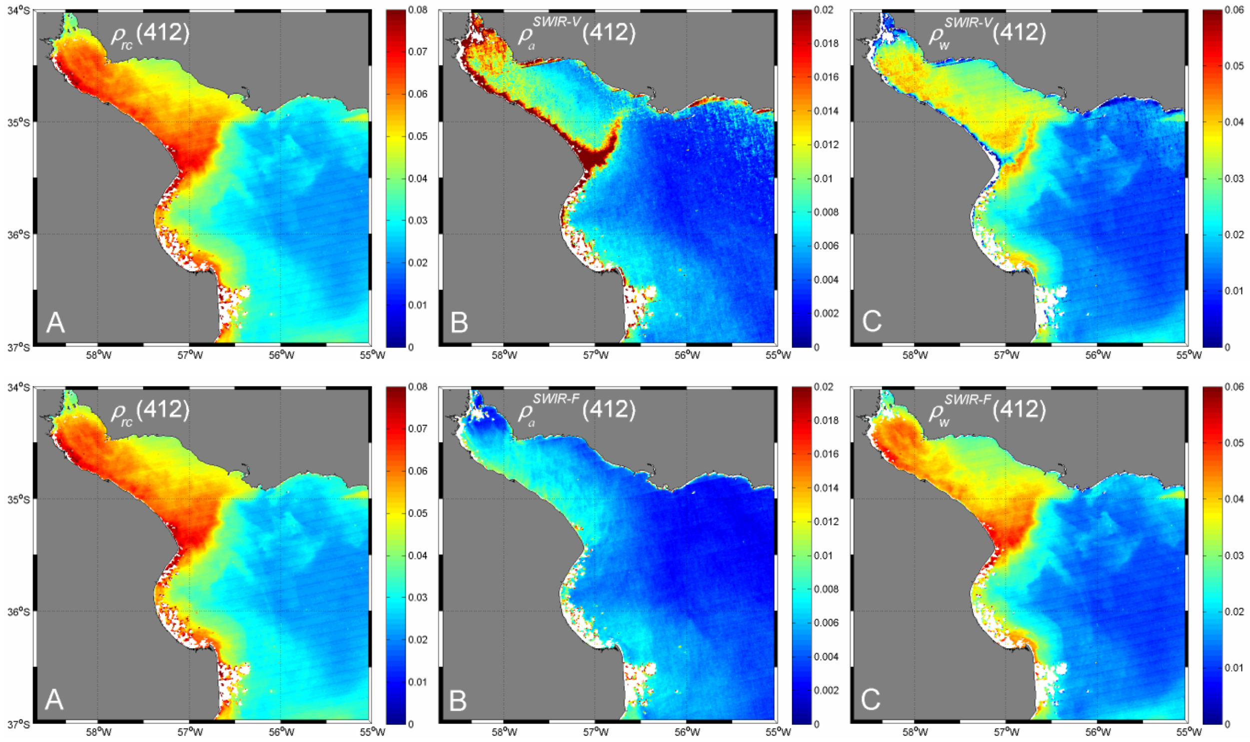


Figure 3. A) Rayleigh-corrected reflectance, B) aerosol and C) water reflectance at 412 nm retrieved from MODIS-Aqua image on Dec. 20, 2010 using the SWIR-V (top row) and SWIR-F (bottom row) approaches. Reproduced from Dogliotti et al (2011, ONW).

The highest differences in the retrieved ρ_w using *SWIR-V* and *SWIR-F* approached were found at the blue bands (~400 nm) and where the most turbid waters are known to occur as shows the spatial distribution and spectral reflectance of the $\rho_w^{SWIR-F} : \rho_w^{SWIR-V}$ ratio at 412 nm (Figure 4).

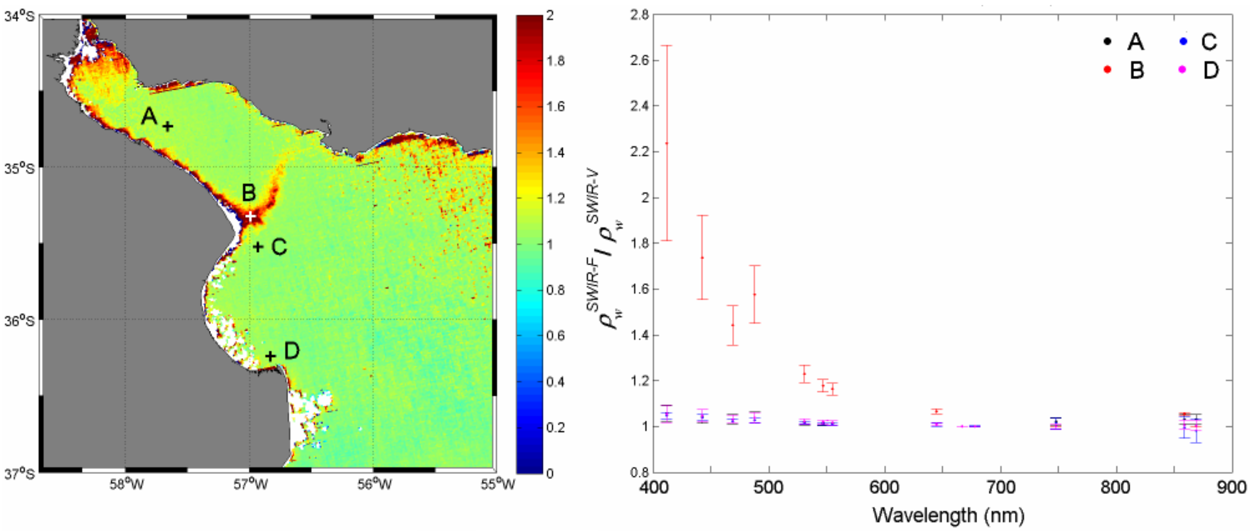
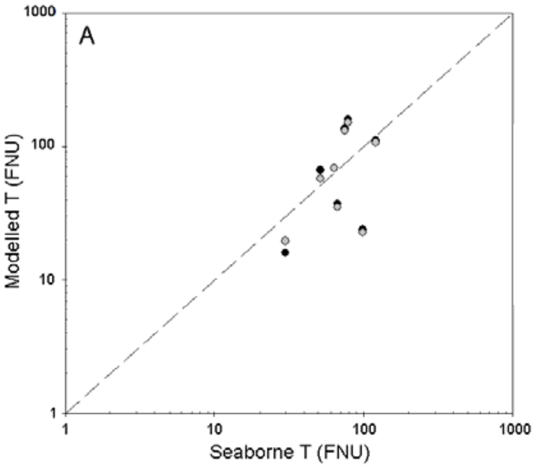


Figure 4. Ratio between ρ_w^{SWIR-F} and ρ_w^{SWIR-V} at 412 nm calculated from MODIS-Aqua image on Dec 20, 2010; Map (left) and mean and standard deviation at all bands from the locations indicated in the map (right). Reproduced from Dogliotti et al (2011, ONW).

Turbidity was then calculated using the one-band turbidity algorithm (Nechad *et al.* 2009) applied to satellite-derived water reflectance at the 859 nm band obtained from the two SWIR approaches and compared to *in situ* measurements.

In general, similar statistics were obtained when comparing the satellite-derived values using both methods, with relatively low correlation (~0.5) and mean ratio close to 1. The *SWIR-F* method showed slope closer to 1, lower $\log_{10}$-RMS, but higher mean percent difference (Figure 4).



B

Algorithm	*Slp*	*Int.*	*R*	*APD(%)*	*$Log_{10}RMS$*	*N*
T_{859}(SWIR-F)	1.02	- 0.10	0.52	49.6	0.3852	8
T_{859}(SWIR-V)	0.88	0.16	0.47	45.3	0.4196	8

Figure 5. A) Scatter plot of seaborne and modelled turbidity (T) using the SWIR-V (grey) and SWIR-F (black) atmospheric correction approaches for stations with T_{ind}>1.3; and B) table showing the statistics using the two approaches (slope (slp), intercept (Int.), correlation (R) and root mean square error in log-scale ($Log_{10}RMS$). Reproduced from Dogliotti et al (2011, ONW).

Conclusions

NASA Standard NIR-based AC approach systematically failed in the turbid waters of La Plata River. Switching between NIR and SWIR based approaches using the turbidity index performed well. Standard SWIR approach (pixel-by-pixel determination of aerosol model) gives better results, but overestimates aerosol reflectance in the most turbid parts of the river, leading to an underestimation of marine reflectance (black pixel assumption in 1240 nm not valid). *SWIR-F* approach, using a fixed aerosol model, was shown to be a good alternative for the more turbid waters. Differences between the two SWIR approaches were highest in the short wavelengths and lower in the NIR bands. No significant differences were found between the two approaches in the derived turbidity values. This is mainly due to the fact that the differences in ρ_w from the two approaches are low in the NIR bands, including the 859 nm band which is used to retrieve turbidity.

Turbidity and Total Suspended Matter algorithm (T3)

Previously developed algorithms to estimate Turbidity (T) and Total Suspended Matter (TSM) using *in situ* and satellite-derived marine reflectance in turbid North Sea waters (Nechad et al 2009 and 2010, hereafter referred as BN09 and BN10, respectively) have been tested over La Plata region. Concentration maps were derived from MODIS band 667 nm standard remote sensing reflectance (R_{rs}) using a one-band algorithm (BN10). The TSM maps obtained showed the river estuary masked most of the time. Analysis of the products and flags obtained with the standard processing showed that:

- MODIS 667, 748 and 869 nm bands generally saturate either over the whole estuary (667 nm band) or where the highest TSM are known to occur (turbidity front) for the longer wavelengths.
- Most of the estuary is generally erroneously flagged as clouds.

To overcome these difficulties, an alternative T/TSM algorithm based on the difference between two bands in the near infrared and short wave infrared has been developed. The use of a Rayleigh-corrected band-difference algorithm avoids the challenging task of performing the aerosol correction in highly turbid waters, like La Plata River. The cloud flagging was performed setting a threshold in the MODIS 2130 nm SWIR band.

The theoretical basis for the algorithm developed is based on the one-band T and TSM algorithms described in BN09 and BN10, respectively. For brevity only the turbidity algorithm will be described, but in a similar way the TSM algorithm can also be derived. The algorithm relates turbidity (T) to water reflectance, ρ_w, through

$$\rho_w = \frac{T}{A_T + T / C} \qquad (1)$$

where A_T and C are two wavelength-dependent calibration coefficients. The parameter C was calibrated using "standard" inherent optical properties, i.e. using average coefficients and typical values for coastal waters find in the literature (see BN10). The A_T factor was obtained by a non linear least-square regression analysis using *in situ* measurements of T and ρ_w from the Southern North Sea (BN09) and is related theoretically to inherent optical properties as shown later. Thus, applying this model at two different wavelengths the following relation between turbidity and the reflectance difference between band 1 and 2 ($\Delta\rho_w^{1,2}$) is proposed

$$\Delta\rho_w^{1,2} = \frac{T}{A_{T1} + T / C_1} - \frac{T}{A_{T2} + T / C_2} \qquad (2)$$

When applied to remotely sensed data, the use of a band difference of Rayleigh-corrected reflectance at two relatively close bands avoids the use of an aerosol correction algorithm by assuming spectrally "white" aerosols. For the present algorithm the MODIS 858 and 1240 nm bands were chosen. Analysis of MODIS imagery over La Plata River estuary showed that the MODIS 869 nm ocean band usually saturates in this region, preventing its use in the turbidity model. Consequently, the high resolution (250 m) land band at 858 nm is used instead.

The calibration coefficients A_T and C have been previously tabulated only between 600-885 nm (BN09 and BN10). Therefore to apply this algorithm to the short wave infrared band, i.e. 1240 nm band, the calibration had to be extended. This extrapolation was performed extending the near infrared similarity spectrum of the water (Ruddick *et al.* 2006) into the SWIR and extrapolating "standard" inherent optical properties to the SWIR region assuming spectrally constant particle scattering to backscattering ratio.

Results

Model calibration

The algorithm described was re-calibrated as in BN09, but using a different data set that included higher T values. The A_T coefficient at 858 nm was determined by non-linear regression analysis of *in situ* water reflectance and turbidity measurements performed in the Southern North Sea (SNS) and the Scheldt River (SR); only values higher than 10 FNU were used. Previous and new calibration coefficients are shown in Table 1.

Table 1: Calibration coefficients C and A_T (FNU) for the MODIS bands used in the previous work (BN09), a recently updated version (BN11) and the one obtained with the new calibration (NEW). ΔA_T is the standard error and n the number of data used in the non-liner regression for the NIR.

λ(nm)	C	A_T (BN09) $\pm\Delta A_T$	A_T (BN11) $\pm\Delta A_T$	A_T (NEW) $\pm\Delta A_T$
858	21.1 10^{-2}	2042.9±175.1 (n=26)	1845.8±222.6 (n=68)	3078.9±178.0 (n=52)
1240	21.6 10^{-2}	-	-	94117.2±5441.2

Validation of Turbidity algorithm

The proposed algorithm to estimate turbidity was tested and evaluated using the MODIS satellite-retrieved Rayleigh-corrected reflectance values for the days of the two cruises (Dec 20 2010 and 21 Mar 2011) in the Samborombón Bay region. Figure 6 shows the location of the sampled stations over the corresponding turbidity maps derived from the model using MODIS 858 and 1240 nm bands.

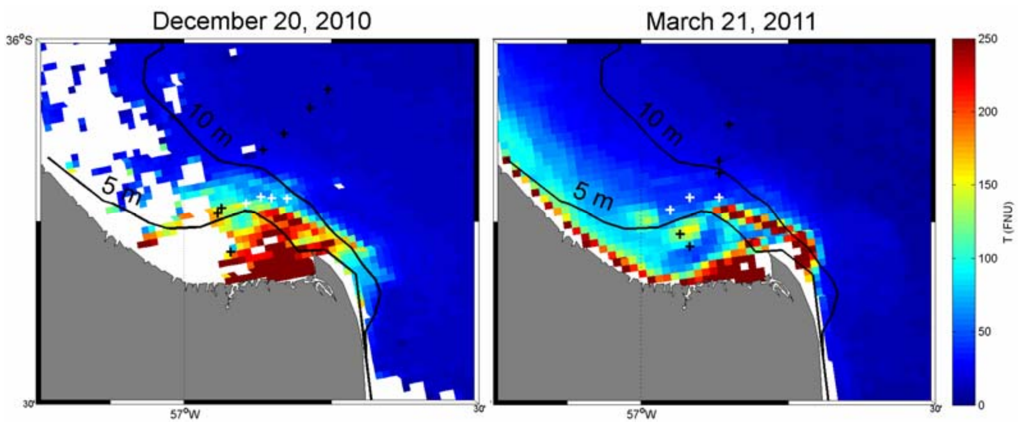


Figure 6: Turbidity maps from MODIS Rayleigh-corrected band-difference on Dec 20, 2010 (left) and on Mar 21, 2011 (right) over Samborombón Bay. Location of the sampled stations (+) and the 5 and 10 meter contours are indicated (black lines). Regions with clouds are in white. Reproduced from Dogliotti et al. (2011, EARSEL).

In general, the band-difference algorithm performed reasonably well. A better agreement was found for the first cruise compared to the second (Figure 7). The first showed a higher correlation (0.89), a slope closer to 1 (1.23) and lower Log_{10}-RMS error (0.1914).

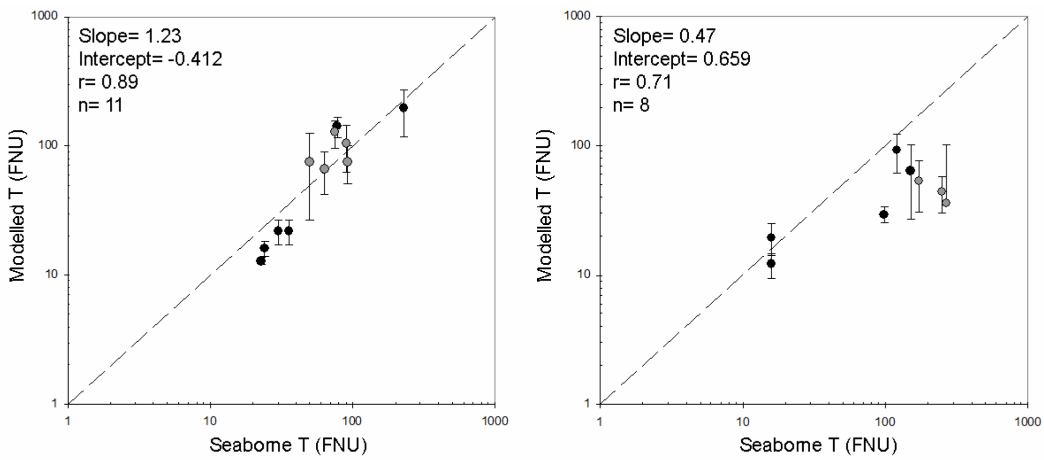


Figure 7: Scatter plots of seaborne and modelled turbidity using MODIS-Aqua Rayleigh-corrected reflectance in Samborombón Bay on Dec 20, 2010 (left) and Mar 21, 2011 (right). Error bars are the standard deviation of a 5x5 pixel window centred at the sampled site. The grey symbols correspond to

stations indicated in white in Fig. 6. The dashed curve shows the 1:1 line. Reproduced from Dogliotti et al (2011, EARSEL).

When considering the performance of the algorithm, it is important to assess the effect of spatial and temporal mismatch between *in situ* and remote sensing data. The relative error showed no significant correlation with the time difference between the sampling and the satellite overpass (p>0.1)

The highly turbid waters of La Plata River can be clearly seen in the MODIS quasi-true-colour images corresponding to the sampling dates by their brown colour (Figure 8). The derived turbidity maps using the proposed algorithm show a spatial distribution of turbidity consistent with known patterns and expected values in the region, i.e. the highest turbidity values can be observed along the Barra del Indio shoal and in the southern tip of Samborombón Bay.

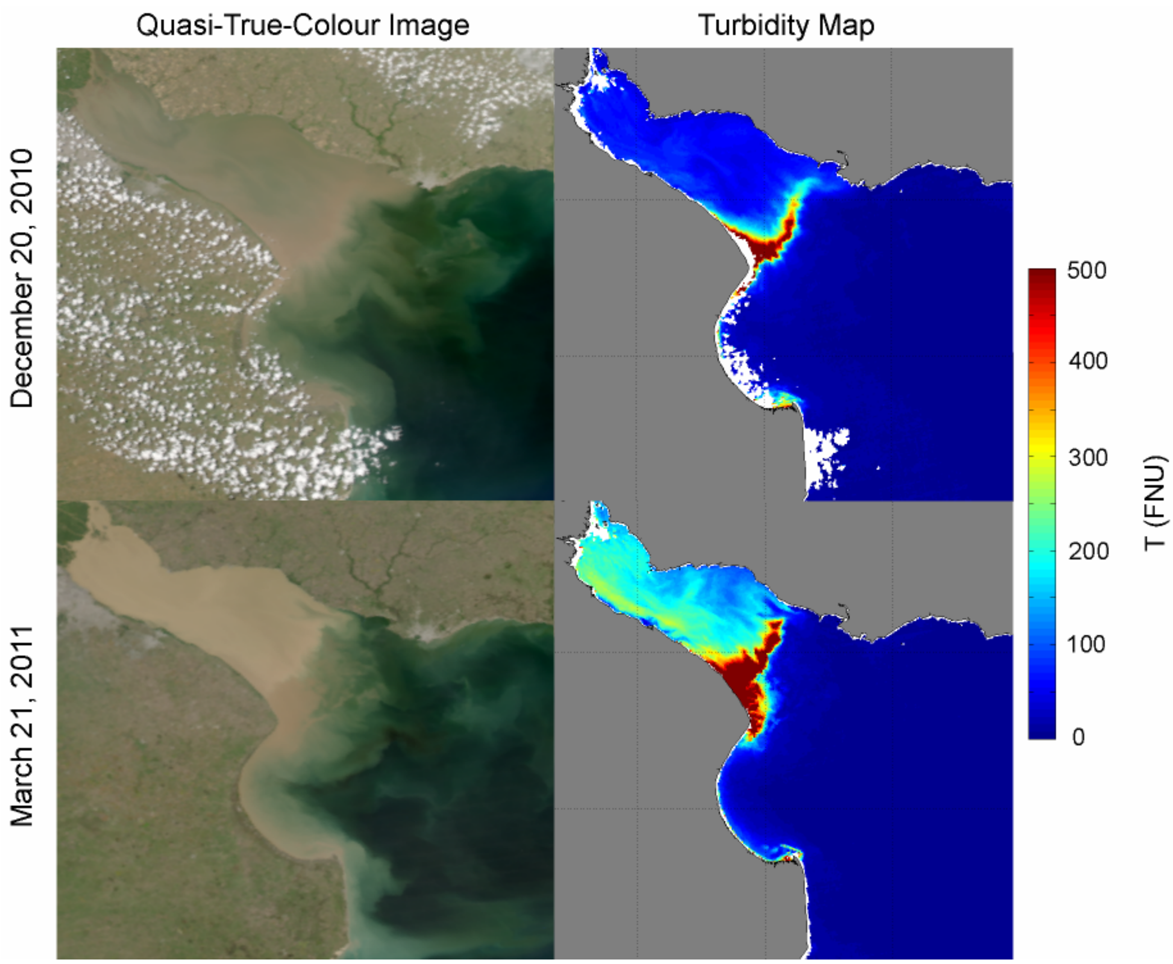


Figure 8: MODIS-Aqua Quasi-True-Colour image (left column) and Turbidity map (right column) for La Plata River Estuary on December 20, 2010 (upper panels) and March 21, 2011 (lower panels). Reproduced from Dogliotti et al (2011, EARSEL).

<u>Conclusions</u>

A model to estimate turbidity based on the difference between two bands in the near infrared and short wave infrared has been developed. An overall good agreement between modelled and *in situ* measurements was found. Sources of discrepancy could be related to the assumption of white aerosols (band difference) does not hold, the high spatio-temporal variability in the sampled region, and differences in the type of sediment (composition and/or size distribution) present in the region compared to the one used for the model calibration, while the time difference between measurements and satellite overpass, which reached up to 4 hours, did not show to be significantly correlated to the relative errors.

MODIS-Aqua image data base of La Plata region

In order to implement the developed methodology in an automated satellite data processing chain, an archive of satellite data for the La Plata region was created. MODIS level 1A and 2 daily images were requested and downloaded from the ocean color webpage (oceancolor.gsfc.nasa.gov) for the Río de La Plata region.

The tool for GRIdding MArine Satellite data (GRIMAS) was adapted and used to process the MODIS archive over La Plata region for the years 2002-2010. GRIMAS is a set of flexible image processing software that can process large numbers of MODIS and MERIS images in order to create a gridded dataset of different ocean color products, such as chlorophyll a concentration (Chl-*a*), sea surface temperature (SST - MODIS only) and of total suspended matter concentration (TSM), developed within the JELLYFOR-BE Project (Vanhellemont *et al.* 2011). Owing to its flexibility, a new region was configured by defining the bounding box in latitude and longitude and it was easily adapted to produce the new developed Turbidity product. Turbidity maps using the 2-band algorithm of two images are shown as an example in Figure 9.

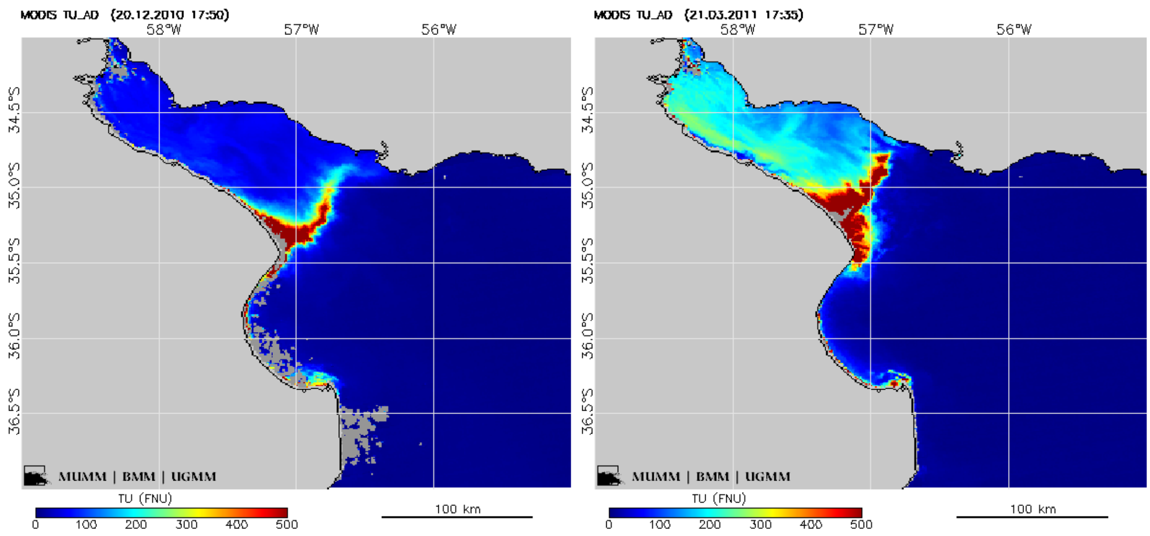


Figure 9. Turbidity maps derived from MODIS images on December 20, 2010 (left) and March 21, 2011 (right) obtained using GRIMAS and the 2-band algorithm developed within this project.

Analysis of MERIS imagery over La Plata region

MERIS imagery over La Plata region has also been analyzed. Since La Plata is one of the test sites of MERIS CoastColour Project, high resolution and enhanced CoastColour (CC) products from MERIS sensor were generated for this region. The CoastColour Project is designed to improve the quality of the coastal ocean products of MERIS sensor and to enhance its use. Consequently, both ESA standard and CC products have been analyzed and results have been presented in two CoastColour User Consultation Meetings.

A first analysis of ESA standard products (3^{rd} reprocessing) showed some difficulties in retrieving reliable water reflectance values (Figure 10). The 'Case II Turbid Water' test failed in the most turbid waters, thus the Clear Water atmospheric correction (AC) is applied retrieving erroneous data. Moreover, negative marine reflectance values in the blue bands (412 and 442 nm) are retrieved even when the bright pixel atmospheric correction (BPAC) is applied. The spatial distribution of the atmospheric intermediate products, such as the Angström exponent, showed unrealistic correlation with marine features indicating a poor performance of the AC.

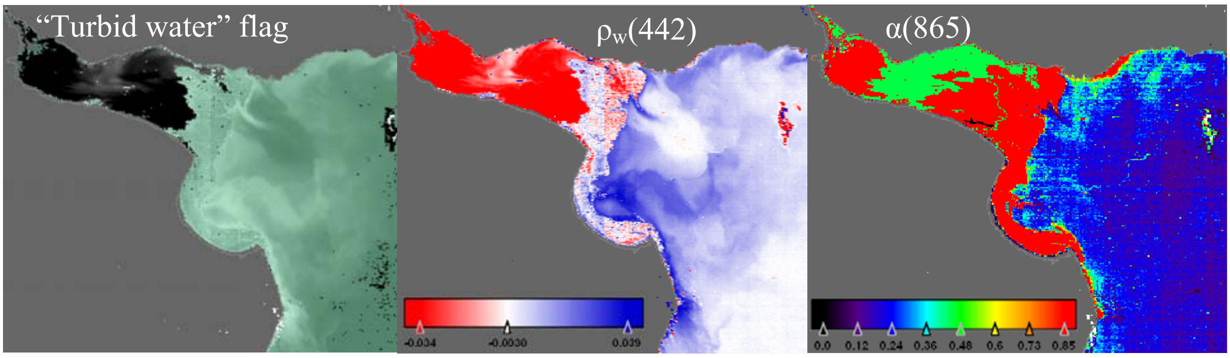


Figure 10. "Case-2 turbid water" flag in green (left);Water reflectance at 442 nm (center); Angström exponent*, α (right).ESA/MERIS 3*[rd] *reprocessing(2011) products.*

The analysis of CoastColour demonstration products (received on September 27, 2011) showed different results. The analysis of the quality control masks and flags showed some problems in the region where the turbidity maximum usually occurs, i.e. the cloud mask is erroneously set in water pixels close to the coast of Buenos Aires, the "Top-of-Atmosphere Reflectance and Atmospheric correction out-of-range" flags are also set indicating as well as the "Spectrum out-of-training range" of the water product level. A qualitative assessment of the atmospheric correction (AC) showed that there is no clear separation of the signal at the top-of-atmosphere into atmospheric and water component. A comparison between ESA standard and Coastcolour spectral water reflectance showed big differences (Coastcolour showed higher values) in the visible region of the spectra (400-700 nm) and for high reflectance (stations closer to the coast). A validation of the Turbidity (Figure 11) and Total Suspended Matter (Figure 12) products using *in situ* data from the Samborombón Bay showed that T product underestimates in situ values and saturates at 92.12 FNU, thus saturating in most of the estuary. On the other hand the TSM product showed a good *performance*, but it should be noted that only concentrations up to 80 mg m^{-3} were included in the comparison and the regression is dominated by a single high concentration value.

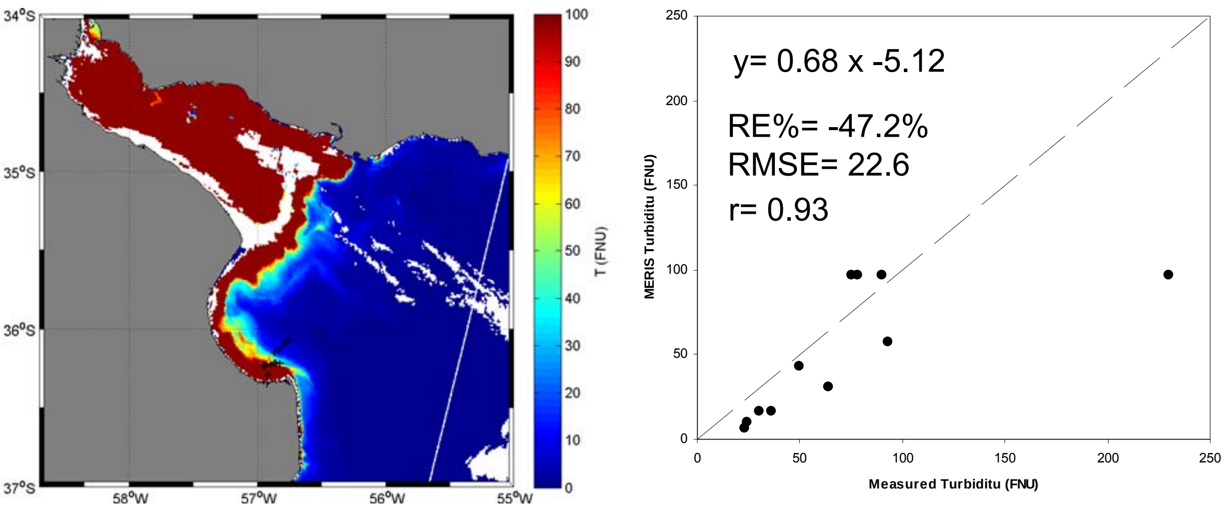


Figure 11. CoastColour Turbidity map (20 Dec 2010), location of the sampled stations (+) are indicated (left); and scatter plot of MERIS-CC product vs in situ values. Statistics and the regression equation are also indicated (right). Dashed line represents the 1:1 relationship.

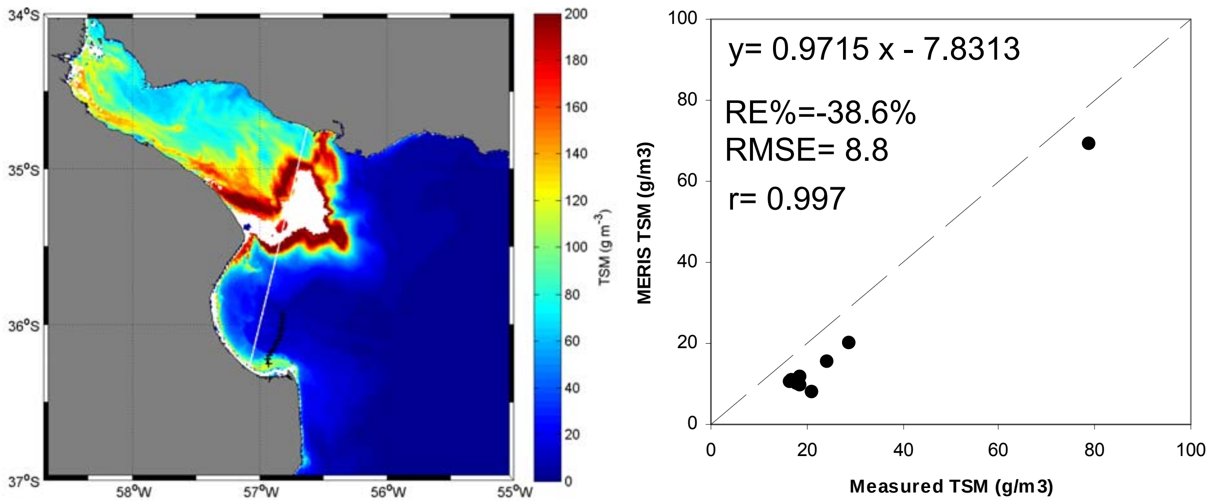


Figure 12. CoastColour TSM map (27 Apr 2011), location of the sampled stations (+) are indicated (left); and scatter plot of MERIS-CC product vs in situ values. Statistics and the regression equation are also indicated (right). Dashed line represents the 1:1 relationship.

In situ measurements (T2)

As part of my activities I also participated in two Belgica cruises and two one-day measurements campaigns on a pontoon in the Scheldt Estuary (Sint Anna) and worked in the improvement and updating of the methodology for measuring marine reflectance using Trios radiometers. A new version of the acquisition software in an up-dated operating system was installed. The whole chain of processing was reproduced in a different and up-dated environment making use of external files for auxiliary information, such as re-calibration coefficients and thresholds, that could be easily modified if required and which makes easier and faster the re-processing of the whole existing data base. The Sint Anna pontoon measurements of reflectance and turbidity contributed to the study of Knaeps *et al* (in press) on the Short Wave Infrared marine reflectance. The ideas for TSM retrieval and improved atmospheric correction developed in that paper, based on measurements in the very turbid waters of the Scheldt Estuary, are relevant for future application in the extremely turbid waters of La Plata estuary.

Conclusions and Future perspectives

The main results of this post-doc fellowship were:

- Calibration and validation of algorithms for estimating turbidity and Total Suspended Matter in the extremely turbid waters of La Plata Estuary (Dogliotti *et al*. 2011, EARSEL)
- Improvement of the atmospheric correction of remote sensing data in extremely turbid waters, such as La Plata Estuary (Dogliotti *et al.* 2011, ONW)
- Measurements of reflectance and turbidity in the very turbid waters of the Scheldt Estuary, contributing to new methods for TSM estimation and atmospheric correction for extremely turbid waters by exploitation of the Short Wave Infrared spectral range (Knaeps *et al.* in press)
- Improvement of processing methodology for measurements of marine reflectance
- Preparation of automated processing for a large archive (10 years) of satellite data for La Plata Estuary.

Future perspectives include:

- Exploitation of the archive of satellite data for La Plata Estuary in support of marine applications, including sediment transport, fisheries (larvae/turbidity processes) and primary production. An abstract outlining such work has been submitted for the International Colloquium on "Remote Sensing of ocean colour, temperature and salinity" (Liège, May 2012).
- Further improvements of methodologies for atmospheric correction and TSM and turbidity retrieval for extremely turbid waters, using La Plata Estuary as an international ocean colour validation site. The SeaSWIR proposal including such work has been accepted for funding by the Belgian Science Policy Office.
- Contribution to the design of future ocean colour sensors and algorithms (OLCI, SABIA/MAR, etc.), especially regarding the use of the Short Wave Infrared spectral range for extremely turbid estuarine and potentially inland waters (IOCCG, 2011).

References

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Cruises

- Sint Anna pontoon measurements (Antwerp, Belgium), 23 July and 26 October 2010.
- BELGICA cruise 2010-18. On board the R/V Belgica. 5th – 9th July 2010.
- BELGICA cruise 2011-19. On board the R/V Belgica. 4th – 7th July 2011.

Conferences and Meetings attended

1. BELCOLOUR-2 Plenary Meeting #4. Laboratoire Océanographique de Villefranche (LOV), Villefranche-Sur-Mer, France. 18-19 October, 2010. Talk: *La Plata River Plume, challenging waters for atmospheric correction and TSM algorithms.*
2. 1st CoastColour User Consultation Meeting. European Space Agency (ESA). Frascati, Italy. November 16-17, 2010. Oral presentation: *La Plata River Plume, challenging waters for atmospheric correction and TSM algorithms.*
3. AERONET-OC: 1st Workshop Overview and Future Developments. JPSS Program Office, Greenbelt, Maryland, USA. February 23 -24, 2011. Oral presentation: *Plans for AERONET-OC stations in turbid waters (Argentina and Belgium).*
4. MERIS Validation Team Meeting. Joint Research Centre. Ispra, Italy. March 8-10, 2011. Oral presentation: *First analysis of MERIS data over the highly turbid waters of La Plata River.*
5. BELCOLOUR-2 Steering Committee Meeting. Oostende, Belgium. 19 May 2011. Talk: *La Plata River Plume, challenging waters for atmospheric correction and TSM algorithms (New results).*
6. 5th EARSeL Workshop on Remote Sensing of the Coastal Zone. Prague, Czech Republic, June 1-3, 2011. Oral presentation: *Mapping total suspended matter using ocean color data over La Plata River Estuary, Argentina*
7. VI International conference «Current Problems in Optics of Natural Waters». St.Petersburg, Russia, September 6-10, 2011. Oral presentation: *Estimating turbidity in the La Plata River from MODIS imagery.*
8. MERIS Validation Team Meeting. Lisbon, Portugal. October 18, 2011.
9. 3rd CoastColour User Consultation Meeting. Lisbon, Portugal. October 19-20, 2011. Oral presentation: *CoastColour products over La Plata River Site*.

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