COASTAL –GILBES' GROUP REPORT
(Performance period: September 1, 2007 to February 29, 2008)

RESEARCH COMPONENT

Thrust: Remote Sensing of Coastal Waters

Project 2: Field measurements in coastal waters for algorithm testing/development and satellite validation

- **Relevance to NOAA's mission and the strategic plan:** This project is well in view with NOAA's vision and mission that establish a comprehensive understanding of the role of the oceans and coasts to meet our Nation's economic, social, and environmental needs. It is aligned with the new priorities for the 21st century presented in the NOAA's strategic plan and in regards of coastal and marine resources through an ecosystem approach to management. The research activities are helping to develop better and most cost-effective tools to monitor coastal processes.
- **Relevance to NOAA Line Office (i.e., National Weather Service, National Ocean Service) strategic plan:** This project provides critical support for NOAA's missions of the National Ocean Service by using and validating environmental satellite data. Especially, it is creating an important database of bio-optical properties from coastal waters affected by rivers discharge. These field data are crucial to develop improved algorithms for the estimation of water quality parameters in coastal waters.
- **Supervising PI or Co-Is:** Fernando Gilbes Santaella
- **Publications (during performance period):** A journal publication is now in preparation and it will be submitted to Applied Optics. Authors have continue working with their chapters for the peer-review book about the oceanography and remote sensing of Mayaguez Bay, including all the work sponsored by NOAA CREST. This book will be published in collaboration with the Center for Hemispherical Cooperation (CoHemis) of UPRM.
- **Dollar amount of funds leveraged with CREST funds (during performance period):**
  1. Study of Benthic Habitats Using Hyperspectral Remote Sensing. Sponsored by NSF-Center for Subsurface Sensing and Imagine Systems (CenSSIS). $25,000
  2. Developing a protocol to use remote sensing as a cost effective tool to monitor contamination of mangrove wetlands. Sponsored by the Puerto Rico Sea Grant. $50,000
- **Ongoing, New or Revised?:** Ongoing
- **Staff:** None
- **Students PhD:** Patrick Reyes and Ramón Lopez, UPRM-Department of Marine Sciences
- **Students MS:** Vilmaliz Rodriguez, UPRM-Department of Geology
- **Students Undergraduate:** José Martinez and Nathlee Hernández, UPRM-Department of Geology (these students worked in a NOAA CREST related topic as part of the course Geol 4049 and 40455, undergraduate research; but they were not directly funded)

- **NOAA Collaborators:** Richard Stumpf from the NOAA's National Centers for Coastal Ocean Science (NCCOS). He is an expert in the application of remote sensing to coastal waters, especially for the estimation of suspended sediments and Chl-a. A possible visit of Vilmaliz Rodriguez to his laboratory will be planed and coordinated for the future.
- **Other Collaborators:** Eric Harmsen (UPRM-Department of Agricultural Engineering), Carlos Ramos-Scharrón (Department of Geosciences, Colorado State University), and Luis Pérez-Alegría (UPRM-Department of Agricultural Engineering), Richard Miller (National Aeronautics and Space Administration), and Roy Armstrong (UPRM-Department of Marine Sciences)
- **Operational Impact:** The on-going project aims to develop the appropriate techniques to use ocean color sensors to monitor the conditions of coastal environments. Estimates of Chlorophyll and Suspended Sediments from space can be used as proxy for the quality of coastal waters. Continuous monitoring of such parameters with satellite sensors will help to better understand and manage our coastal environments.
- **Status of the project with respect to the goals/objectives and benchmarks previously identified:** Validation of MODIS data in Mayaguez Bay was continued. Estimates of Suspended Sediments using bands 1 and 2 (250 m) and Richard Miller's algorithm were compared with field measurements. The first version of site-specific algorithms have also been developed and tested, although further testing and tuning is necessary. Remote sensing reflectance measurements obtained with the GER-1500 spectroradiometer are being used to estimate these parameters and compared with MODIS data. The standard algorithm developed and used by NASA to estimate Chl-a using MODIS was tested in Mayaguez Bay using the GER-1500 remote sensing reflectance data. Bio-optical data collected during the past six years with a rosette have been incorporated in a GIS-database for further analyses and comparisons with satellite data.

Tasks (For year I as per the Milestone Chart)

Task (1) Compare to satellite water leaving products and atmosphere retrievals
Task (2) Intercomparison of the below/above water signals with aircraft and satellite data as available.

This project aims to develop a method to monitor sedimentation processes in a coastal environment by using remote sensing technology. The main objectives of this study were to generate, validate and apply an algorithm to estimate suspended sediment concentration (SS) based on remote sensing reflectance (R_{rs}) and MODIS data. It was expected to establish the relationship between *in situ* measurements of SS and Rrs, to then apply the generated equation to MODIS band 1 and band 2 data (620-670 nm and 841-876 nm, respectively). Considering that R_{rs} values are significantly lower than MODIS data, a second relationship was establish associating band 1 and band 2 of Rrs and MODIS data. The algorithm produced was validated by applying both resultant equations to three MODIS images from which *in situ* data was available. In general, the estimations of the algorithm tended to sub-estimated field measurement values, however, abundance and spatial variations of these estimations responded as expected. An application component was included in this study, which consisted on estimate total river discharge by applying the algorithm produced to an image associated to a significant rain event.

This allowed to calculated total mass for a determined area based on SS concentration. This study provided a base to the desire method but various refinements still need to be applied in the approach for more reliable results. More information can be found in the appended report of Vilmaliz Rodriguez.

Project 3: Improvement/Development of algorithms for remote sensing of coastal waters

- **Relevance to NOAA's mission and the strategic plan:** This project is well in view with NOAA's vision and mission that establish a comprehensive understanding of the role of the oceans and coasts to meet our Nation's economic, social, and environmental needs. It is aligned with the new priorities for the 21st century presented in the NOAA's strategic plan and in regards of coastal and marine resources through an ecosystem approach to management. The research activities are helping to develop better and most cost-effective tools to monitor coastal processes.
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Tasks (For year I as per the Milestone Chart)

Task (1) Analysis of optical field measurement together with Chl, TSS concentrations

During this time period we have focused on finishing the data processing gathered for the ac-9 instrument. A data set including all the measured parameters were compiled by stations for all eleven cruise from 2004-2007 with there values at the surface and depth. The data includes Remote Sensing Reflectance (R_{rs}), Chlorophyll-a concentration (Chl-a), Total Suspended Solids (TSS) and Chromophoric Dissolved Organic Matter absorption coefficient (a_g at 412 and 443 nm) and the Spectral Slope parameter (S, various ranges) in the UV and visible spectrum. This spectral slope can be further used in remote sensing and in the geochemistry for local CDOM dynamics. Profiles we generated for the time period for the complete cruises, (salinity, Chl-a fluorescence, (absorption and attenuation at 412 and 440 channels). The R_{rs} data was correlated with the ac-9 412 nm absorption channel and CDOM (a_g412) water samples taken at the surface. Good correlations have been observed between R_{rs} and the 412 nm absorption channel, R_{rs} vs. CDOM (a_g) and ac-9 total absorption vs. a_g412. Analyses between the two seasons indicate that differences exist between the measured parameters being only the spectral slope and TSS means similar for both seasons being the bottom resuspention the responsible for this during the rainy season. Laboratory experiments indicate that river water dilution with marine water end members cause a slight decrease in CDOM (a_g375) from its theoretical dilution indicating the possible flocculation of this material. In a similar approach but this time with clays extracted from the river waters a further reduction in a_g375 was observed. This indicates that clay may play an important role during estuarine mixing processes buy adsorbing some of the CDOM to its surface. More information can be found in the appended report of Patrick Reyes.

Task (2) Evolution and tuning of algorithm for Chl retrieval in PR coastal waters

The Moderate Resolution Imaging Spectroradiometer (MODIS) is considered an improved generation of ocean color sensors. However, its validation for coastal monitoring is still underway. The main objective of this research was to validate the accuracy of MODIS to measure phytoplankton Chlorophyll-a (Chl-a) and suspended sediments (SS) in Mayagüez Bay, Puerto Rico. Field measurements of Chl-a and SS were compared with those estimated from MODIS data. A low correlation was found between field and MODIS Chl-a values obtained with both, Terra (R^2=0.0283) and Aqua (R^2=0.0265), satellites and using the standard NASA OC3 algorithm. Since the standard Chl-a product provided by NASA routines was not good for our study area, it was decided to derive and test a local empirical algorithm using MODIS Bands 3 (469 nm) and 4 (555 nm), which provide 500 meter of spatial resolution. The regressed linear equation for B3/B4 ratio and field Chl-a was $y = -0.6614x + 1.4937$ and the $R^2 = 0.3886$; while the logarithmic equation was $y = -0.4939\text{Ln}(x) + 0.7243$ and the $R^2 = 0.3688$. In order to estimate SS with MODIS, Band 1 (645 nm) with 250 meter of spatial resolution was used to validate the algorithm developed by Miller and McKee (2004) in the Gulf of Mexico. However, the suggested equation failed in Mayagüez Bay. A second approach intended to develop a site-specific algorithm for SS using this same band, but low correlation was also found on various testing scenarios. They were R2 = 0.1443 (overall), R2 = 0.0695 (dry season), R2 =0.2788 (rainy season), R2 = 0.0473 (inshore stations), and R2 = 0.0468 (offshore stations). Image processing and analyses clearly demonstrated that MODIS is not the most appropriate ocean color sensor for Mayagüez Bay. Another sensor with better temporal, spatial, and spectral resolutions is still needed for the estimation of Chl-a and SS in coastal waters.

Future Tasks (From the Milestones)

Efforts for developing site-specific algorithms for Chlorophyll-a and suspended sediments will continue. More pre-processing, quality control, and corrections of the bio-optical data are needed before the GIS databases can be developed. Once these steps are completed the data will be exported to ArcView format in order to prepare the databases. Synoptic maps of all parameters will be developed then compiled in the web-base environment ArcIMS. This activity will allow people to access and manipulate the data via internet for better understanding of land-sea interactions in Mayaguez Bay. A new doctoral student, Ramón Lopez, has been hired and he will work with this important aspect of the project. A publication of the Vilmaliz Rodriguez work will be submitted to the Applied Optics journal very soon. Patrick Reyes will defend his dissertation and will submit one chapter of the Mayaguez Bay book.

Dynamics of Chromophoric Dissolved Organic Matter (CDOM) in Coastal Tropical
By: Patrick Reyes Pesaresi

Abstract

During this time period we have focused on finishing the data processing gathered for the ac-9 instrument. A data set including all the measured parameters were compiled by stations for all eleven cruise from 2004-2007 with there values at the surface and depth. The data includes Remote Sensing Reflectance (R_{rs}), Chlorophyll-a concentration (Chl-a), Total Suspended Solids (TSS) and Chromophoric Dissolved Organic Matter absorption coefficient (a_g at 412 and 443 nm) and the Spectral Slope parameter (S, various ranges) in the UV and visible spectrum. This spectral slope can be further used in remote sensing and in the geochemistry for local CDOM dynamics. Profiles we generated for the time period for the complete cruises, (salinity, Chl-a fluorescence, (absorption and attenuation at 412 and 440 channels). The R_{rs} data was correlated with the ac-9 412 nm absorption channel and CDOM (a_g412) water samples taken at the surface. Good correlations have been observed between R_{rs} and the 412 nm absorption channel, R_{rs} vs. CDOM (a_g) and ac-9 total absorption vs. a_g412. Analyses between the two seasons indicate that differences exist between the measured parameters being only the spectral slope and TSS means similar for both seasons being the bottom resuspention the responsible for this during the rainy season. Laboratory experiments indicate that river water dilution with marine water end members cause a slight decrease in CDOM (a_g375) from its theoretical dilution indicating the possible flocculation of this material. In a similar approach but this time with clays extracted from the river waters a further reduction in a_g375 was observed. This indicates that clay may play an important role during estuarine mixing processes buy adsorbing some of the CDOM to its surface.

Introduction

During this work period we have focused in finishing the editing and processing all the gathered data for the Mayaguez Bay from 2004-2007 for the ac-9 submersible absorption and attenuation beam meter. The data for the ac-9 was further corrected and was included on the previous developed Excel data set sheet were all the different parameters have been grouped by stations, cruises and season. With this data set it should be possible for other persons using GIS related software to manipulate and generate the required layers for all the measured parameters (CDOM, salinity, Chl-a etc) for the Bay area. Secondly we focused on the R_{rs} data set where we separated the next remote sensing reflectance at the next wavelength 412, 443, 510 and 555 nm. With this values we calculated a series of band ratios (R_{rs}412/R_{rs}443, R_{rs}443/R_{rs}510, and R_{rs}510/R_{rs}555). The relationship between this ratios and the measured total absorption for the ac-9 instrument for the 412 channel, and the measured and CDOM a_g(412) values measured in the laboratory were addressed. Good fits have been found between all the performed relationship with the best found during the rainy season.

Another question we wanted to answer was if it could be possible that the terrestrially derived CDOM could be diluted with marine waters and if it could also be possible that the co-occurring clay material brought by the rivers could be adsorbing CDOM material when they enter in contact with marine waters. This experiments revealed that simple dilution can remove part of the CDOM from solution reducing the a_g(375 nm). In a similar experiment but this time using clay material extracted from the river waters, indicate that the clay particles reduce even further the a_g375 than the dilution experiment alone. This fact indicates that clay material brought at the same time with the terrestrial CDOM can be adsorbed to these particles during estuarine mixing and that even during mixing some of the material can be lost possible due to flocculation.

Material and methods

Ancillary data:

Files containing the precipitation data For the Añasco, Guanajibo and Yagüez River watershed were taken from the national whether service Web page and the River flow data was downloaded from the USGS River Flow web page. Precipitation and river flow graphs were done for the study period. After checking the natural fluctuations due to precipitation and hence River flow we divided the seasons between dry and rainy season. The cruises were divided between the rainy and dry season as the months were the river discharge were on average more that 15 m^3/s for the three previous days. In this case July that was taken as a dry month was included in the data set of the cruises of the rainy season. ANOVA Statistical analysis showed that their where significantly differences between the rainy and dry seasons no matter the time scale that was evaluated.(three, one week, two weeks an monthly). A time series graph was generated for the precipitation and River flow (Appendix)

Ac-9 data correction and editing.

After binning the ac-9 profile data at 0.5 meter depth, the raw data was corrected with the instrument calibration files for temperature and water blank. After this step the data was further corrected by the in *situ* measured salinity and temperature and by subtracting the 715 nm channel for scattering at each depth (Pegau et al., 1997). This correction was done for each of the absorption (a) channel and attenuation (c) channel no scattering correction has to be performed for the attenuation channel. The final values were then organized by stations generating 9 columns for absorption (412, 443,488, 510, 532, 555, 650, 676 and 715 nm) and the same channel for attenuation, binned at 0.5 meter depth. I further refined my data set and isolated the data only for only 412 a and c and 440 a and c channel since this values are the ones relevant for my research.

Remote sensing reflectance

Remote sensing reflectance was evaluated as a tool for the estimate of CDOM absorption. After calculating and correcting the Remote Sensing Reflectance for each station. We proceeded for our analysis to calculate an average value at (412,443, 510 and 555 nm) by taking the R_{rs} values five nanometers up and down the mention values. Then with the calculated averages we calculated a band ration between (R_{rs}412/R_{rs}443, R_{rs}443/R_{rs}510, and R_{rs}510/R_{rs}555) as described by (D’Sa and Miller 2007). This was done to evaluate the relationship between CDOM a_g (412) at one meter depth and the total absorption measured by the ac-9 412 nm channel also at one meter depth. The relationship between for CDOM a_g 412 and the measured values for the ac-9 412 total absorptions were also evaluated.

CDOM dilution and clay adsorption experiments:

Four liters of water at the offshore Y2 Station (Marine water) and a same volume for the Anasco river were collected in amber ashed crystal bottles. The samples were immediately were filtered trough ashed GF/F glass fiber filters and refrigerated. A series of progressive dilutions were made between the marine and river water. The samples were left at room temperature overnight, and the next day the samples were re-filtered through the same GF/F filters and CDOM absorption was determine for each of the 9 dilution and two end members in duplicates. CDOM a_g375 was calculated for each dilution the final salinity was measured.

In a second experiment a similar approach was conducted, but this time the Añasco river water end member was amended with 0.150 mg of clay material recover from the same river in a 208 liter drum and was left to settle by gravity after a week. The Clay material was then oven dried at 60^{o}C and pulverized with a mortar and pestle. Two replicate dilution of one liter filter water were made by adding the weighted clay material. The next day dilution were made using this dilution stock After a day of equilibration at room temperature the samples were re-filtered and the optical density measured. Then the salinity for each dilution was determined by an YSI portable salinometer.

Statistical analysis:

For all the evaluated parameters number of Parsons regression analysis and ANOVA analysis have been performed.

Results

In the performed statistical analysis seasonality was indeed observed for the measured parameters. Significantly differences were found between the rainy and dry season for salinity, a_g375 and Chl-a. In the case of the spectral slopes and TSS no significant differences were found between seasons. From an inshore to offshore stations salinity, TSS, Chl-a and CDOM a_g375 were significantly different. The Spectral slope parameters were not significantly different between the rainy and dry season. (Table: 1-5)

For the laboratory CDOM experiments it was found that simple dilution between marine and river end members can remove a fraction of this material and that CDOM does not behaves in a conservative way during mixing. In the next experiment were clay material was added to river waters and this solution mixed with marine water end members it was found that the loss of CDOM absorption (a_g375) was even larger an that this could be due to adsorption of the CDOM material to clays (Figure: 6)

Table: 1 Salinity ANOVA between Season and Inshore- Offshore stations

Salinity		
Dry Season Inshore Offshore	**p = 0.15724 (NS)**	**At the 0.05 The means are NOT significantly different.**
Rainy Season Inshore Offshore	**p = 2.14605E-5*****	**At the 0.05 The means are significantly different.**
Dry vs Rainy	**p = 7.45395E-10*****	**At the 0.05 The means are significantly different.**

Statistical significace
NS (p>0.05)
weak (0.01<p<0.05)*
moderate (p< 0.01)**
strong (p<. 001)***

Table: 2 Total suspended solids ANOVA between Season and Inshore- Offshore stations

TSS		
Dry Season Inshore Offshore	**p = 4.24301E-5*****	**At the 0.05 The means are significantly different**
Rainy Season Inshore Offshore	**p = 0.00519 ***	**At the 0.05 The means are significantly different.**
Dry vs Rainy	**p = 0.40295 (NS)**	**At the 0.05 The means are NOT significantly different.**

Statistical significace
NS (p>0.05)
weak (0.01<p<0.05)*
moderate (p< 0.01)**
strong (p<. 001)***

Table: 3 Chlorophyll-a ANOVA between Season and Inshore- Offshore stations

Chlorophyll-a		
Dry Season Inshore Offshore	**p = 1.95523E-5*****	**At the 0.05 The means are significantly different**
Rainy Season Inshore Offshore	**p = 1.2221E-7*****	**At the 0.05 The means are significantly different.**
Dry vs Rainy	**p = 0.14865 (NS)**	**At the 0.05 The means are NOT significantly different.**

Statistical significace
NS (p>0.05)
weak (0.01<p<0.05)*
moderate (p< 0.01)**
strong (p<. 001)***

Table: 4 Spectral Slope ANOVA between Season and Inshore- Offshore stations

Spectral slope (375-400 nm)		
Dry Season **Inshore** **Offshore**	**p = 0.06508(NS)**	**At the 0.05 The means are NOT significantly different.**
Rainy Season **Inshore** **Offshore**	**p = 0.08903(NS)**	**At the 0.05 The means are NOT significantly different.**
Dry vs Rainy	**p = 0.02784 ***	**At the 0.05 The means are significantly different.**

Statistical significace
NS (p>0.05)
weak (0.01<p<0.05)*
moderate (p< 0.01)**
strong (p<. 001)***

Table: 5 CDOM ANOVA between Season and Inshore- Offshore stations

CDOM a_g375 surface only		
Dry Season **Inshore** **Offshore**	**p = 3.09064E-6*****	**At the 0.05 The means are significantly different.**
Rainy Season **Inshore** **Offshore**	**p = 2.2949E-6*****	**At the 0.05 The means are significantly different.**
Dry vs Rainy	**p = 6.89081E-5******	**At the 0.05 The means are significantly different.**

Statistical significace
NS (p>0.05)
weak (0.01<p<0.05)*
moderate (p< 0.01)**
strong (p<. 001)***

Figure: 1 Dilution diagram experiment with Marine and Anasco River end member

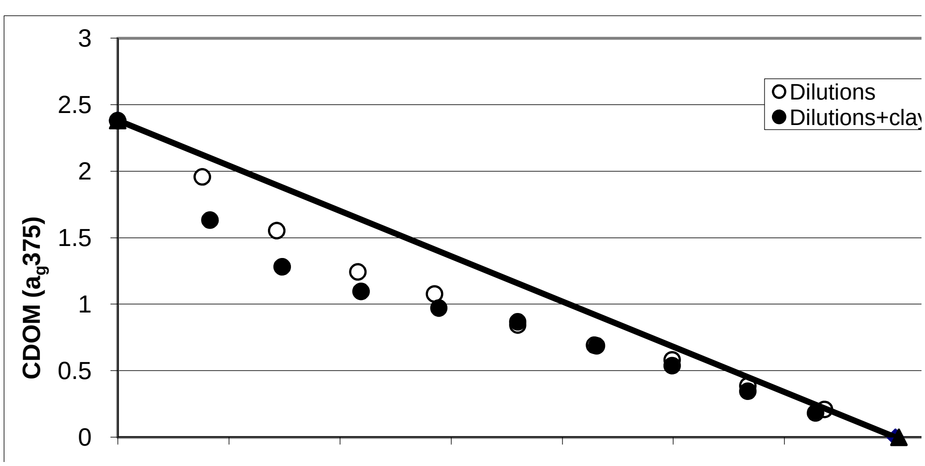


Figure: 2 Remote sensing reflectance vs. ac-9 412 channel correlation

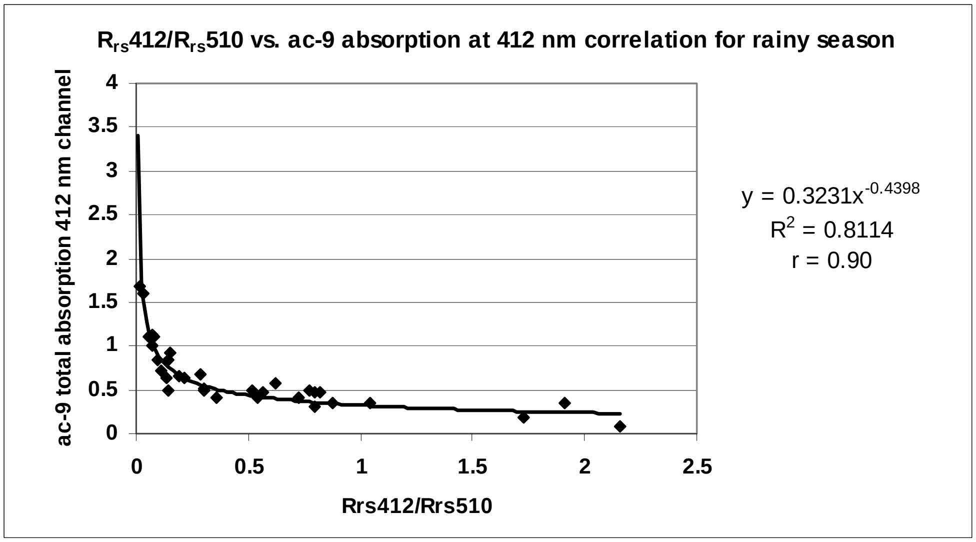


Figure: 3 Remote sensing reflectance vs. a_g 412 correlation

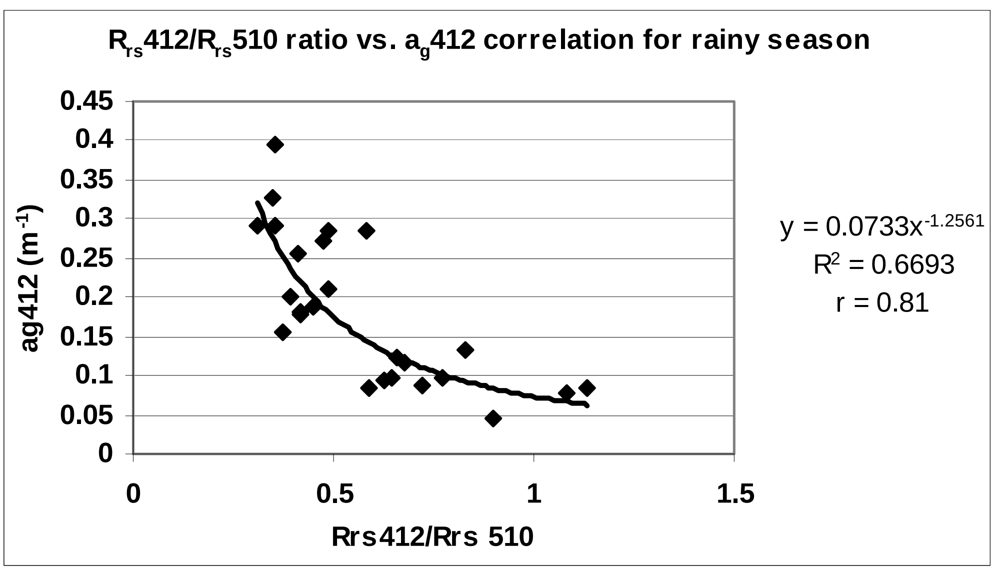


Figure: 4 AC-9 412 absorption channel vs. a_g 412 correlation for the rainy season

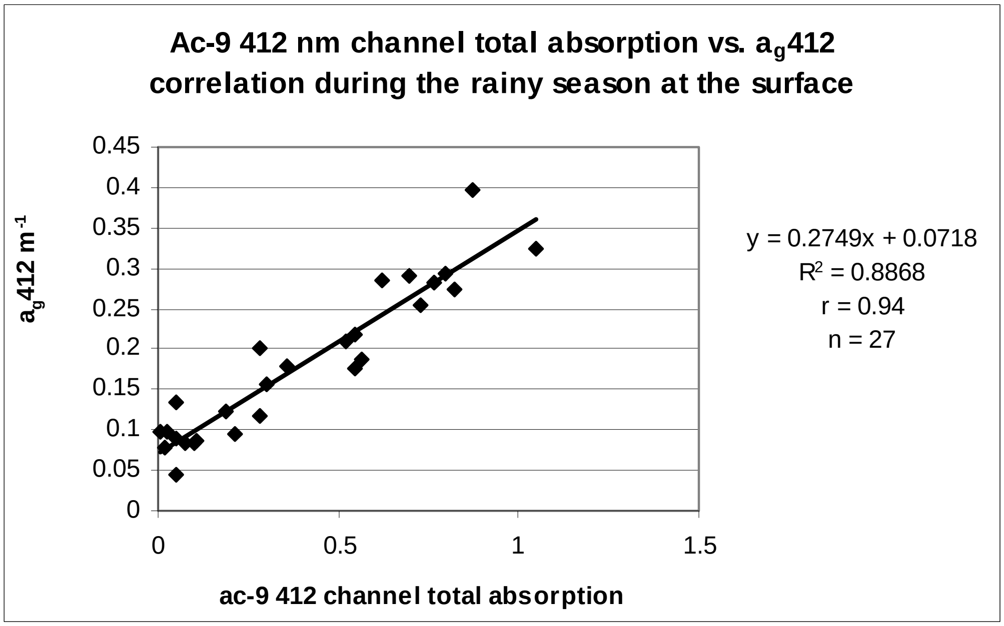
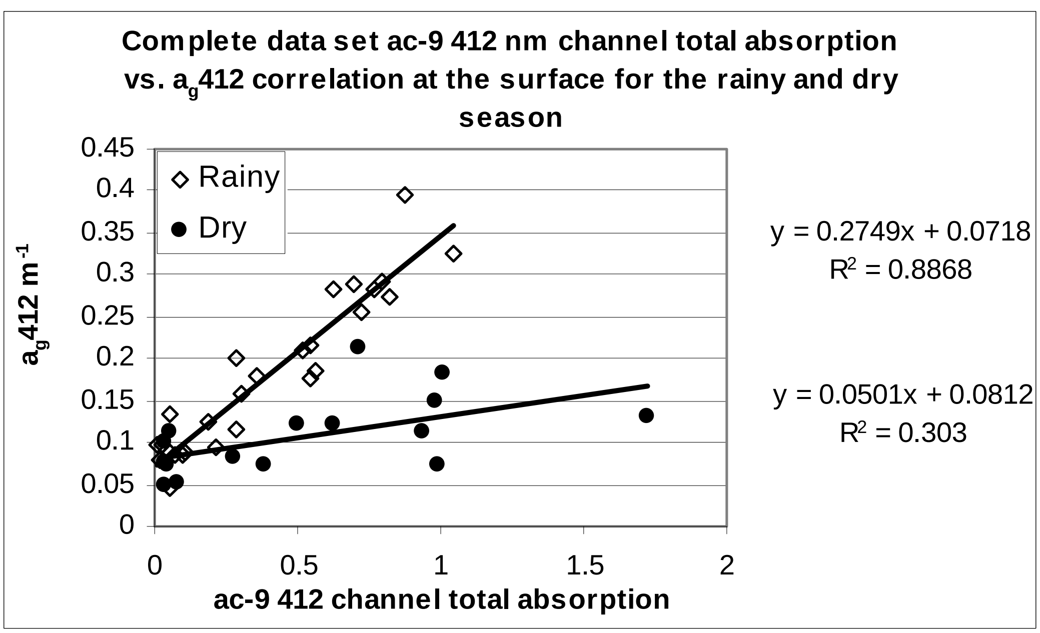


Figure: 5 AC-9 412 absorption channel vs. a_g 412 correlation for both seasons



Discussion

For precipitation and River flow data it was found a marked seasonality are observed for both cases. Since our cruises could no be performed on a regular basis this was one of the criteria to divided the cruises between the rainy and dry season. Seasonality has also been observed by a number of other works in the bay (Alfaro, 2002, Parilla, 1996, Rosado, 2000, Gilbes, 1992; Gilbes et al., 1996). I is observed that a marked seasonality is observed between season during the rainy season salinity are markedly lower due to local river flow with the consequence of higher TSS and a_g375. increasing from an inshore offshore gradient. During the dry season the salinities are higher but in the case of TSS the average values no significantly different from those of the rainy season mining that other processes such as resuspention during the winter months causes that bottom sediment are distributed in the water column. During this period is when the river flows and lower so that the TSS must come from the shallow bay area that are influence by strong currents and wave action. This fact could also explain that CDOM Spectral slope or not significantly different between seasons. And that CDOM material might come from bottom sediments due to this event characteristic of the winter season.

Our analysis indicates that the total absorption 412 channel of the ac-9 channel is well correlated with the calculated with the R_{rs} band ratio at (R_{rs}412/R_{rs}510), in a similar manner the a_g412 is also well correlated with the same bands ratios(Figure 7 and 8). In a similar manner a_g412 and the total absorption values for the ac-9 are also well correlated only during the rainy season only (Figure: 9). During the dry season other processes no related to the local rivers might be involved since the lack of correlation between a_g412 and ac-total absorption (Figure 10).

The laboratory experiment indicate that dilution between end members from marine waters and Añasco River can cause a reduction a_g375 absorption coefficient suggesting that some process like flocculation might be the responsible (Figure: 6). This reduction in CDOM signal was more evident in the lower ranges of salinity. This indicates that during the initial mixing at the lower salinity same of this CDOM material can be lost due to flocculation. In a similar experiment (Sholkowitz, 1976) recorded that during estuarine mixing between dissolved organic and inorganic mater flocculation of organic resulted. But in other experiment no flocculation effects were recorded by (Preston and Riley 1982) using a similar approach. In our experiment only dilution had a reducing effect of the CDOM signal at 375 nm indicating the flocculation of this material that was removed from the solution after filtration process.

CDOM is mainly compose of humic and fulvic acids (Kirk, 1994) and in the coastal environment terrestrial derived CDOM dominates in the aquatic environment. Humic and fulvic acids are known to react with clay material in the soils (Ghabbour et al., 2004; Krestschmar et al., 1997. Tachitzky et al., 1993). The humic acids-clay interactions are influence by a verity of factor like the nature of the clay (kaolinite, illite, montmorillonite etc.) ionic strength, pH, and cations associated to the surfaces of the clays and temperature. In a similar manner the humic acids are affected by ionic strength and pH this can cause changes in the molecule conformation, charge and solubility increasing or decreasing its affinity to the clay material. X-Ray Diffraction performed to the collected water solids from the Anasco River reveled that (kaolinite, illite, montmorillonite) are being transported in the river waters. And that the clays found in the bottom sediments of the Mayaguez Bay (Ramirez, personal communication) are composed of the same clay material.

In a second experiment with another set of dilution but this time to the river waters we added solid material extracted from the same river, a reduction in (a_g375) was again observed and also was noticed in the lower salinity range (Figure: 6). So it is possible that flocculation decreases the CDOM signal during mixing and increases in the presence of solid material transported in river waters.

Conclusion

Remote sensing reflectance can be used as an effective tool to monitor the dynamics of CDOM in the Mayaguez Bay area. Marked differences were observed between the rainy and dry season for most of the measured parameters. The laboratory experiments give a new insight to the geochemistry of the clay-CDOM interactions derived from the terrestrial environment when they enter in contact with marine water. This result is promising since this result has never been address for the Mayaguez Bay. Other biological and bio-optical implication could be explained.

References

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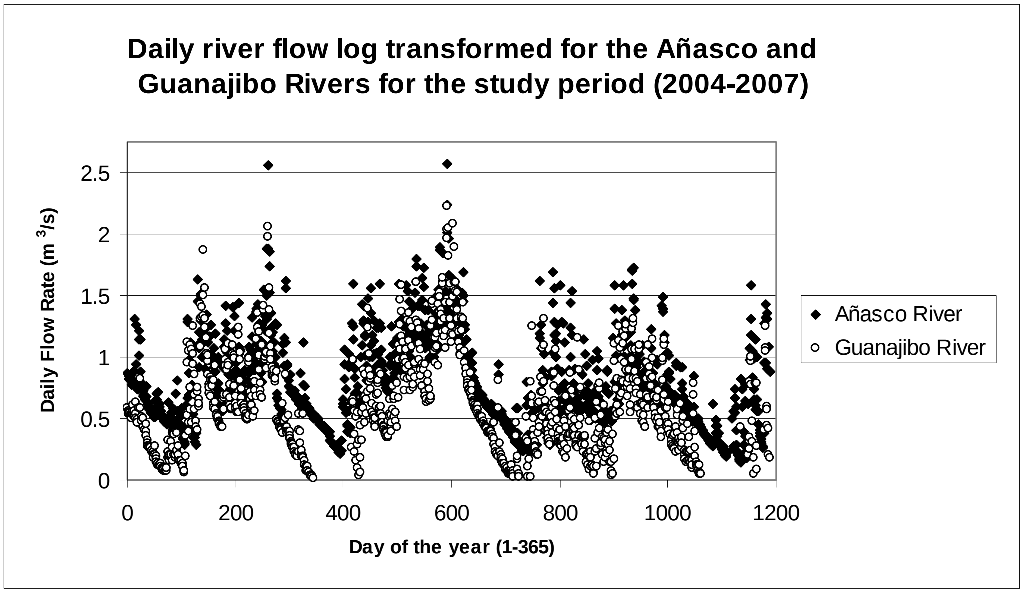
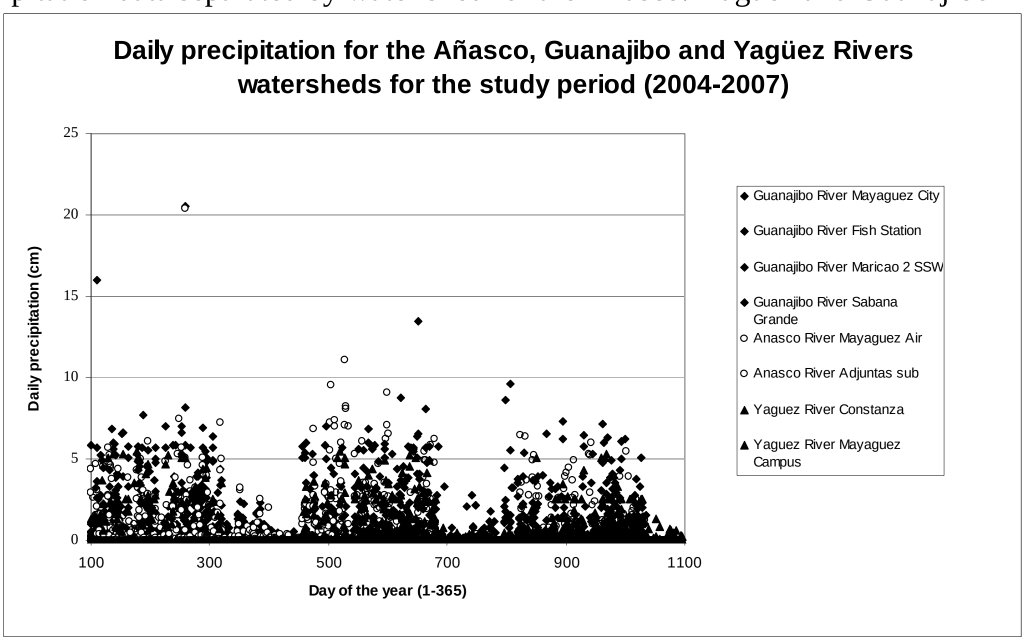
Appendix

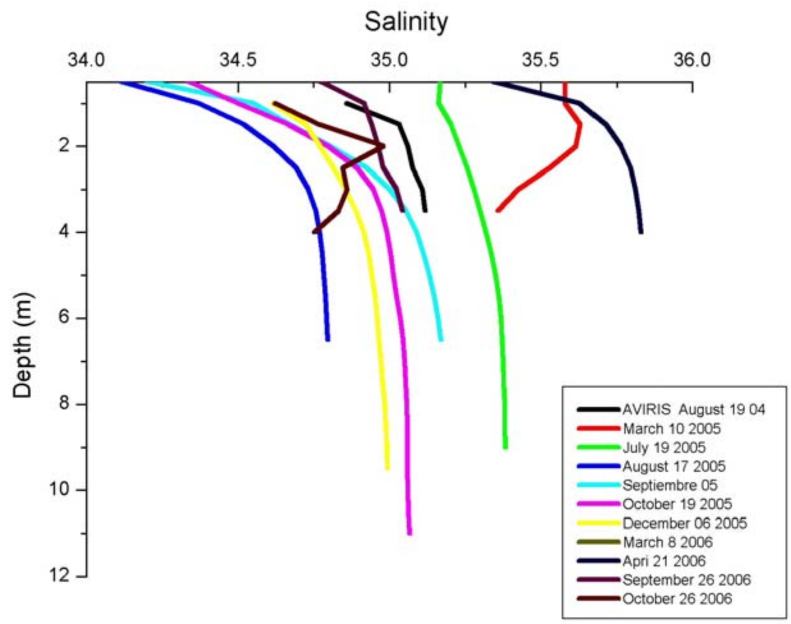
River flow for the Añasco and Guanajibo no monitoring station is located in the Yagüez River



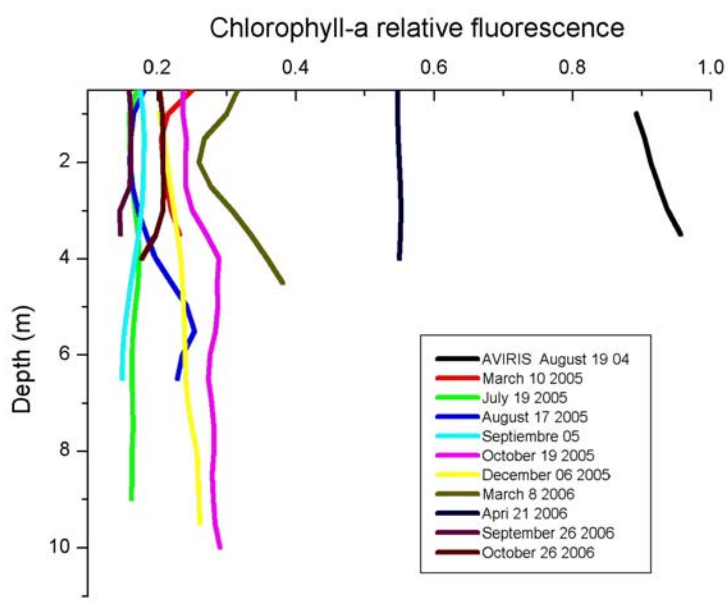
Precipitation data separated by water shed for the Añasco. Yagüez and Guanajibo Rivers



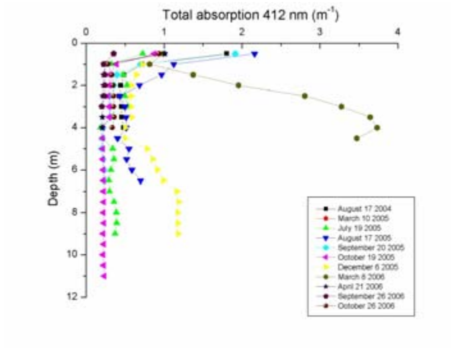
Salinity Profiles for the A1 stations



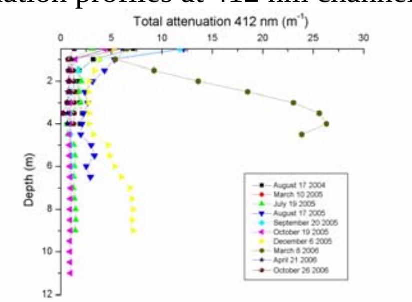
Chlorophyll-a profiles for the A1 station



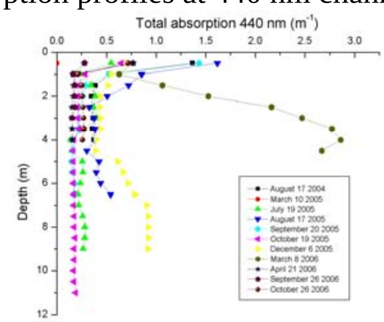
Total absorption profiles at 412 nm channel for the A1



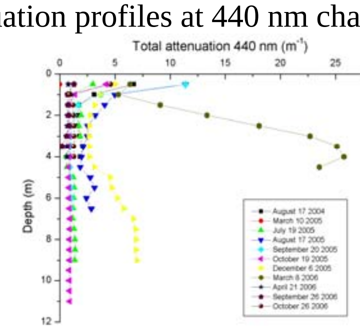
Total attenuation profiles at 412 nm channel for the A1



Total absorption profiles at 440 nm channel for the A1



Total attenuation profiles at 440 nm channel for the A1



DEVELOPING A METHOD TO MONITOR SEDIMENTATION PROCESSES IN MAYAGÜEZ BAY USING MODIS DATA

Vilmaliz Rodríguez-Guzmán & Fernando Gilbes-Santaella

ABSTRACT

This project aims to develop a method to monitor sedimentation processes in a coastal environment by using remote sensing technology. The main objectives of this study were to generate, validate and apply an algorithm to estimate suspended sediment concentration (SS) based on remote sensing reflectance (R_{rs}) and MODIS data. It was expected to establish the relationship between *in situ* measurements of SS and Rrs, to then apply the generated equation to MODIS band 1 and band 2 data (620-670 nm and 841-876 nm, respectively). Considering that R_{rs} values are significantly lower than MODIS data, a second relationship was establish associating band 1 and band 2 of Rrs and MODIS data. The algorithm produced was validated by applying both resultant equations to three MODIS images from which *in situ* data was available. In general, the estimations of the algorithm tended to sub-estimated field measurement values, however, abundance and spatial variations of these estimations responded as expected. An application component was included in this study, which consisted on estimate total river discharge by applying the algorithm produced to an image associated to a significant rain event. This allowed to calculated total mass for a determined area based on SS concentration. This study provided a base to the desire method but various refinements still need to be applied in the approach for more reliable results.

Introduction

The Mayagüez Bay is located at the west coast of Puerto Rico, delimited by Mayagüez and Añasco cities. Many biological, chemical and geomorphologic processes are affected by the distribution and abundance of suspended sediments in this bay. Suspended Sediments (SS) consist of material composed of clasts derived from pre-existing rocks that can be transport in suspension. The concentration of SS is considered one of the most important water quality parameters (Wang et al., 2005) and can produce non-point source pollution. In coastal environment the presence of SS reduces the amount of light available through the water column, producing habitat detrimentation.

Spatial and temporal variations in SS concentration can be the effect of anthropogenic or natural factors. Various studies have been developed to better understand and define the processes affecting these variations (Grove, 1977; Miller et al. 1994; Gilbes et al. 1996). It has been determined that the presence of SS in the bay is highly influence by resuspension events (Morelock, 1983; Miller et al. 1994), additionally to the rivers discharging in the area (Grande Añasco River, Yagüez River and Guanajibo River). A study of the sedimentation processes in the coastal environment will define aspects associated to the production, transport or deposition of sediments. However, all the field work necessary to monitor these processes could require plenty of money, effort and time, factors that limit the development of this type of studies. This limitation is reduced by incorporating components based on remote sensing, where desire information can be obtained from spectral data. Before using remote sensing data for a specific application, a relationship between the parameters of interest (e.g. SS) and spectral data must be defined. This study expects to establish the relationship between *in situ* measurements of SS concentration and Remote Sensing reflectance (R_{rs}) with MODIS bands 1 and 2 data.

The present study is focused on develop a method to monitor the distribution and abundance of SS associated to river discharge using MODIS data. To accomplish this, three main objectives were defined: (1) Develop a site-specific algorithm to estimate SS concentration based on MODIS data, (2) Validate the generated algorithm using *in situ* SS measurements (3) Estimate total river discharge for a significant rain event by applying the generated algorithm to day after a storm event occurred.

Methodology

Two of the parameters used for the development of the algorithm were measured during various research cruises in the study area. In each visit around six to eight stations are monitored for SS concentration and Remote Sensing reflectance (R_{rs}) with a spectoradiometer (GER 1500). The SS data to be used in this study corresponded to all the material larger than 0.7 μm collected at approximately 1 meter depth. With the GER 1500 we obtained spectral information of the water surface from about 370nm to 1,000 nm. Considering that the measurements of this instrument were going to be correlated to MODIS band 1 and 2 data, mean values were calculated between the ranges of 620-670nm and 841-876nm corresponding to band 1 and 2, respectively.

MODIS Data

Images corresponding to the dates of the research cruises were downloaded through a NASA Internet server called Landweb. The product selected was MOD02QKM, which includes reflectance and radiance information of MODIS first two bands.

Three pre-processing routines were applied to the images before they were used for analysis: georeferentiation, spatial subset and atmospheric correction. The image processing software used was ENVI v. 3.4, which provided the tools necessary for this pre-processing part and for the analysis. All the images were georeferenced as UTM NAD83 for Puerto Rico region. This georefentiation was validated by taking, with a GPS unit, 17 points along the shoreline of Mayagüez Bay and then overlaying these points on a georeferenced image (band 2) to then see how effectively they represented what it was observed in the image (Fig. 1). After the georefentiation, an atmospheric correction was applied. For this process it was used the pre-defined routine called “Dark Substract” with the “User Value” option. In this case the band 2 was used to select the darkest pixel and defined that as the “User Value”.

Algorithm Development

The final product of this algorithm will be able to estimate SS concentration in Mayagüez Bay based on MODIS data (MOD02QKM). Three data sets were used for the development of the algorithm, (1) the data obtained with the GER 1500, (2) the SS measured and (3) MODIS reflectance values of the pre-processed images. Firstly, the relationship between the R_{rs} and the SS concentration was established and defined by an equation. Then, as an intermediate part of the algorithm, it was necessary to also establish the relationship between R_{rs} and MODIS reflectance. The MODIS reflectance values used were obtained from three of the most cloud and errors free images; the values were extracted from the pixels corresponded to stations monitored for R_{rs}. Defining the relationship between these parameters helped to convert MODIS reflectance to R_{rs} equivalent values, step necessary to be able to apply the equation that estimates SS concentration from R_{rs}.

ALGORITHM VALIDATION

Previously developed equations were applied to six images corresponding to dates of research cruises. The equations were defined in ENVI as follows:

$$0.4033 * \text{float (B1)} - 0.006 \tag{1}$$

where, B1=MODIS band 1

$$452.41 * \text{float (B1)} + 2.9603 \tag{2}$$

where, B1=MODIS band 1

Finally, the product of these equations was compared with the *in situ* measurements to determine the error of the estimations.

SIGNIFICANT RAIN EVENTS

The developed algorithm was applied to an image representative of the day after a significant rain event occurred. The days with significant rain were identified using daily river discharge data of two gauges stations located within the Mayagüez Bay watershed (Fig. 2). For the Añasco river the station used was the 50144000 and for the Guanajibo river the 50138000. The Yagüez River does not have any active gauge station therefore it could not be included in this analysis. For each station it was considered the historic data, and it was determined the daily mean discharge and the standard deviation for each river. Then, two hydrographs were plotted using mean daily discharge of 2005 and the historic mean discharge and the standard deviations were included as lines. The percent of standard deviation was defined with "trial and error", until the line reached the base flow. Using this method it was possible to identified significant rain events, mean flows and base flows within 2005.

Various images corresponding to days after a significant rain event occurred were examined for clouds and instrument errors. The image selected was from October 26, 2005 and it was pre-processed using the same methods described before and equations (1) and (2) were applied. For this analysis it was necessary to apply a third equation to convert SS concentration to total mass, assuming a volume of water of 31,250 m^3 per pixel (length=250m; width=250m; depth=0.5m).

$$31.25 * \text{float (B1)} \tag{3}$$

where, B1= equation (2) product

The application of this equation generates a product of SS mass (kg) for all the volume of water within each pixel until 0.5m depth, assuming and homogenous concentration in all the area. A polygon was defined delimiting the Mayagüez Bay and all the values within that area were summed.

Results and Discussion

ALGORITHM DEVELOPMENT

A significant relationship (R^2=0.72; n=38) was defined between SS (mg/l) and R_{rs} of both spectral bands (620-670nm and 841-876nm) (Fig. 3). Observing this correlation, it is evident the limited amount of measurements corresponding to conditions of high concentrations; most of these measurements are less than 15 mg/l. In this case, it is difficult to know how representative is the linear equation defined to the actual relation between these two parameters. Additionally, this fact indicates that the general concentration of SS in the bay is relatively low and, therefore it limits the development of this type of studies because it is more difficult to detect the signal of interest.

Considering that both bands showed a good relationship with the measurements of SS, a single relationship was established using both bands in order to improve the algorithm. The result of this approach is illustrated in Fig. 4, where it can be observed that the estimated values are very close to the observations and the R^2 increased to 0.78.

In general, it was observed that MODIS reflectance values were considerable higher than the R_{rs}, therefore it was not possible to directly apply the previously defined equation to MODIS data. The relationship between R_{rs} and MODIS data was defined finding a significant relationship (R^2=0.92; n=10) with band 1 and a poor relationship with band 2 (R^2=0.13; n=7) (Fig. 5). This result indicates that the band 2 should not be integrated in the algorithm because the signal in this region is highly affected by the atmosphere.

ALGORITHM VALIDATION

For validation purposes, equations (1) and (2) were applied to six images corresponding to cruises dates that were not included in the previous analysis (Fig. 6). These products showed an expected spatial variability of SS, where river discharge dominates the Añasco River area during the rainy season, and re-suspension events dominates during the dry season near the Guanajibo River. In various products can be observed what it seems to be the effect of the bottom (Fig. 6d), but a more specific analysis including the bathymetry of the area have to be develop.

The comparison of the estimated values (extracted from the products generated) with *in situ* measurements showed that even though the estimations are within the expected range, they tended to sub-estimate the observations (Fig. 7). This plot showed that the relative changes are similar in both lines indicating that the signal detected by MODIS sensor in band 1 is highly affected by SS concentration. The limitations of this algorithm can be attributed to various factors: (1) the lack of data representative of high SS concentrations, (2) the sensor is not capable of detecting the SS signal in under low concentrations conditions and (3) the effect of the bottom and/or atmosphere in the signal.

ALGORITHM APPLICABILITY

This section shows the results of the application component of this study, which it attempted to estimate SS river discharge of a significant rainy event. For 2005 a total of 83 days were identified with significant rainy events; this represents a 23 percent of the total of days in one year. Based on previous knowledge, this percent is reasonable. The selected image for this analysis was from October 26, 2005, and the flow discharge associated to this event was 718 cf/s in Grande de Añasco River (USGS). After applying the algorithm developed, the product showed that the higher concentration of SS is associated to the discharge of this river, while a big plume is observed near the Guanajibo River (Fig. 8). Total SS discharge associated to this event was estimated as 392 metric Tons. The main purpose of this part of the study was to develop a method using ENVI to calculate SS discharge from the algorithm product. In future work, the values obtained will be discussed based published information by the USGS.

Conclusions

The development of an algorithm capable of estimate SS concentration in Mayagüez Bay is a very useful mechanism that will reduce the field work and will allow the development of studies covering larger areas. Remote Sensing techniques provide tools and advantages that helped in the development of a base method to monitor SS spatial and temporal variations in Mayagüez Bay. This study described a method that combines parameters of different origin (SS, R_{rs} and MODIS reflectance) to generate a product of SS.

It was determined that the geometric and radiometric corrections that are included during the pre-process are crucial for this type of analysis. The atmospheric correction must be a cautious process given that a poor correction has a negative impact in the final results. It was determine that the pre-defined routine in ENVI to georeference MODIS images is reliable.

Although the initial approach in the development of the algorithm, included both MODIS bands 1 and 2, the results indicated that band 2 should not be included in this type of studies, especially if conditions are dominated by low SS concentrations. No relationship could be determined between MODIS band 2 and R_{rs} (mean 841-876). The algorithm estimations were able to detect spatial variations associated to SS distribution, but the estimated values tended to sub-estimated the *in situ* measurements. The estimation are within an acceptable range considering the lack of data corresponding to high concentrations, the weak signal present in this area, and other factors such as bottom and atmospheric effects. The results of this study support the development of a Remote Sensing based method to monitor important sedimentation processes, further analysis will be incorporated for full application of the method.

Aknoledgements

This study was developed in collaboration with Francisco Torres-Vega. Special thanks to Patrick Reyes and José Martinez for helping in getting and processing part the data. Finally, thanks to all the people that collaborate in the field and laboratory work.

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Apendix

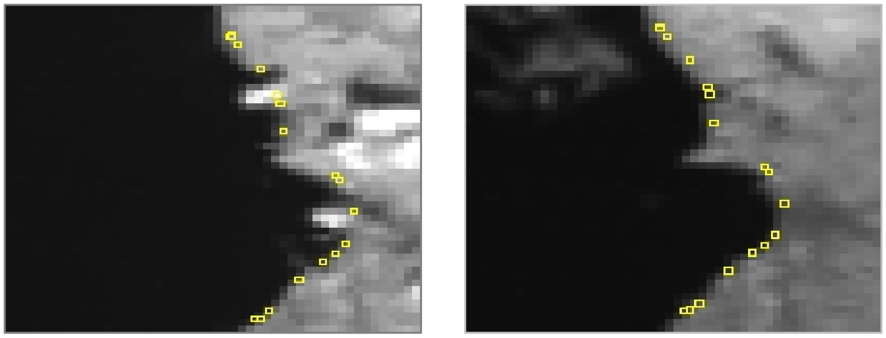


Figure 1. Georeferentiation validation; October 19, 2005 (left) y December 6, 2005 (right).

Figure 2. Study area hydrography with USGS stations

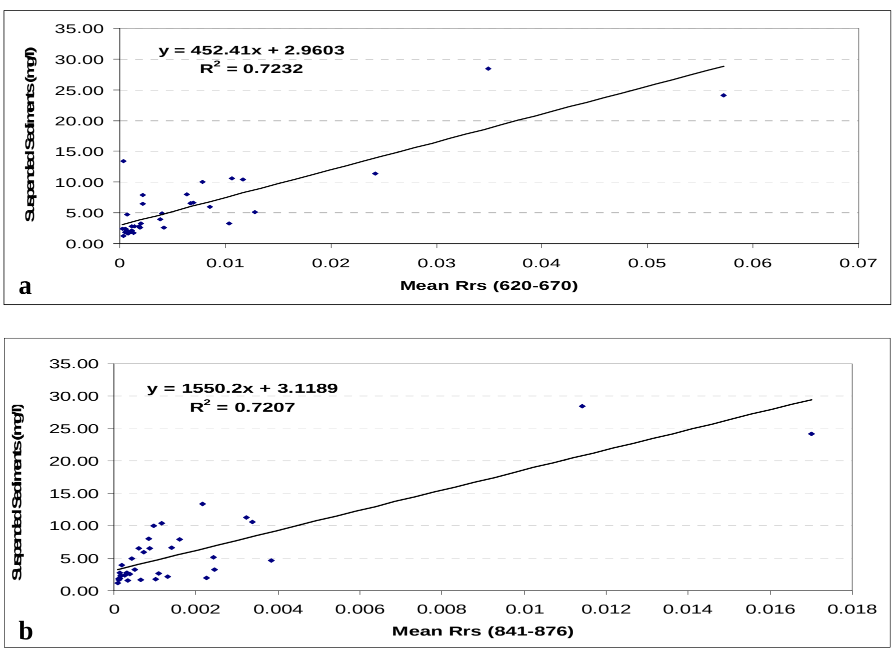


Figure 3: Relationship between SS conc and R_{rs} based on MODIS (a)band 1 and (b)band 2

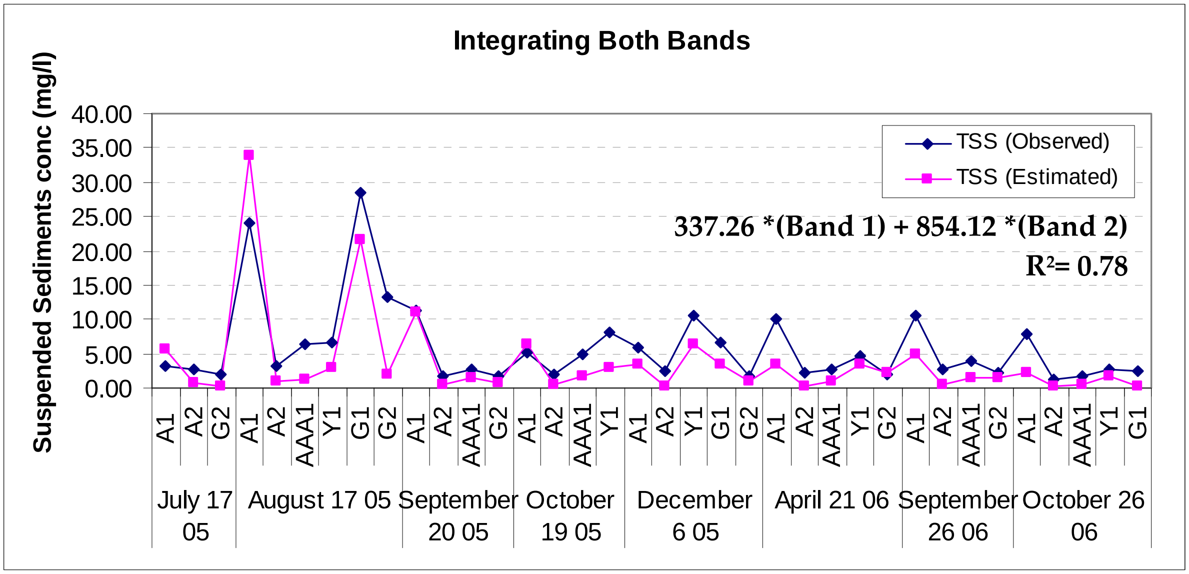


Figure 4. Results of integrating both bands (1 and 2) in the same equation (Spectoradiometer data)

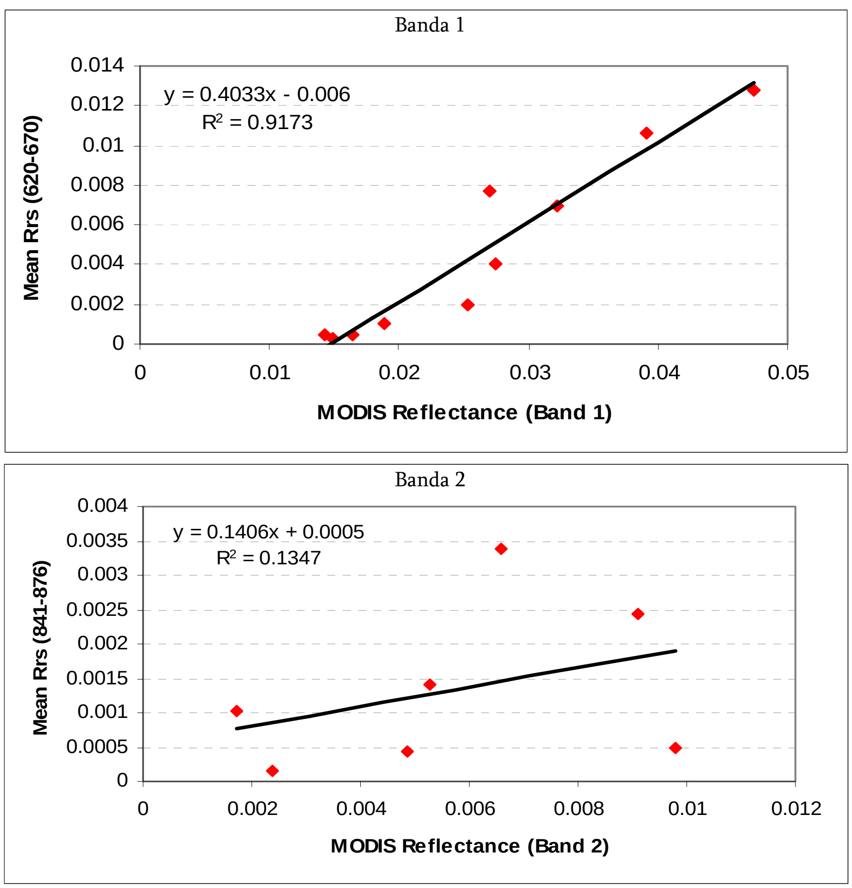
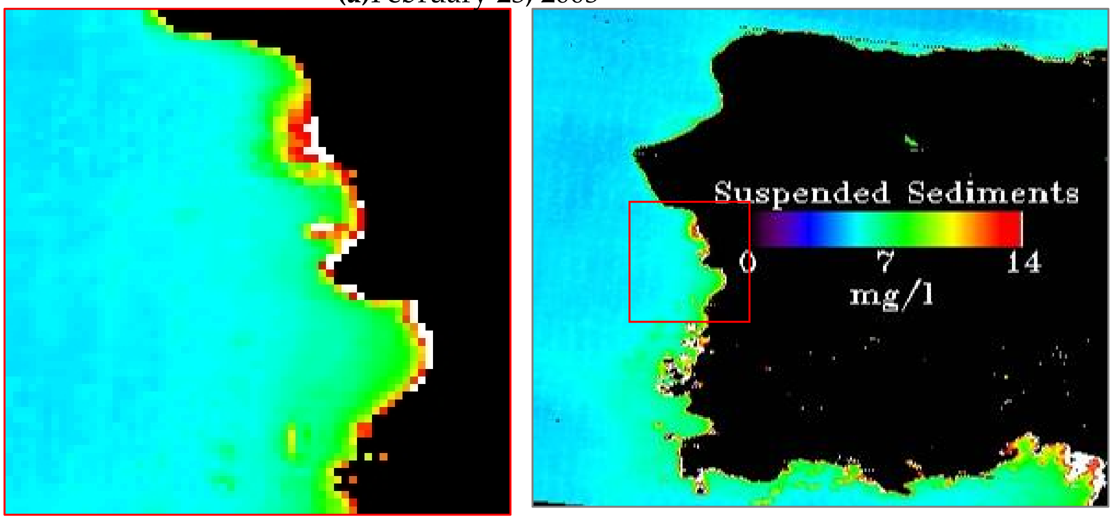
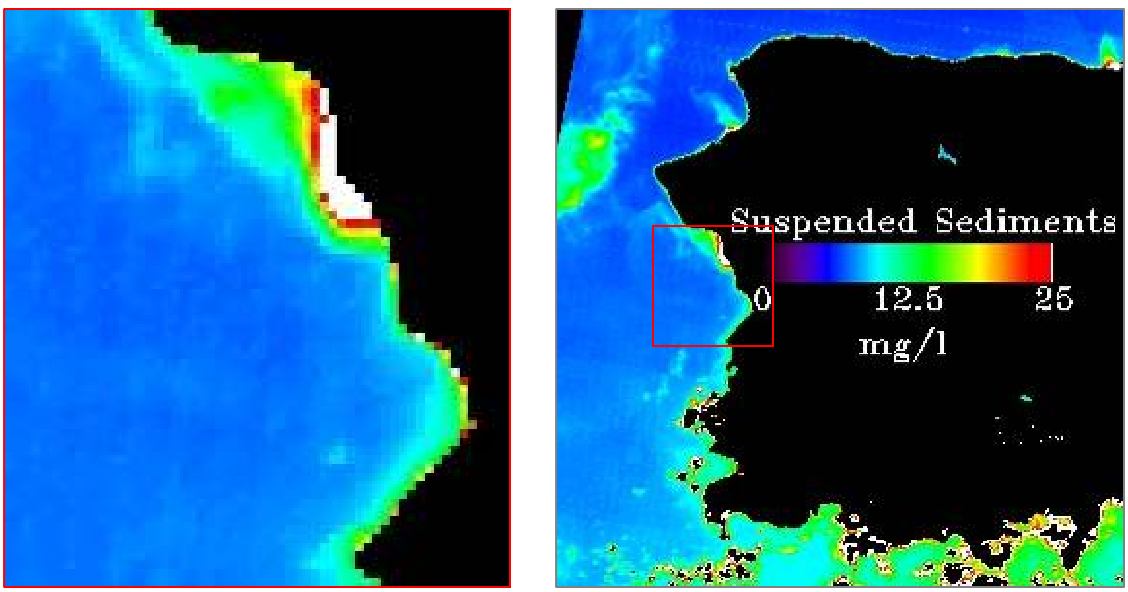


Figure 5. Relationship between R_{rs} and MODIS reflectance

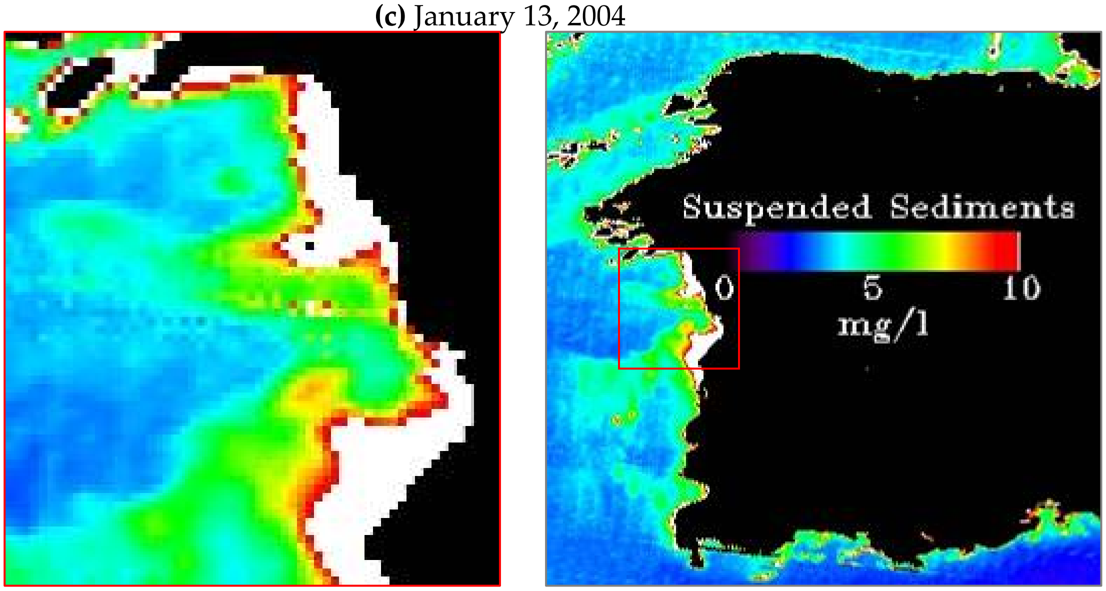
(a) February 23, 2003



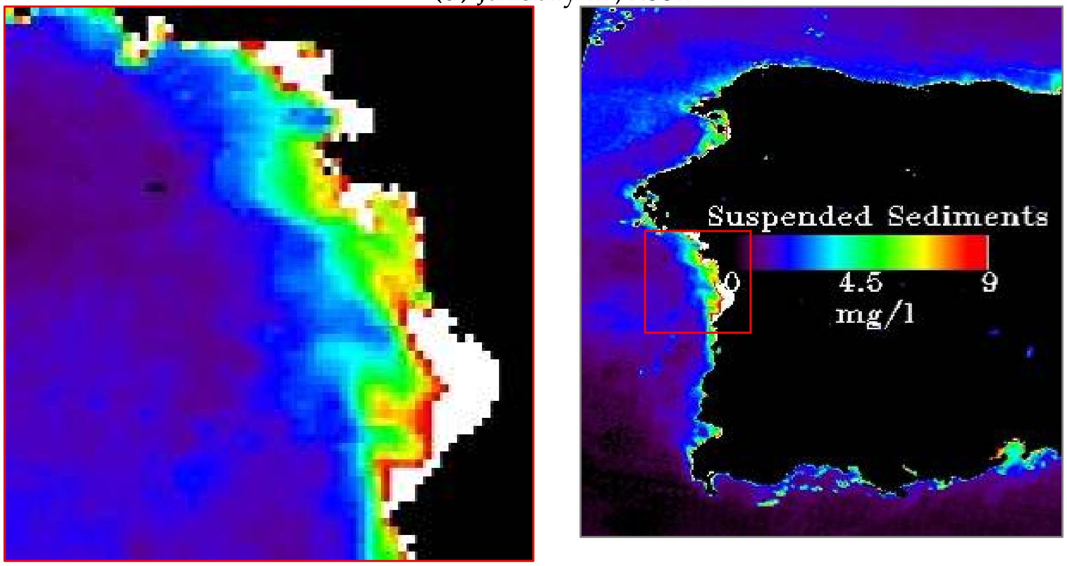
(b) October 7, 2003



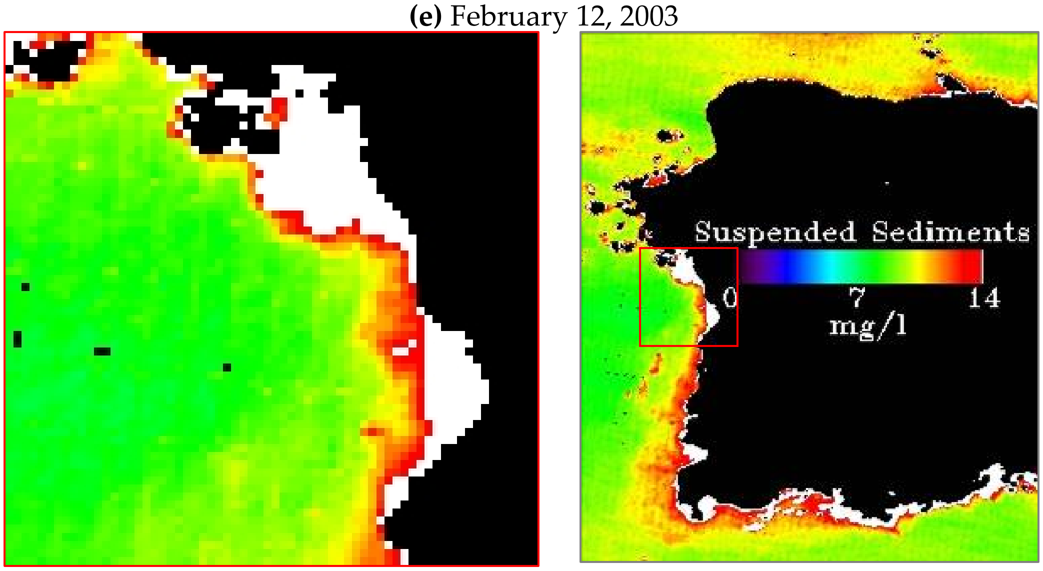
(c) January 13, 2004



(d) January 14, 2004



(e) February 12, 2003



(f) March 8, 2006

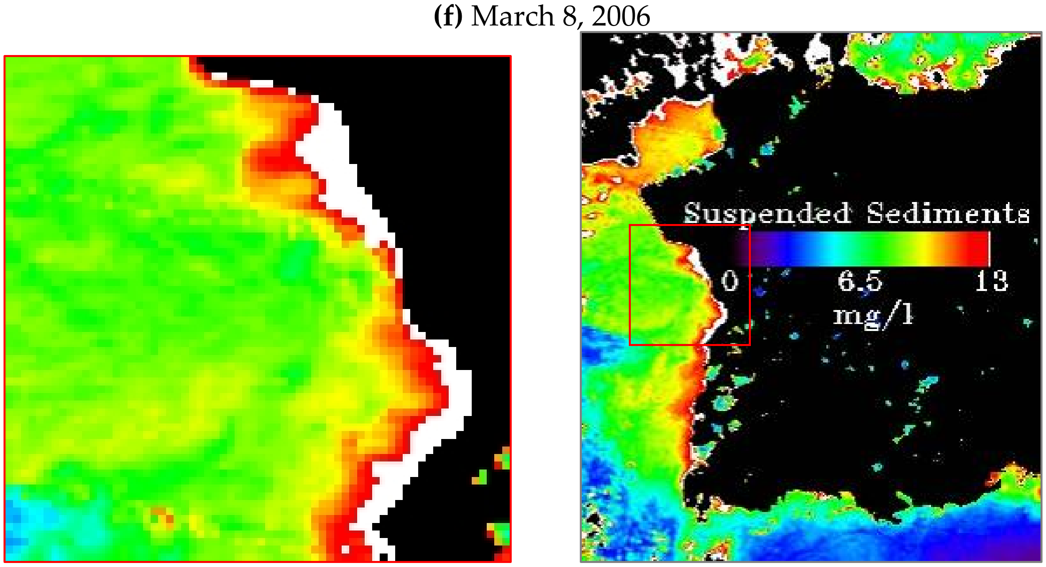


Figure 6. SS concentration estimations

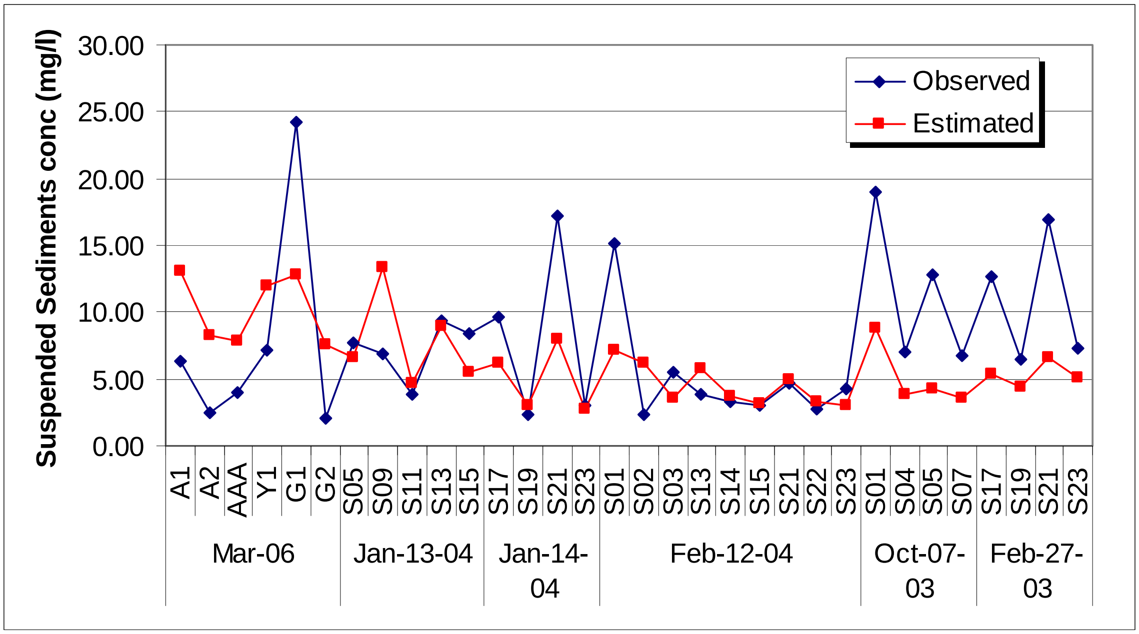


Figure 7. Comparison of algorithm estimated values and in situ measurements

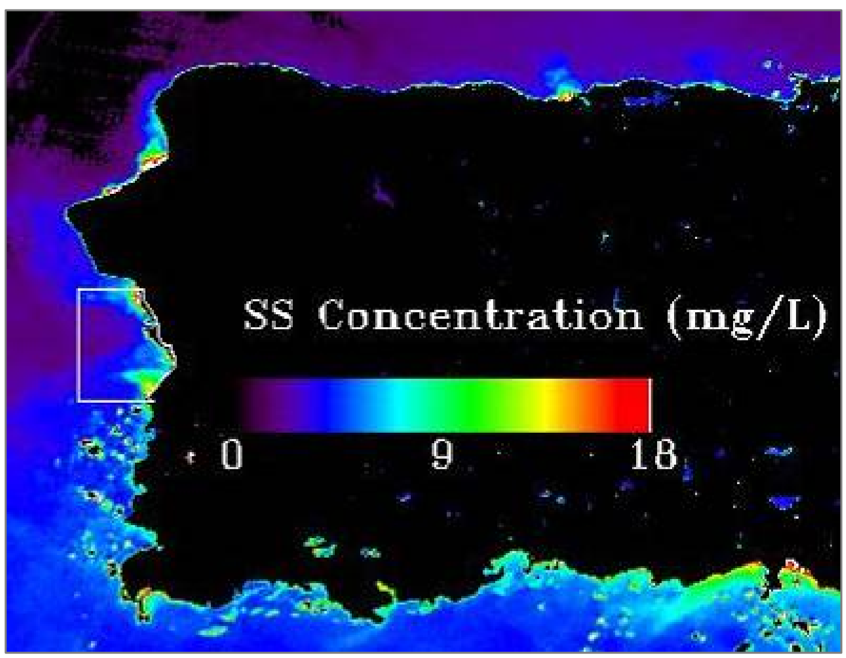


Figure 8. SS conc associated to a significant rain event

Data corrections of the AC 9 field spectrophotometer in Mayagüez Bay
Ramon Lopez

The in-situ spectrophotometer AC9 determines the spectral transmittance and spectral absorption of water over nine wavelengths and it has provided versatility to the study of ocean optics by taken traditional laboratory measurements such as absorption and attenuation measurements to in situ. Therefore this instrument has become an invaluable tool in the assessment of the inherent optical properties of marine environments. However when optical analysis are taken to the filed environment environmental factors have to be taken in consideration. For instance instrument drift has to be addressed by a field water calibration. The field water calibration directly before or after an in-water measurement will thus serve as the effective blank.

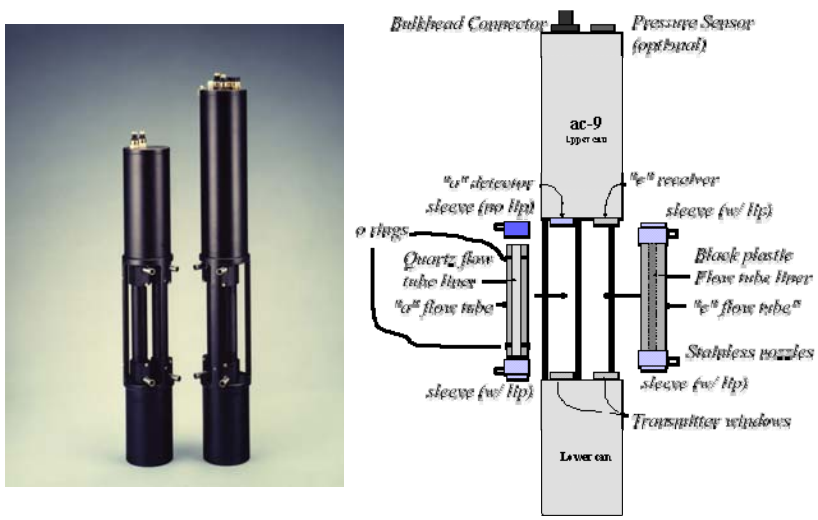


Figure 1 Left :AC-9 Spectrophotometer. Diagram on the right shows sampling chambers, a quartz reflective for absorption measurements and black plastic inner tube for attenuation measurements.

Another factor to take in consideration is the temperature and the dependence of absorption and attenuation on it. When calibrated the instrument response is analyzed by exposing the instrument to various samples of reference pure water of varying temperatures. Thus when used in the field the instruments is not only at a constant temperature the medium is sampling is of varying temperature and salinity, requiring post processing of the sampled data to correct for the deviations caused by these changeable environmental conditions. Pegau et al., 1997 developed a model to address the dependence of temperature and salinity in the absorption and attenuation of the light at the visible and infrared portion of the spectra. Such model is been used widely by the ocean optics community to adjust field measured data by AC-9 spectrophotometers. In this model the goela was to determine if there was a linear temperature slope (**(phi TSW** and salinity slope (**phiSC)** so that the absorption and attenuation coefficients of water can be given :

c_corr(L) =c(L) - (phi TSW(L) * (T_meas - T_cal) + phiSC(L) * (Sal_meas);

a_corr(L) =a(L) - (phi TSW(L) * (T_meas - T_cal) + phiSA(L) * (Sal_meas);

Where c(L) and a(L) are the measured attenuation and absorption and T_meas and T_cal are the measured and calibration temperatures and Sal_meas is the measured salinity.

Scattering correction is another adjustment typically apply to AC-9 data to compensate for the over estimation of the absorption coefficient due to scattering losses. Once temperature and salinity corrections are applied a none zero absorption signal is observed at 715 nm, due to the fact that particulate and dissolved materials exhibit negligible absorption in this region this signal is attributed to scattering loses out of the reflecting tube (Roesler, 1998). In conventional approaches with bench spectrophotometers the signal in the region of 715 is deduct from the rest of the spectra, subtracting equal portions to the spectra, hence it is named flat correction. Scattering coefficients are not spectrally flat and subtraction of the 715 nm from the entire measured absorption spectrum will not accurately correct the absorption coefficient. To remove the effect of scattering a spectral correction is calculated as a fraction of the spectral scattering coefficient. Characteristically the scattering coefficient is underestimated $b(\lambda) = c_{TS}(\lambda) - a_{TS}(\lambda)$, when part of the scattered signal is attributed to absorption in the reflecting tube. This error is removed by accounting the spectral variations in the scattering coefficient. The spectrally corrected absorption coefficient is then obtained by

$$a(\lambda) = a_{TS}(\lambda) - b(\lambda) +* \frac{a_{TS}(715)}{b(715)}$$

where $a_{TS}(\lambda)$ is the measured absorption coefficient with the salinity and temperature corrections applied, $a_{TS}(715)$ the absorption at 715, $b(\lambda)$ the scattering coefficient and $b(715)$ the scattering at 715 nm.

The Remote Sensing of Coastal Waters group over the years of the project has acquired a data set of inherent optical properties of the Mayaguez Bay. This data set includes a AC-9 spectrophotometer data that has been acquired over diverse environmental conditions due to the nature of the dynamics of the Mayaguez bay. This bay is subject to the influence of various river discharges therefore is characterized by different temperature and salinities regimes. For that reason this data set is been subject to the previously discussed corrections. For the water blank correction the factory temperature specific corrections is been applied according to the temperature of the instrument recorded temperature during each cast.

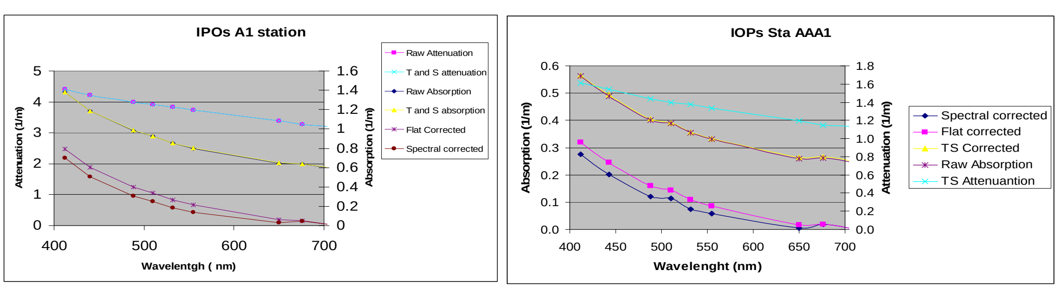


Figure 2. Data sample of the Añasco station 1 during October 2005 and Triple A station during September 2005 subjected to temperature-salinity corrections, and scattering corrections to absorption (flat and spectral corrected).

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MODIS Validation for Water Quality Parameters in Mayaguez Bay

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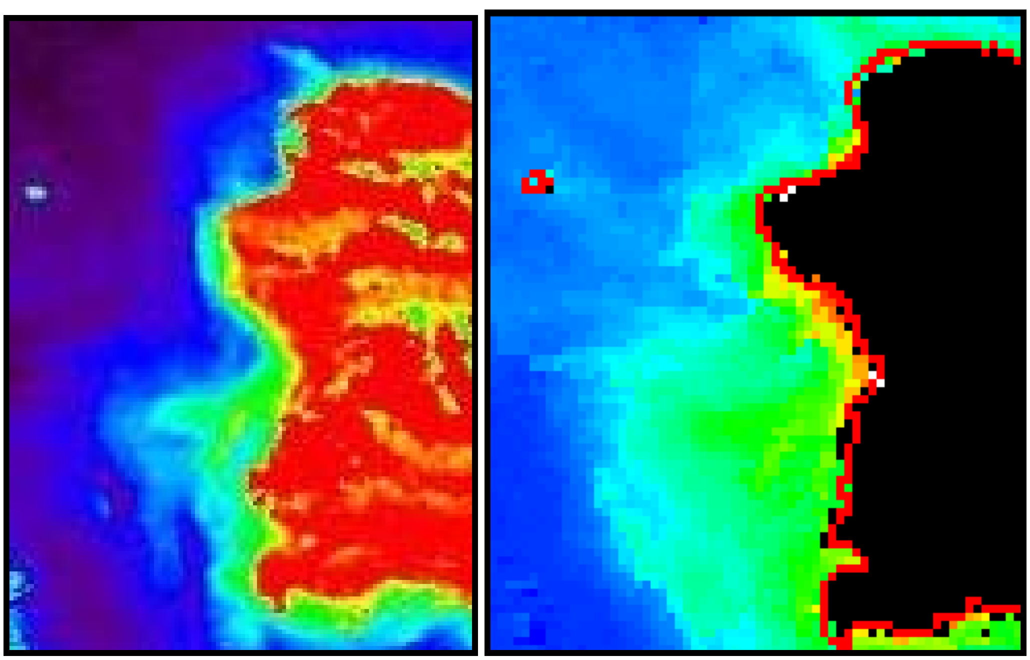
The Moderate Resolution Imaging Spectroradiometer (MODIS) is considered an improved generation of ocean color sensors. However, its validation for coastal monitoring is still underway. The main objective of this research was to validate the accuracy of MODIS to measure phytoplankton Chlorophyll-a (Chl-a) and suspended sediments (SS) in Mayagüez Bay, Puerto Rico. Field measurements of Chl-a and SS were compared with those estimated from MODIS data. A low correlation was found between field and MODIS Chl-a values obtained with both, Terra (R^2=0.0283) and Aqua (R^2=0.0265), satellites and using the standard NASA OC3 algorithm. Since the standard Chl-a product provided by NASA routines was not good for our study area, it was decided to derive and test a local empirical algorithm using MODIS Bands 3 (469 nm) and 4 (555 nm), which provide 500 meter of spatial resolution. The regressed linear equation for B3/B4 ratio and field Chl-a was $y = -0.6614x + 1.4937$ and the $R^2 = 0.3886$; while the logarithmic equation was $y = -0.4939\mathrm{Ln}(x) + 0.7243$ and the $R^2 = 0.3688$. In order to estimate SS with MODIS, Band 1 (645 nm) with 250 meter of spatial resolution was used to validate the algorithm developed by Miller and McKee (2004) in the Gulf of Mexico. However, the suggested equation failed in Mayagüez Bay. A second approach intended to develop a site-specific algorithm for SS using this same band, but low correlation was also found on various testing scenarios. They were $R^2 = 0.1443$ (overall), $R^2 = 0.0695$ (dry season), $R^2 = 0.2788$ (rainy season), $R^2 = 0.0473$ (inshore stations), and $R^2 = 0.0468$ (offshore stations). Image processing and analyses clearly demonstrated that MODIS is not the most appropriate ocean color sensor for Mayagüez Bay. Another sensor with better temporal, spatial, and spectral resolutions is still needed for the estimation of Chl-a and SS in coastal waters.



Left: Image generated with new algorithm for Chl-a
Right: Image generated with NASA OC-3 algorithm for Chl-a