Chapter 16

Algorithms for Processing and Analysis of Ocean Color Satellite Data for Coastal Case 2 Waters

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16.1 INTRODUCTION

SeaWiFS has the ability to enhance our understanding of many oceanographic processes. However, its utility in the coastal zone has been limited by valid bio-optical algorithms and by the determination of accurate water reflectances, particularly in the blue bands (412-490 nm), which have a significant impact on the effectiveness of all bio-optical algorithms. We have made advances in three areas: algorithm development (Table 16.1), field data collection, and data applications.

Table 16.1: Issues and advances to atmospheric correction.

Issues	Advances
1. The previous atmospheric correction poorly estimates water leaving radiance in the near infrared (NIR) when detritus and chlorophyll don't co-vary.	1. We offer an NIR correction, which draws on coupling the atmospheric and oceanic models (Stumpf et al., 2003), to better estimate water reflectance. NASA has implemented this correction to process of SeaWIFS data in July 2002.
2. The current atmospheric correction neglects the effects of absorbing aerosols associated such as pollution.	2. We offer a technique to estimate and remove the unresolved absorbing aerosol component in water reflectance (Ransibrahmanakul and Stumpf, 2003).

Data Collection

We have collected data sets of bio-optical properties in turbid Case 2 waters, which are relatively few in SeaBASS database. We have collected over 300 stations of AC9, remote sensing reflectance spectra, and HPLC (Table 16.2).

These data sets will provide the basis for improving and evaluating *in situ* bio-optical and atmospheric correction algorithms for coastal waters. The coastal waters with a high sediment load and/or high concentrations of colored dissolved organic matter (CDOM), standard processing algorithms typically fail (negative or erroneous retrievals of water-leaving radiance) due to invalid assumptions related to the atmospheric correction. Our efforts have focused on describing the reflectance properties at near-infrared (NIR) and blue wavelengths in coastal waters, and utilization these properties to improve the atmospheric correction. We have modified and developed new coastal bio-optical algorithms, as well as validated the algorithms and atmospheric corrections.

We are also preparing for MODIS. We have implemented MODCOLOR and MODSST into the NRL processing software. This has included modifying the MODIS processing software in cooperation with NASA and University of Miami to use the same NIR atmospheric correction SEADAS is using.

Table 16.2: Number of stations of various data collected.

AC9/CTD	ASD/remote sensing reflectance	HPLC
352	404	413

Data Applications

In addition to algorithm development, we also utilize the new products to monitor and predict harmful algal blooms along the west Florida shelf and develop new products for SeaWiFS and MODIS.

16.2. RESEARCH ACTIVITIES

Cruises

We have collected in situ bio-optical data on twenty-five cruises. Measurements in the Northern Gulf of Mexico include absorption coefficient, beam attenuation coefficient, scattering coefficient (ac9), remote sensing reflectance (above water method), aerosol optical thickness (Microtops), and HPLC pigments (Table 16.2). A substantial number of these stations were collected during minimum cloud cover and matched up with SeaWIFS and MODIS passes. Measurements in North Carolina waters include water samples, water profile measurements (YSI), and remote sensing reflectance. The water samples were collected to determine chlorophyll, CDOM, filter pad absorption, HPLC, total suspended solids (TSS), and nutrients. Measurements along the Gulf coast include remote sensing reflectance from 400-900 nm, spectral absoprtion and scattering profiles (from an ac9), water samples, and aersol optical depth (MICROTOPS sunphotometer). The water samples were collected to determine chlorophyll, CDOM, filtered pad absorption, HPLC (through CHORS), total suspended solids (TSS), and nutrients.

The Use of LIDAR to Improve Bio-optical Algorithms (NOAA)

The current chlorophyll algorithm fails in high CDOM areas. We have collected simultaneous SeaWIFS, LIDAR, hyperspectral radiance, and water samples from Pamlico Sound to develop a more robust Case 2 bio-optical algorithm. Airborne LIDAR have been used to determine synoptic chlorophyll-*a* and CDOM in coastal North Carolina. Pat Tester has started a collaborative research project with Bob Swift at NASA Wallops Island. She has contracted for six more over flight windows to use LIDAR during the spring and fall from 2003 through 2005. In addition to the utility of CDOM (and organic C), CDOM signals may serve as mimics for salinity or nutrients pulses after runoff events.

16.3. RESEARCH RESULTS

NIR atmospheric correction implemented to latest SEADAS (NOAA & NRL)

We submitted NIR atmospheric correction code and manuscript to Sean Bailey in March and September 2002, respectively. After Gene Feldman compared the products derived from many atmospheric corrections and posted them to SeaWiFS community for review, NASA implemented our NIR-correction approach into SEADAS 4.4 (released July 2002). In addition to NASA's evaluation, we independently compared the products derived from different atmospheric corrections against measured data. The comparison shows that the proposed NIR reduced both the bias and root-mean square error. Description NIR correction may be found in Volume 22 of a NASA technical memo: Algorithm Updates for the Fourth SeaWiFS Data Processing.

Table 16.3: Summary of Data Collected

Experiment	Cruise	Date	Ac9/CTD Etc.	ASD rrs	HPLC
Cojet 3–Northern Gulf of Mexico	Mopex	5/16/01	26	36	0
Cojet 3–Northern Gulf of Mexico	Lgssur	5/16/01	31	31	29
Cojet 3–Northern Gulf of Mexico	Ocolor	5/16/01	22	22	25
NGLI Lake Bourne Apr01	Ocolor	04/01	4	3	4
NGLI Biloxi 11Sep01	Ocolor2	09/01	8	8	8
Leo2001- East Coast –New jersey	R/V NorthStar	7/31- 8/02/01	15	28	23
Cojet 4 – Barrier Islands, Mobile Bay		9/2/01 – 9/6/01	17	16	33
Cojet 5 – Barrier Is., Mobile Bay	Pelican	12/3/01-12/7/01	26	25	26
Cojet 6- Barrier Is., Mobile Bay	Pelican	3/5/02-3/6/02	8	9	9
Cojet 7 – Barrier Island	Pelican	5/17/02-5/26/02	29	17	27
Cojet 7 – Barrier Island	Ocolor	5/17/02-5/26/02	24	25	25
NGLI Biloxi 19Nov01		5/01			5
ECOHAB- West Florida Shelf	ECOHAB	9/25/00-9/29/00			25
NC-04/01- North Carolina	Pamlico	4/10/01-4/11/01	8	10	14
NC-05/01 – North Carolina		5/24/01		4	4
NC 07/01 North Carolina	Pamlico	7/24/01 – 7/26/01		4	11
NC 08/01	Pamlico/NC shelf	08/1/01-8/2/01			5
NC-10/01	NC Shelf/Pamlico	10/16/01-10/19/01		8	13
NC-02/02	Pamlico	2/19/02-2/21/02		8	8
CA-03/02	Offshore San Francisco, Gulf of Farallones	3/2/02-3/4/02		7	20
NC-07/02	Pamlico	7/3/02		2	6
Dolche-Vita	Adriatic Sea	Feb 03	35	35	
Monterey		April 03	59	55	60
Fort Lauderdale		Aug 8 – 10, 2003	18	18	0
Horn Island, near Biloxi, MS		Sep 17- 19, 2003	22	22	22
NC03		4/15/03-4/16/03		11	11
		TOTALS	352	404	413

Absorbing aerosol correction

Although the NIR correction improves the accuracy of the derived water reflectance, the correction only corrects for the Rayleigh and aerosol scattering but neglects absorption due to aerosols. Thus, the current 'water absorption' is an overestimate of true water absorption when absorbing aerosols are present. The overestimated water absorption begets underestimated reflectance and underestimated chlorophyll. We have a proposed algorithm to correct for absorbing aerosols and will submit the manuscript to Applied Optics.

Calibration (NOAA)

At the AGU meeting in San Francisco, December 2001, Ransibrahmanakul and Stumpf (2001) presented a new method for validating calibration gain values in the blue bands.

Background & Problem

The current calibration of SeaWiFS involves two steps: correction for temporal changes using lunar observations and periodic vicarious calibration of the radiance based on comparison with the Marine Optical Buoy (MOBY) sites. The later has potential uncertainty of 0.5 % in the top-of-atmosphere (TOA) radiance calibration (Barnes et al. 2000), partly because each band is calibrated independently. In coastal areas, the calibration of the 412 nm band is of particular concern owing to the need to correct for absorbing aerosols in the atmosphere and the need to monitor and compensate for colored dissolved organic matter (CDOM) in the water. Calibration errors of 0.5-1% between bands in the blue (412 nm, 443 nm, 490 nm) can introduce significant errors in the retrieved water reflectance (5-10% in case 1 water, and 20-100% in case 2 water).

We proposed two methods: one involving examination of case 2 water; another, in all water types. Both methods use an inter-band relationship found in the field (and assumed to be intrinsic) to validate the spectral shape observed in satellite data. The coastal method examines spectral curvature in the blue bands. Satellite data typically shows a convex shape from 412 to 490 nm, while field data shows a concave shape. By defining coastal water spectra as those with remote sensing reflectance at 443 nm greater than remote sensing reflectance at 412 nm, we found that 90% of the 420 field coastal water spectra are concave (index < 0). In contrast, 90% of the satellite coastal water spectra are convex (index > 0).

Using the latest calibration and software, we found the calibration at 412 nm appears to be underestimated by about 1%. For validation, we computed the overall bias and root mean square error (rms) from 105 pairs of satellite and same-day cloud-free measured remote sensing reflectance in US waters. Using the adjusted calibration, the bias at 412 nm is reduced by four folds. Adding a component to the current protocol to calibrate multiple bands simultaneously may improve the total calibration.

Remote Sensing Relectance at 670 nm (NOAA)

Remote sensing reflectance at 670 nm is used in the NIR correction. Inaccurate remote sensing reflectance at 670 nm would contribute errors in all bands. We have observed large patches of negative remote sensing reflectance at 670 nm near the coast in the North Atlantic. In an effort to identify the problem, we compared SeaWiFS remote sensing reflectance at 670 nm with two modeled estimates in the Sargasso Sea. This area was chosen because of its extremely low chlorophyll characteristics, therefore reducing the number of assumptions made in the models. We observed satellite remote sensing reflectance at 670 nm to be higher than both modeled estimates. This was unexpected, considering that negative remote sensing reflectance has been observed. In conclusion, adjusting the calibration at 670 nm in any direction is not a global solution, indicating that a local problem, possibly in some of the atmospheric correction models, may be producing the negative radiances at 670 nm.

Validation of Atmospheric Correction and Chlorophyll Algorithms for Processing SeaWiFS data (NOAA)

With at least four atmospheric corrections and chlorophyll algorithms for SeaWiFS available, a user may be interested in their performances in different water types. To facilitate this comparison, Zhong Ping Lee and Bob Arnone have started an Ocean-Color-Algorithm working Group (OCAG), where the first meeting will take place on November 17, 2002, Sata Fe, NM, prior to the Ocean Optics Conference.

We presented the results comparing atmospheric corrections and five chlorophyll algorithms in different water types at the 7th International Conference on Remote Sensing for Marine and Coastal Environments, Miami, May 2002 (Ransibrahamanakul et al., 2002). We have developed an evaluation protocol to evaluate the performance of the available atmospheric corrections (including the NOAA/NRL developmental atmospheric correction) and chlorophyll algorithms. To date, we have used 159 same-day field-satellite pairs of remote sensing reflectance spectra to determine the best atmospheric correction applicable to the entire US coastline. The five atmospheric corrections considered were developed by Gordon & Wang (1994), Siegel et al. (2000), Gould et al. (1998), Ruddick et al. (2000), and NOAA/NRL (Stumpf et al., 2003). We did not include the atmospheric correction developed by Hu et al. (2000) because it requires manual interaction and is not appropriate for automated processing.

Similarly, we have developed protocols and software for evaluating multiple chlorophyll algorithms for regional application. The analysis involves examination of spatial matches and ranking of the procedures. In both the evaluations of atmospheric correction and chlorophyll algorithms, the selection procedure was designed to determine an algorithm that works best over a range of water types and compensates for distribution biases. The process also allows comparison of the chlorophyll with unique optical properties where algorithms may fail. This occurs in Pamlico Sound, North Carolina, during flood conditions, and in Atchafalaya Bay, Louisiana, under high flow. We are examining the potential factors.

MODIS Terra processing (NRL)

We are working with the University of Miami and NASA Goddard for processing MODIS ocean color data. We have obtained MODCOLOR and MODSST and implemented on our Linux operating system and integrated it into the Automated Processing System (APS) (Navy's satellite processing software). We have modified the MODIS software with the NIR atmospheric correction used in SeaWIFS processing and implemented coastal algorithms. The output of all the APS is an HDF file format that is directly input into SEADAS or ENVI. Our efforts in MODIS processing required that we closely coordinate efforts with the MODIS Science team and MODIS calibration Science Team. These required updated calibration, level 0 and 2 processing etc. We have worked with the programmers and scientists at University of Miami (Evans group), and Goddard (Esaisas group, and C. Lyons group). They have provided quality data and cooperative efforts which have allowed us the ability to do our research. This cooperation is strongly acknowledged.

We are generating the standard NASA products (Chlorophyll, absorption and scattering) in addition to bio-optical navy algorithms (over 50 products) in both MODIS (TERRA) and SeaWIFS. We are comparing the differences in the sensors for a 2 year period in the Gulf of Mexico by looking at weekly composites. These results are being presented at the Ocean Optics Conference in Nov 02.

We have implemented routine processing of MODIS-TERRA for selected ocean regions in the US (Gulf of Mexico, and Chesapeake Bay) and other areas. We have automated the procedure for transfer and processing of MODIS data from the "MODIS Direct Broadcasting" and the NOAA/NASA Project. We have obtained software and data from MODIS –AQUA but are not currently processing this data routinely.

We have added the capability to process MODIS AQUA data with the NRL Automated Processing System (APS), in addition to our capabilities for TERRA imagery. We have worked closely with folks at University of Miami, NOAA, and NASA/Goddard on this effort. We are implementing the new NIR algorithms we developed for SeaWiFS under SIMBIOS. The processing is now implemented and we process daily MODIS AQUA and TERRA imagery from several regions, including the Gulf of Mexico, Adriatic Sea, Persian Gulf, Arabian Sea, and New York Bight.

We have automated transfer of MODIS data to our APS. Automated MODIS data streams are in place from both NASA/Goddard and NOAA, and we generally process scenes within about 6-8 hours of the satellite overpass. The processed imagery is archived at NRL/Stennis and is accessible via our web browser.

We are working with NASA/Stennis to receive MODIS data over the Gulf of Mexico in real time. We have successfully captured, transferred, and processed a test scene from their X-band receiving system. We developed preliminary MODIS c660, absorption, scattering, and diver visibility products at 250m resolution for the Persian Gulf (in support of Operation Iraqi Freedom). Work is underway to improve the products and the atmospheric correction routines used for the 250m MODIS channels, including both Rayleigh and aerosol corrections.

Work is underway to implement new bio-optical optimization algorithms for MODIS into the NRL APS. We are in the process of validating MODIS TERRA-retrieved estimates of remote sensing reflectance (Rrs), through comparisons with our in situ shipboard measurements. After completing this effort, we will validate the derived optical properties (absorption, backscattering) for TERRA, then we will conduct similar comparisons for AQUA. We have implemented new SQL search engines on our web page to facilitate browsing for daily and composited MODIS scenes in our image archive.

Other SeaWiFS activities

- We have developed new methods to understand terrestrial flux from coastal rivers. By unravelling the ocean color signatures into the basic in water constituents; we developed a 2 year time series of

SeaWIFS optical properties. We established the covariance of this 2 year satellite time series with river discharge of the Mississippi river.

- We developed new algorithms for extending the satellite near surface chlorophyll algorithms to depth. We assimilate the mixed layer depth and surface wind stress from NCOM with the latest satellite observations and define a vertical profile. This is being performed daily and has been automated for the Gulf of Mexico.

- We developed methods to limit cloud cover by using the spatially and temporally varying time series of satellite imagery. We developed methods of compositing more recent imagery into latest pixel composite. This method has created new products for optimizing ocean color products. We are using these methods for SeaWIFS and MODIS in the Gulf of Mexico.

- We have used the data collected in SIMBIOS to validate the coastal algorithms. We have tested the algorithms used for bio-optical properties (absorption and scattering derived from SeaWIFS). We have published this in Sea Technology.

- We have organized a real time data base on our web server to provide real time access to ocean products. These include SeaWIFS and MODIS sensors. Real time access is available to test algorithm products and determine the sensitivity of the algorithms for SeaWIFS and MODIS. http://www7333.nrlssc.navy.mil

- We developed a relationship between absorption and salinity, to derive surface salinity maps from coastal SeaWiFS imagery.

- We developed a relationship between b(555) and total suspended solids (TSS), to derive surface TSS maps from SeaWiFS.

- We linked physical processes (currents, tides, winds, wave resuspension) to optical distribution patterns in northern Gulf of Mexico.

- We developed new algorithms to estimate particulate inorganic matter (PIM) and particulate organic matter (POM) from SeaWiFS imagery.

- We developed new SeaWiFS algorithms to estimate separate CDOM and detritus absorption coefficients, rather than a single combined term. This will facilitate development of a new optical water mass classification system.

- We have improved coastal SeaWiFS optical algorithms through investigation of b_b/b and F/Q parameters.

- We have implemented a new Quasi- Analytical Algorithms (QAA) into the NRL APS processing of SeaWIFS and MODIS for coastal bio-optical algorithms. The QAA s a linearized version of the optimization algorithms which accounts for the majority of the optimization within the computation required. Products of chlorophyll, scattering and absorption from CDOM, phytoplankton and particles are currently being generated. They are available on the web. (Lee et al 2002).

- We have developed automated methods for collection and processing *in situ* ocean optics data for processing of field data. These methods have been applied to all our advanced *in situ* instrumentation. We have organized a calibration laboratory and track all our instrumentation. These include the ac9 and above water reflectance instruments and particle size instrument measurements. Additionally we have developed methods for partitioning particles into organic and inorganic fraction. These new methods are providing measurements for advanced algorithms.

- Work is underway to implement new bio-optical optimization algorithms for SeaWiFS into the NRL APS.

- We have developed new methods to understand terrestrial flux from coastal rivers, using new algorithms to estimate total suspended sediments (partitioned into organic and inorganic components). We calculated particle mass and areal plume extent, for the Mississippi River and Mobile Bay plumes. Results were presented at the Ocean Optics meeting in Santa Fe in November, 2002, and at the Oceanography Society meeting in New Orleans in June, 2003.

- We developed a new optical water mass classification system to trace water masses. The technique is based on the separation of the total absorption coefficient into components due to detritus, phytoplankton, and CDOM. It can be used to quantitatively characterize and trace coastal features over time. Results were presented at Ocean Optics and will be presented at the Optics of Natural Waters Conference in St. Petersburg, Russia, in September 2003.

- Work is underway to implement algorithm changes into our APS, for consistency with changes made by NASA/Goddard during the 4^{th} SeaWiFS reprocessing. Following the algorithm updates, we will validate the SeaWiFS Rrs and optical products through comparison with our shipboard in situ data.

- We have implemented new SQL search engines on our web page to facilitate browsing for daily and composited SeaWiFS scenes in our image data base. Work is underway to add the capability to search for level 1 imagery and in situ data from our web page, to facilitate validation and reprocessing efforts (http://www7333.nrlssc.navy.mil).

16.4 CONCLUSIONS

Between the two groups, NOAA and NRL, we are developing an extensive data set for coastal and case 2 waters. We are in the process of merging the information for examination of remote sensing reflectance and chlorophyll. NRL has a data set from over 21 cruises. There are now 218 vertical profiles, 263 field spectra, and 320 HPLCs. NOAA has approximately 100 same-day match-ups of remote sensing reflectance and chlorophyll from the southeast and Gulf of Mexico. We assembled a database of *in situ* optical properties to evaluate SeaWIFS-derived properties collected from 1997 to present in a variety of coastal regions (Mississippi Bight, Mississippi River, West Florida Shelf, Loop Current, North Carolina, New Jersey). The data cover a broad range of absorption (0.4 – 15 m^{-1}) and scattering (0.1 – 27 m^{-1}) coefficients and remote sensing reflectance. The collected data set contributes to the SEABASS database, particular its Case 2 component. In addition to data collection, our groups produced the NIR-iterative technique used by the SeaWiFS project for the fourth reprocessing (repro4).

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