

The Backscattering Enigma in Natural Waters

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LONG-TERM GOALS

One of the fundamental problems in ocean optics over the past several decades has been understanding the source of backscattering in the ocean. Because of experimental limitations and the limitations in available theoretical models, our knowledge of the causative agents for backscattering remains poor. Experimentally, we have been limited by a lack of scattering sensor instrumentation and a methodology for routine measurement of the submicron particle size distribution. Theoretically, most models have used Mie theory with the hope that natural particles of complex shape and structure can be approximated well by homogeneous spheres. For the Navy, poorly parameterized backscattering greatly compromises applications that involve the interpretation of passive remote sensing or lidar. This is particularly true in coastal regions where current inversion models break down because the effects of changing particle composition are not adequately understood. Our long term goal is to better understand the source of backscattering in natural waters.

OBJECTIVE

Our objective is measure particle size distributions (PSD) from both natural and laboratory samples using a variety of instruments and methods. This effort fits into the larger objectives of the project understanding the sources of backscattering in natural waters (see attached reports by co-PIs Twardowski and Sullivan) and is critical for analyses of the volume scattering function in natural waters.

APPROACH

A key focus over the last year has been determining the scattering properties of phytoplankton populations and understanding how best to model these properties in a bulk sense. Measurements being made are listed in Table 1.

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Table 1. Measurements to test backscattering hypotheses.

Physical parameter	Instrument	Specific
Volume Scattering Function, β ($\text{m}^{-1} \text{sr}^{-1}$)	WET Labs ECO sensors	β_p ($[100^\circ, 117^\circ, 125^\circ, 150^\circ]$, $[450, 532, 650 \text{ nm}]$)
	Goniometer	β_p ($[\sim 15^\circ - 155^\circ @ 1 \text{ resolution}]$, $[532 \text{ nm}]$)
Attenuation, absorption, scattering coefficients (m^{-1})	WET Labs AC9 and ACS instruments	ap_g , ag , ap , bp , cp_g , and cp at 84 wavelengths
Particle Size Distributions (PSDs)	LISST-100	Sizes ranging from ~ 1.3 - $250 \mu\text{m}$
	LISST-FLOC	Sizes ranging up to $1500 \mu\text{m}$
	Electrical resistance particle sizing	Sizes ranging from ~ 0.6 - $12 \mu\text{m}$ and ~ 2.4 - $48 \mu\text{m}$
	Light Microscopy	Sizes ranging from ~ 1 - $250 \mu\text{m}$

We are responsible for the PSD measurements made with the LISST-100X (Sequoia Scientific) defined as an instrument for Laser In-Situ Scattering and Transmissometry. This instrument uses laser diffraction to obtain size distributions for an ensemble of particles, without actual counting. The light scattered at small forward angles is relatively unaffected by the composition of the particles and is measured using an annular ring detector. A mathematical inversion is used to fit a size distribution that would produce the observed multi-angle scattering. This mathematical inversion, however, assumes spherically shaped particles and may not be accurate for the complex shapes of particles.

Finally, we also have a LISST-FLOC (Sequoia Scientific) which measures particles up to $1500 \mu\text{m}$ in size. The instrument is similar in design to the LISST-100X, but has a larger pathlength and measures scattering at even smaller forward angles. Coupled with the LISST-100X, we can assess the particle size distribution from a few micron up to $1500 \mu\text{m}$ and test the hyperbolic model across a large range of particle sizes. The larger particles are primarily forward scatterers and may not contribute significantly to backscattering. However, monitoring large aggregates is nearly impossible with laboratory measurements that require discrete water samples. Large particles are known to settle in the bottom of Niskin bottles and are, therefore, difficult to retrieve without a mechanism for resuspending the bottom materials (i.e., shaking). In addition, the dilute and episodic nature of large particles often require more water volume than is available from discrete samples in order to produce statistically rigorous data. *In situ* instrumentation can provide continuous monitoring across a large size spectrum and will allow us to track changes in large aggregates over time.

WORK COMPLETED

Much of the past year has involved extensive field projects throughout the coastal and open ocean to measure PSD with the LISST-100X and LISST-FLOC and coincident bio-optical measurements.

A. Optics and PSD measurements in natural water

1. North Atlantic – 16-20 October, 2005
2. Port St. Joe, FL – 12-18 June, 2006.

3. Florida Keys, FL – 20 June - 3 July, 2006, and 16 June-5 July 2005
4. Monterey Bay, CA – 4-9 Sept. 2006
5. Long Island Sound – Cruises throughout 2005 and 2006, as follows:

Table 2: Metrics on data collected during seven cruises in Long Island Sound

Cruise	OGC 004	LISICOS 0305	OGCO 05	LISICOS 0705	LIS 0106	LISICOS 0306	OGCO 06	Totals
Dates	May-04	Mar-05	May-05	Jul-05	Jan-06	Mar-06	Jul-06	
Stations	21	9	32	31	4	5	31	133
IOPs	19	7	20	24	1	5	23	99
Rrs	11	5	16	27	2	4	32	97
IOPs, Rrs	11	5	13	22	1	4	19	75
Chl	19	6	18	24	0a	0a	0a	67
All	11	5	13	22	0	0	0	51

aData still to be processed.

B. Deep-water large particle PSD

The LISST-FLOC has been deployed on a mooring linked to a sediment trap:

1. July 21, 2005 - August 1, 2005: FLOC deployed on and recovered from sediment trap in Western Long Island Sound.
2. April 27, 2006 – June 7, 2006: FLOC deployed on sediment trap in Western LIS. Trap depth 7m. Sampling for 2 min every 2 hours.
3. June 7-July 6 2006 : FLOC deployed on sediment trap in Western LIS. Trap depth 7m. Sampling for 2 min every 2 hours.

C. Sediment grain size measurements with LISST-100X in laboratory to determine linkages between benthos and water column

1. Port St. Joe, FL – 12-18 June, 2006.
2. Florida Keys, FL – 20 June - 3 July, 2006, and 16 June-5 July 2005
3. Monterey Bay, CA – 4-9 Sept. 2006

D. PSD measurements of laboratory cultures of different phytoplankton

Five lab experiments have been conducted using cultures of the diatom *Chaetoceros socialis*, the dinoflagellate *Gyrodinium instriatum*, the diatom *Thalassiosira weissflogii*, the diatom *Chaetoceros*

teres, and the diatom *Stephanopyxis turris*. The experiment with the latter organism was carried out through a full phytoplankton growth cycle. Measurements with both the LISST and the Elzone particle counter were conducted.

E.. Manuscripts and Presentations

- Lead or coauthor on nine conference presentations in the last year alone, including presentations in the scattering session at Ocean Sciences meeting
- A manuscript published in 2006 in *Limnol. Oceanogr.* that includes scattering information on the red edge of phytoplankton. Dierssen et al. (2006)
- A manuscript has recently been completed for submission to *J. Geophys. Res.* documenting the high backscattering measurements from natural waters entitled “Windrows and whittings: Benthic and optical processes in the shallow Bahamas Banks shaped by wind-driven Langmuir supercells”. Dierssen et al. (for submission).
- A manuscript has recently been submitted to *IEEE Transactions on Geoscience and Remote Sensing* entitled “An atmospheric correction algorithm for remote sensing of bright coastal waters using MODIS land and ocean channels in the solar spectral region.” Gao et al. (submitted).
- A manuscript is in preparation for publication, entitled “Relative Influences of Spectral Absorption and Backscattering on Remote Sensing of Chlorophyll”. Dierssen et al.
- A manuscript is in preparation for publication entitled “Demystifying the red edge” discussing enhanced near-infrared scattering and implications for remote sensing dense algal blooms.
- A manuscript in preparation on phytoplankton culture experiments with Twardowski and Sullivan as lead

RESULTS

Results from the laboratory experiments conducted with co-PI’s Twardowski (WET Labs) and Sullivan (URI) are presented in their annual reports. Here we document additional efforts to better identify and model the sources of backscattering in natural waters.

Photosynthetic pigments produce the red edge signature by absorbing visible, but not NIR, radiation (Fig. 1). Terrestrial vegetation and submerged macrophytes (seagrasses and seaweeds) exhibit strong reflectance in the near-infrared (NIR) portion of the spectrum. This NIR reflectance is commonly attributed to scattering from cell and leaf structures (cell walls and membranes, organelles, air spaces, etc.), and forms the basis of the terrestrial biomass parameter NDVI (normalized difference vegetation index). However, plant cell structures are capable of scattering visible, as well as NIR radiation. In fact, reflectance from unpigmented white leaves lack a “red edge” because light is reflected similarly across both the visible and NIR portions of the spectrum. Thus, photosynthetic pigments produce the red edge signature by absorbing visible, but not NIR, radiation. Near-infrared reflectance is generally

ignored for dilute suspensions of microscopic phytoplankton because water strongly absorbs these photons. For most natural populations of phytoplankton, the peak reflectance observed in the far red region can be assigned to fluorescence. However, pigmented microalgae also reflect near-infrared light with much higher efficiency than visible light (Fig. 1). For dense suspensions of algal cells at the sea surface (i.e., "red tides"), the infrared reflectance signal can be strong enough that it is not fully attenuated by the water, producing peaks in the reflectance spectra that are red-shifted relative to those produced by chlorophyll fluorescence. This NIR scattering can be used to remotely sense dense algal blooms or red tides.

Conventional bio-optical models of the relationship between backscattering and chlorophyll need to be revised (Fig. 2). Data from a variety of regions have been compiled to illustrate the relationships between backscattering and chlorophyll. Traditional models for understanding scattering and backscattering generally follow a power-law from low to high chlorophyll. As shown by Sullivan for California waters, however, the relationship is typically linear in nature. Certain regions are truly "Case 2" (e.g., Long Island Sound, Bahamas) where backscattering exhibits no relationship to chlorophyll. Other regions show a positive correlation with increasing chlorophyll, but have varying levels of background backscattering.

The highest backscattering ratio in natural waters was measured during a sediment "whiting" event on the Great Bahama Bank (Fig. 3). Suspended sediment in the whiting event consists of fine-grained white mud with extremely high backscattering and high backscattering ratio (0.06). A description of this event is prepared for submission to *Journal of Geophysical Research*. The mechanism responsible for sediment resuspension of whittings has been debated in the literature. Measured currents are not high enough to produce resuspension. Some contend whittings are the result of tidal "bursting" cycles. Others have considered the possibility that resuspension is caused by fish activities. We propose that Langmuir supercells present a plausible mechanism for sediment resuspension and subsequent whiting formation. There is clearly a need for new methods to assess resuspension of sediments. The optical data presented in this paper are the foundations for developing models to quantify the amount of suspended matter in the water column from remotely sensed ocean color data. Suspended sediment increases the backscattering in the water resulting in greater reflectance across the visible spectrum. Temporal and spatial estimates of resuspended sediment obtained from remote sensing imagery can then be related to the amount of carbonate precipitation over this shallow basin and incorporated into global biogeochemical models.

LISST-100X can be used to effectively measure sediment grain size from sediment cores. Sediment resuspension events are common to shallow water ecosystems. Understanding the bio-optical properties of sediment is critical to assessing the optical properties of the water column and the ability to conduct remote sensing in these Case 2 regions. We are actively comparing the PSD from sediment cores to the PSD and backscattering properties of the overlying water column from a variety of shallow water habitats. We are exploring the possibility of using the LISST to determine sediment settling rates.

In high backscattering regimes, like Long Island Sound, traditional ocean color algorithms tend to underestimate chlorophyll. A selection of four ocean color algorithms (empirical, semi-analytic, spectrally optimized and quasi-analytical) have been evaluated for performance in Long Island Sound. The predictive capability of the model is based on a linear regression between the model (mod) and the data (meas), and expressed as the r^2 , while the ability to accurately retrieve bio-optical properties is compared using the percent difference. Both inversion models and semi-analytic methods show

promise for remote sensing in these Case 2 waters and explain greater than 70% of the variability in the data. However, these models will require tuning, because they significantly underestimate retrieved parameters.

IMPACT/APPLICATIONS

The results from this project represent important steps toward understanding the sources of backscattering in the ocean. Naval applications requiring an understanding of the optical properties of water will benefit from this work. Since the optical properties of seawater are driven by the composition of suspended materials, we must understand this link to know how the underlying biogeochemical processes influence seawater optics. Applications directly influenced by seawater backscattering include lidar, laser line scanning systems, and remote sensing. Oceanographic research implications of this work include better inversion models for estimating the composition and concentration of suspended particles from optical sensors.

RELATED PROJECTS

This project benefits from data collected in conjunction with various other funded projects in the COLORS lab (<http://color.uconn.edu>). Particle size distributions, backscattering, and related data have been collected from Florida Bay, Port St. Joe, Long Island Sound, North Atlantic, and Bahamas.

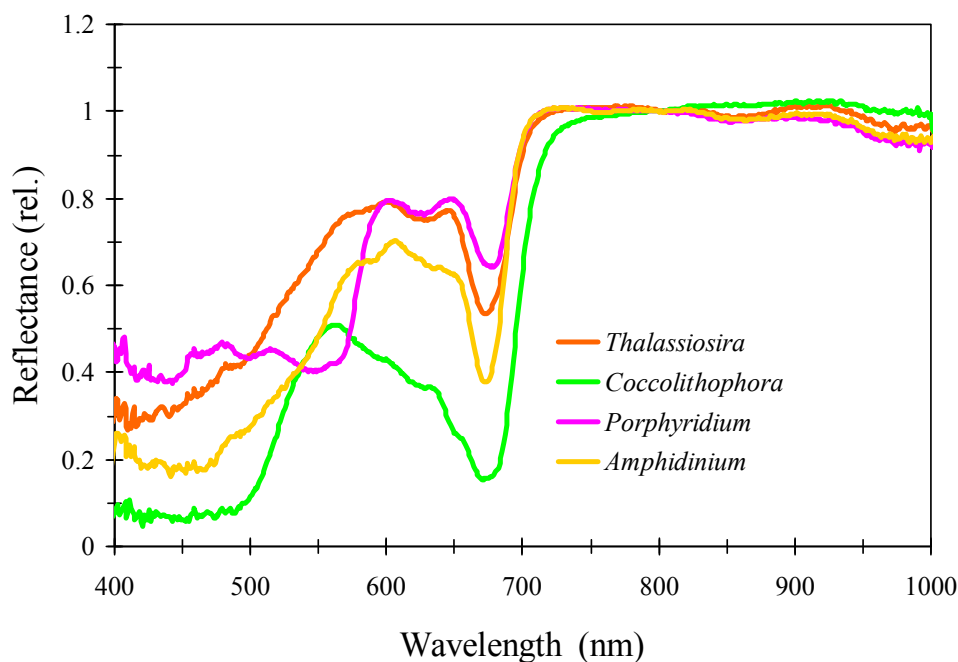


Fig. 1. Amplified near-infrared reflectance or the “red edge” is measured in different phytoplankton taxa, regardless of the different phytoplankton shell composition and morphologies.

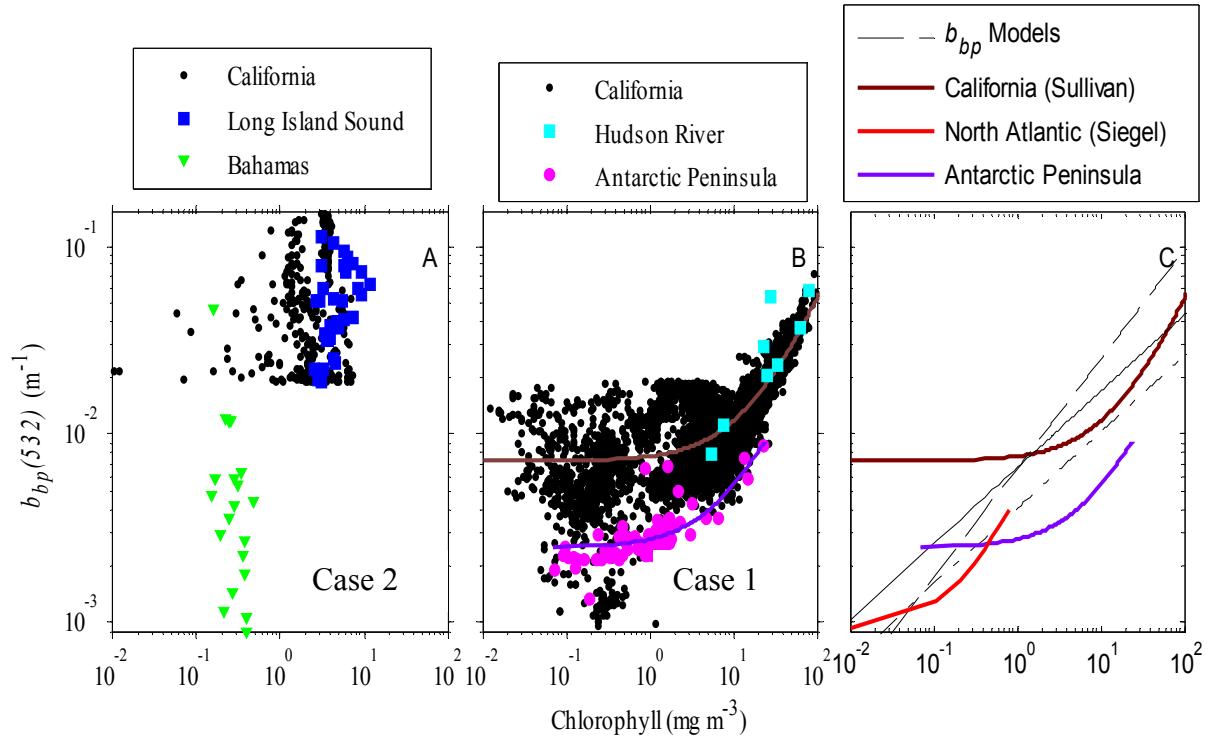


Fig. 2. A) For Case 2 waters like Long Island Sound, no relationship exists between backscattering (bbp) and chlorophyll (chl). B) For “Case 1” waters, bbp and chl follow a linear relationship. C) Most bio-optical models use a power-law description of this parameter.

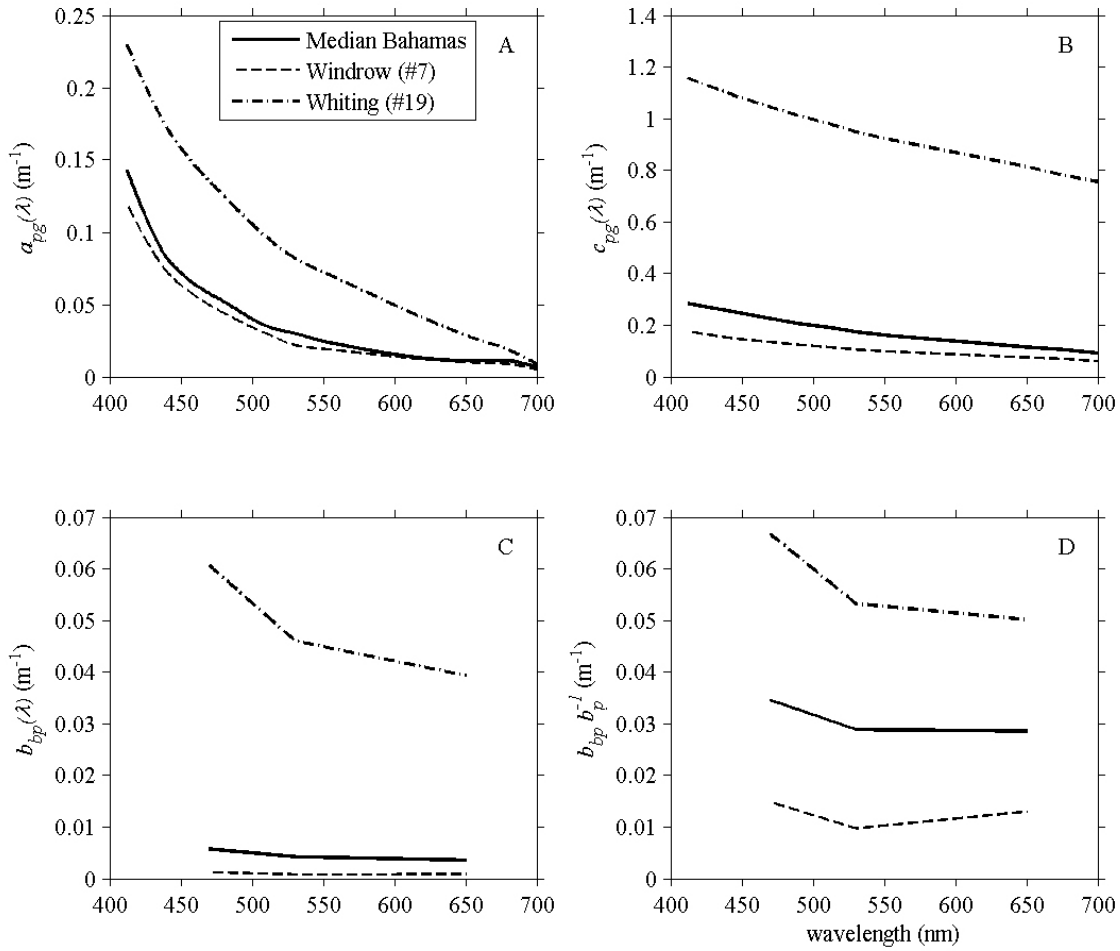


Fig. 3. Inherent optical properties measured over the algal windrows (Station #7) and a station with high suspended sediment (“whiting”; Station #19) compared to the median measured throughout the Bahamas Banks. Measured parameters include: A) Absorption by particulate and dissolved material (a_{pg}); B) Spectral light attenuation by particulate and dissolved material (c_{pg}); C) Spectral backscattering of particulate (b_{bp}); D) The backscattering ratio defined as particulate backscattering normalized to total particulate scattering (\tilde{b}_{bp}). The backscattering ratio of ~ 0.06 is one of the highest measured in natural waters.



Fig. 4. Slopes of the particle size distribution in Long Island Sound measured with the LISST instrument are high relative to Hudson River plume indicating a prevalence of small highly backscattering particles.

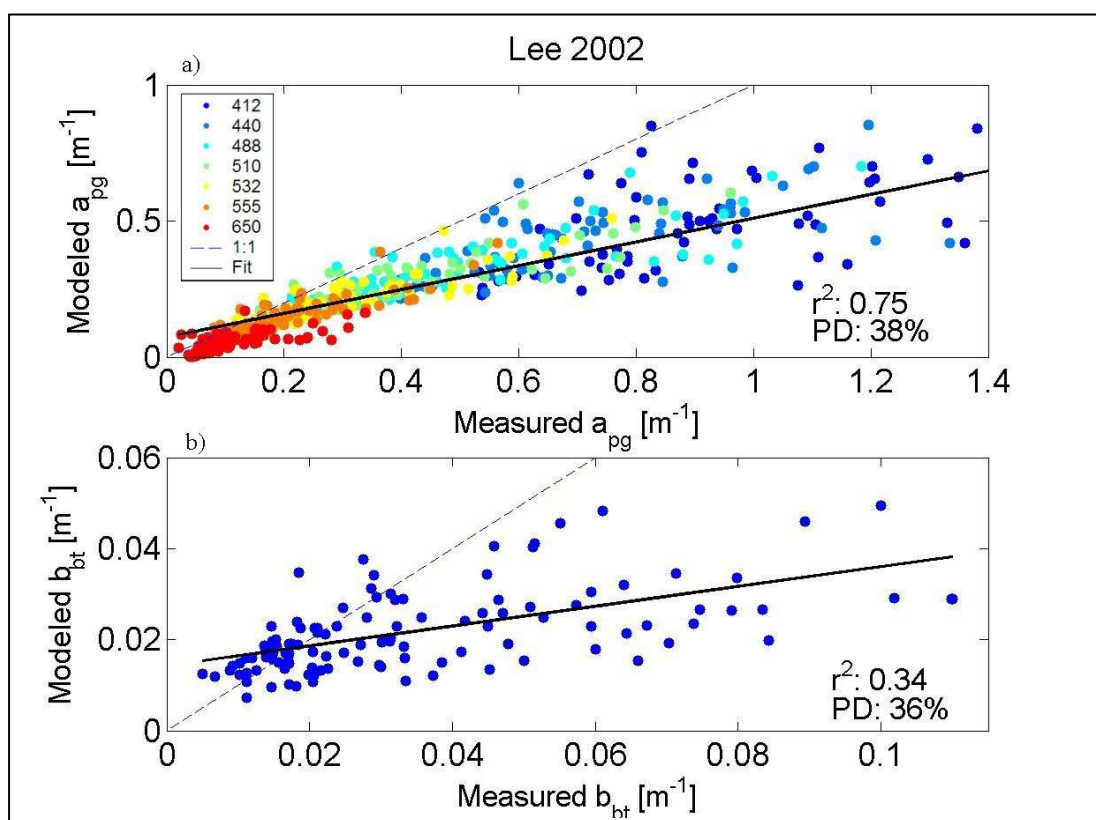


Figure 5. Results of the Lee et al. 2002 algorithm for remotely deriving a) whole water absorption and b) total backscatter in Long Island Sound show good correlation to measured properties. The difference from the 1:1 line, however, indicates that the approach must still be tuned to account for the high backscattering waters in this region.

PUBLICATIONS IN THE LAST FIVE YEARS

Dierssen, H.M., Ryan, J., and R. Kudela. 2006. Red and black tides: Quantitative analysis of water-leaving radiance and perceived color for phytoplankton, colored dissolved organic matter, and suspended sediments. *Limnology and Oceanography*. 55 (6).

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Smith, R.C., K. Baker, H.M. Dierssen, S. Stammerjohn, M. Vernet. 2001. Variability of primary production in an Antarctic marine ecosystem as estimated using a multi-scale sampling strategy. *American Zoologist*. 41:40-56

HONORS/AWARDS/PRIZES

H. Dierssen, Ocean Biology and Biogeochemistry Working Group, NASA

H. Dierssen, Coastal Ocean Applications and Science Team (COAST) Member. 2005

H. Dierssen, MODIS Science Team Member, 2005

H. Dierssen, Ocean Optics Planning Committee. Office of Naval Research. 2005

H. Dierssen, MBARI Postdoctoral Fellowship, 2002-2004

H. Dierssen, NASA Earth System Science Fellowship, 1997-2000.

H. Dierssen, Merit Fellowship Geography Department. Univ. California Santa Barbara, 1998

H. Dierssen, Nominated GSA Excellence in Teaching Award, 1997-1998

H. Dierssen, California Space Grant Fellowship, 1995