Comparisons of optical properties of the coastal ocean derived from satellite ocean color and in situ measurements

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Abstract: Satellite-derived optical properties are compared to in situ mooring and ship-based measurements at a coastal site. Comparisons include remote sensing reflectance ($R_s$), chlorophyll concentration (Chl) using two different Chl algorithms, and spectral absorption [$a_{pg}(\lambda)$] and backscattering coefficients [$b_b(555)$] using three different bio-optical algorithms. For mooring/shipboard comparisons, we observed mean relative errors of 70.5%/–3.8% (SeaWiFS OC4v4), -21.4%/–49.3% (SeaWiFS Stumpf), 109.5%/13.4% (MODIS OC3m) and 0.5%/–48.9% (MODIS Stumpf) for Chl. For satellite-derived and mooring comparisons of $a_{pg}(412)$, we found mean relative errors of -69.4% (-67.1%), -52.6% (-48.9%), and -62.7% (-65.4%) for the Arnone, GSM, and QAA algorithms for SeaWiFS (MODIS), respectively. Mean relative errors of 21.3%, 19.9%, and 16.5% were found between SeaWiFS-derived (Arnone, GSM, and QAA algorithms, respectively) and moored $b_b(555)$ measurements. Discrepancies in $R_s$ at blue wavelengths are attributed to the satellite atmospheric correction and sea surface variations of the moored radiometers. High spatial and temporal variability of bio-optical properties coupled with differences in measurement techniques (pixel versus point) contribute to inconsistencies between remotely sensed and in situ bio-optical properties.

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1. Introduction

Technological advances in remote sensing have allowed scientists to utilize ocean color satellite images to synoptically investigate large-scale surface features in the world’s oceans. Over the past 25 years, ocean color data have primarily been used to infer chlorophyll concentration (Chl) and phytoplankton biomass in open ocean waters. Several ocean color algorithms have been developed for this environment [1]. Empirical algorithms generally employ waveband ratios of upwelling or normalized water-leaving radiance, or remote sensing reflectance (Rrs). Semi-analytical algorithms are based on the $b_b/(a + b_b)$ to Rrs relationship [2], where $b_b$ is the backscattering coefficient, and $a$ is the absorption coefficient (wavelength dependent; notation suppressed).

It is essential to improve understanding of coastal ocean processes since the majority of the world’s primary production occurs on continental shelves and the coastal ocean is most utilized and impacted by humans. In recent years, many oceanographic studies in the U.S. have shifted from the open to coastal ocean to address many of these issues [3]. Algorithms to determine total and partitioned spectral absorption for colored dissolved organic matter (CDOM) and particulate absorption from ocean color data have been developed [4,5,6]. Satellite estimation of optical constituents (including phytoplankton, detrital, CDOM absorption coefficients) in the coastal ocean can be used to develop new optical water mass classification schemes, and to track water masses and river discharge plumes [7]. Spectral particulate and phytoplankton absorption data are essential for ecological studies including harmful algal bloom monitoring and mitigation. The derivation of spectral backscattering from measurements of Rrs is now possible with newly formulated algorithms. Spectral backscattering data can be utilized for assessment of suspended particulate material and fluxes in the coastal ocean [8]. This is important for investigations of the transport and fate of sediments and pollutants on continental shelves.

The Office of Naval Research-sponsored Hyperspectral Coastal Ocean Dynamics Experiment (HyCODE) was designed to study optical properties on shallow continental shelves. One of the central goals of the HyCODE program was to develop ocean color algorithms for remote sensing of the coastal ocean. Some other objectives included deployment and evaluation of technologically advanced hyperspectral instrumentation (in situ and aircraft remote sensing) and the investigation of the relation of inherent optical properties (IOPs) to apparent optical properties (AOPs). Here, we present results from 2001 HyCODE field experiments at the Long-term Ecological Observatory site (LEO-15; [3]) site in the New York Bight, New Jersey shelf.

The objectives of this paper are to: 1) compare satellite and in situ measurements of Rrs, Chl, absorption ($a_{pg}$), and backscattering coefficients ($b_b$), and 2) examine differences between spatial and temporal measurements of optical properties in a dynamic coastal setting.

2. Observations

The LEO-15 site is an extremely dynamic region characterized by coastal jets and fronts, eddies, small-scale convergence and divergence zones, river and estuarine inputs, and upwelling and downwelling, resulting in relatively short temporal and spatial scales of decorrelation for optical properties [10]. In general, temporal variability of optical and physical properties in the area is dominated by the semi-diurnal tidal cycle. Diel signals are apparent in some biological parameters, e.g., Chl. Spatial variability is primarily controlled
by coastal fronts caused by the interaction between different physical processes, e.g., tidal currents with coastal jets, upwelling with river plumes, etc. [10, 11].

During the HyCODE summer field campaign from June to August 2001, LEO-15 oceanographic conditions were mainly characterized by localized upwelling and downwelling cycles. These cycles resulted in strongly stratified waters, with warm surface waters (>20°C) separated from cold bottom waters (<15°C). Above the thermocline, phytoplankton absorption dominated total absorption whereas CDOM and detrital absorption dominated total absorption in bottom waters. Overall, phytoplankton, CDOM, and detrital concentrations were greater above the thermocline than in bottom waters [11]. The average Chl at the mooring at 5 m water depth between 19 June and 6 August 2001 was 3.4 μg l⁻¹ (minimum was 0.8 and maximum was 7.1 μg l⁻¹). Time series of Chl (5 m), and absorption and attenuation coefficient (cₚ₉) at 5 and 20 m, are shown in Fig. 1. The 1-km SeaWiFS image from 21 July 2001 [Fig. 1(d)] shows the spatial variability along the coast of New Jersey and at the mooring location, and the higher chlorophyll values associated with the Hudson River plume (identified using temperature-salinity relationships and collected by satellites and on the mooring and by nearby complementary sampling; data not shown) impacting the area from the north.

![Fig. 1. Mooring time series of (a) Chl at 5 m, (b) aₚ₉(440) and (c) cₚ₉(650) at 5 m (solid blue lines) and 20 m (dashed red lines); (d) SeaWiFS-derived Chl image at the LEO-15 site on 21 July 2001. The black circle indicates the mooring location. The blue circle indicates Hudson Bay plume waters.](image-url)
3. Methods

3.1 In situ

Optical instruments were deployed on a mooring in the New York Bight at the LEO-15 site between 19 June and 6 August 2001 at 39°20’N, 74°05’W in 24 m water depth. Relevant instruments included: (1) Satlantic Inc. MiniSpecs (hyperspectral radiometers; 3.3 nm wavelength resolution between 400 and 800 nm) for downwelling irradiance and upwelling radiance just above the surface and at 2, 5, and 11 m; (2) WET Labs, Inc. ac-9s ($\lambda = 412, 440, 488, 510, 532, 555, 650, 676, \text{ and } 715 \text{ nm}$) at 5, 11, and 20 m; (3) HOBI Labs HydroScat-6 for spectral backscattering ($\lambda = 442, 470, 510, 589, 620, \text{ and } 671 \text{ nm}$) at 5 m; and (4) chlorophyll fluorometers at 5 and 11 m. MiniSpecs sampled once per hour for 5 minutes from 6 am to 6 pm, EDT. The sampling rates for the ac-9 and Hydroscat-6 were once per hour and once every 2 hours for several minutes, respectively.

For calibration purposes, $a_{pg}(\lambda)$ and $c_{pg}(\lambda)$ mooring measurements were compared with ac-9 profiles at our mooring site on 27 July 2001 (performed by Oregon State University). Differences between moored and profiled measurements were less than 5%. Chl derived from fluorometers was compared with Chl computed from ac-9 measurements ($R^2 > 0.90$; [12,13]).

Using mooring radiometer measurements, we computed remote sensing reflectance:

$$R_{rs}(\lambda) = \frac{L_w(\lambda)}{E_d(\lambda,0^+)}.$$  

where $L_w(\lambda)$ is water-leaving radiance and $E_d(\lambda,0^+)$ is downwelling irradiance measured just above the sea surface. $L_w(\lambda)$ was calculated by use of measured upwelling radiance, $L_u(\lambda,z)$, the diffuse attenuation coefficient for upwelling radiance, $K_d(\lambda)$, and an extrapolation of radiance through the sea surface:

$$K_d(\lambda) = -\frac{d}{dz} \ln L_u(\lambda,z),$$  

$$= \frac{1}{\Delta z} \ln \frac{L_u(\lambda,z_2)}{L_u(\lambda,z_1)},$$  

$$L_w(\lambda) = \frac{1}{n^2} L_u(\lambda,0^+)$$

where $z_1$ and $z_2$ are different depths, e.g., 2 and 5 m and 5 and 11 m, $t$ is the radiance transmittance of the sea surface ($t \approx 0.98$; [14]), $n$ is the real index of refraction of water ($n = 1.34$), and $L_u(\lambda,0^+)$ is upwelling radiance just below the sea surface.

Remote sensing reflectance was also calculated from above-water reflectance measurements collected at 19 ship stations from 31 July to 2 August 2001. At each station, spectral reflectance measurements of water, sky, and a gray-card reference were collected with an Analytical Spectral Devices, Inc. (ASD) field spectroradiometer (wavelength range 350 - 1050 nm, 1.4 nm sampling interval), following Gould and Arnone [15] and references cited therein. ASD $R_{rs}$ spectra were corrected for surface sky/cloud reflection using ancillary ac-9 data (Path 2 correction technique in Gould et al. [16]). Discrete surface water samples were collected at nine stations over this same three-day period. The water samples were filtered through GF/F filters, stored in liquid nitrogen, and shipped to the Center for Hydro-Optics and Remote Sensing (CHORS, San Diego State University) for fluorometric chlorophyll and HPLC pigment analyses [17]. Ship stations are shown in Fig. 2.
3.2 Satellite

SeaWiFS imagery covering the LEO-15 area was collected in real-time via HRPT downlink to the receiving system at the Naval Research Laboratory (NRL) at Stennis Space Center, MS. Data are downlinked while satellite elevations exceed 5° horizon-to-horizon. For eastern orbital passes (western passes cover the west coast of the U.S.), the imagery collected at the Stennis receive site generally extends from the Great Lakes to the southern Yucatan Peninsula and eastward covering the U.S. coast and portions of the Caribbean Sea. MODIS imagery was provided by the NASA Goddard Distributed Active Archive Center (DAAC) within several days of reception.

Both the SeaWiFS and MODIS imagery were processed with consistent atmospheric correction and bio-optical algorithms and archived using the NRL Automated Processing System (APS; [18]). The most recent processing code from University of Miami and NASA/Goddard are incorporated into APS, including sensor calibration coefficients, look-up tables, atmospheric correction, and bio-optical models (SeaDAS version 4.8, MSL12 version 5.3). The standard atmospheric correction algorithm assumes water-leaving radiances (Lw) at near-infrared (NIR) wavelengths are zero (i.e., the ocean is totally absorbing at these wavelengths), and this forms the basis for the correction of aerosol path radiance (La). In coastal waters, scattering from suspended particles results in non-zero NIR Lw, resulting in over-correction for the aerosol component and even some negative Lw values derived at blue wavelengths, because aerosol models are used to extrapolate La from the NIR to shorter wavelengths. To correct for this, we employ an iterative NIR correction scheme, to improve reflectances from coastal waters [19]. This NIR scheme has also been implemented in the latest (4th) SeaWiFS global reprocessing effort at NASA [20].

The LEO-15 atmospheric conditions can be characterized as extremely hazy during the summer months, presumably due to absorbing aerosols such as urban pollution (containing soot). Absorbing aerosols cause serious problems for satellite atmospheric correction schemes commonly in use. Not only is it impossible to determine whether absorbing aerosols are present (using the NIR wavelengths employed), but it is also difficult to correct for them because the standard aerosol models do not correctly account for the scattering spectral
dependence [21]. Thus, when absorbing aerosols are present and an incorrect aerosol scattering model is used to extrapolate aerosol radiance from NIR to blue wavelengths, satellite-derived $R_{rs}$ values are erroneously low at blue wavelengths due to overcorrection for the atmosphere. This error is in the same direction as the overcorrection due to non-zero NIR $L_w$ mentioned above, further driving down $L_w$ at blue wavelengths. In an effort to correct for absorbing aerosols, we employed a 412-iteration algorithm during the atmospheric correction to “bump up” low radiances at blue wavelengths [22]. Both the NIR-iteration and 412-iteration schemes are applied to both the SeaWiFS and MODIS imagery.

Ten clear SeaWiFS scenes (cloud-free over the mooring site) and six clear MODIS scenes were collected during the time period of the summer 2001 mooring measurements. Three (one) SeaWiFS (MODIS) scenes were used for match-ups with seven (three) discrete ship stations collected over a three-day period. Mooring measurements collected at the times of the satellite overpasses are used in all comparisons with the satellite retrievals, to eliminate issues associated with temporal differences between the two data sets. For comparisons between satellite and in situ data, this is a great advantage for continuous mooring measurements over temporally sparse, discrete ship measurements.

### 3.3 Satellite bio-optical algorithms

SeaWiFS satellite Chl estimates were derived using two algorithms, the standard NASA OC4v4 algorithm [23] and for comparison, an algorithm developed for U.S. southeast coastal waters [Stumpf algorithm; 24]. MODIS Chl was derived using the standard NASA OC3m algorithm [23] and the Stumpf algorithm [24].

Following the NIR atmospheric correction, both SeaWiFS and MODIS $a_{p}(\lambda)$ (pure water subtracted) and $b_{b}(555)$ are calculated from the $R_{rs}$ spectra. We compare three bio-optical algorithms, one we refer to as the Arnone algorithm, the Quasi-Analytical Algorithm (QAA; [5]), and the Garver/Siegel/Maritorena model (GSM01; [6]).

The Arnone algorithm uses the basic equation

$$R_{rs}(\lambda) = C(\lambda) \cdot b_{b}(\lambda) / a(\lambda),$$  \hspace{1cm} (4)

with $C$ assumed constant and equal to 0.051, as in Sydor and Arnone [25]. First, spectral $b_{b}(\lambda)$ is calculated. For coastal waters, where we assume $R_{rs}(670)$ exceeds a threshold value of 0.0003 sr$^{-1}$, we solve Eq. (4) for $b_{b}$:

$$b_{b}(670) = R_{rs}(670) \cdot a_{w}(670) / 0.051,$$  \hspace{1cm} (5)

where $a_{w}$ is a known value for pure water absorption [26]. Spectral $b_{b}(\lambda)$ is then calculated following Gould et al. [27]. For offshore waters [$R_{rs}(670) < 0.0003$], $b_{b}(\lambda)$ is calculated from Chl [28]. Finally, for both coastal and offshore waters, $a(\lambda)$ is calculated from Eq. (4), knowing $R_{rs}(\lambda)$ and $b_{b}(\lambda)$. Refer to Lee et al. [5] and Maritorena et al. [6] for details of the QAA and GSM01 algorithms.

### 4. Results and discussion

#### 4.1 Remote sensing reflectance ($R_{rs}$)

Remote sensing reflectance measured from satellites agreed well with ship measurements; comparisons between satellite and mooring were somewhat weaker. The blue waveband (412 nm) showed the largest differences (>100% error; Fig. 3 and Table 1). To better understand the source of the errors, we reprocessed the 1 August SeaWiFS scene with the 412-iteration for absorbing aerosols turned off (results not shown). Without the iteration, many coastal pixels have negative $R_{rs}$ values at 412 nm, and values at 443, 490, 510, and 555 nm are also obviously too low when compared to in situ $R_{rs}$. The 412-iteration algorithm does a good job increasing the satellite $R_{rs}$ values to more closely match the in situ values, particularly at 490, 510, and 555 nm, but it also seems to over-correct the $R_{rs}$ values at 412 nm, causing the $R_{rs}$
spectrum to “tail up” at this wavelength (Fig. 3, Table 1). Perhaps the algorithm requires some additional adjustment to improve retrievals at these blue wavelengths. Both SeaWiFS and MODIS \( R_m \) values were very close to \textit{in situ} values at the longer wavelengths, particularly in the blue-green to green wavebands (Table 1).

Table 1(a). Linear regression results for comparisons between satellite-derived (SeaWiFS and MODIS) and \textit{in situ} measured (mooring and ship measurements) \( R_m \).

|        | \( R^2 \) | Slope | y-intercept |
|--------|----------|-------|-------------|
| Mooring vs. SeaWiFS | 0.76     | 0.55  | 0.002       |
| ASD vs. SeaWiFS     | 0.80     | 1.01  | 0.0006      |
| Mooring vs. MODIS   | 0.78     | 0.50  | 0.001       |
| ASD vs. MODIS       | 0.66     | 0.78  | 0.001       |

Table 1(b). Average relative error (%) between satellite-derived and \textit{in situ} measured \( R_m \).

\[
\text{Rel err} \% = \frac{100 \times (R_m \text{ satellite} - R_m \text{ in situ})}{R_m \text{ in situ}} \quad \text{and} \quad \text{Avg rel err} \% = \frac{\sum \text{Rel err} \%}{n}
\]

| nm   | 412 /490 | 443   | 488 /510 | 531 /555 | 667 /670 | 678   |
|------|----------|-------|----------|----------|----------|-------|
| Mooring vs. SeaWiFS | 255.5    | 104.3 | 6.6      | -8.2     | -18.8   | 33.4  |
| ASD vs. SeaWiFS    | 37.3     | 19.5  | 0.1      | -6.8     | -8.7    | -26.9 |
| Mooring vs. MODIS  | 398.7    | 203.8 | 3.03     | -20.7    | -25.2   | 64.16 |
| ASD vs. MODIS      | 111.1    | 65.0  | 1.0      | -1.7     | -8.9    | -12.2 |
|                  |          |       |          |          |         | -19.6 |
Fig. 3. Mooring-measured $R_{\text{rs}}$ (solid blue lines with filled circles) compared with (a) and (b) SeaWiFS-derived (dashed red lines with triangles) $R_{\text{rs}}$ on 16 July and 31 July 2001, respectively; and (c) and (d) MODIS-derived (dashed pink lines with squares) $R_{\text{rs}}$ on 14 July and 21 July 2001, respectively. Ship-measured $R_{\text{rs}}$ (solid blue line with open circles) is compared with SeaWiFS- and MODIS-derived $R_{\text{rs}}$ on 31 July 2001 at (e) Station 5 and (f) Station 6 (see Fig. 2 for station locations). Note the issues with the satellite atmospheric correction factors.

Some of the mooring discrepancies can be attributed to in situ measurement errors. Chang et al. [29] compared $L_w(\lambda)$ measured by two different in situ techniques (hyperspectral tethered spectral radiometric buoy and profiled spectroradiometer; n = 53) and found average percent differences of 26%, 13%, and 17% for the blue (400-500 nm), green (500-625 nm), and red (625-700 nm) wavelengths. Radiance mooring measurement uncertainties are mainly attributed to changes in the distance between the sea surface and the mooring depth of the $L_u(\lambda,z)$ sensor. Chang et al. [29] show that a 5 (10) cm change in depth of the $L_u(\lambda,z)$ sensor could cause inconsistencies in $L_u(\lambda,z)$ of up to 14.4% (17.6%), 21.7% (22.3%), and 12.6% (14.8%) in the blue, green, and red wavelengths. Other lesser measurement uncertainties are credited to below-to-above surface extrapolation, sensor tilt, self-shading, instrument calibrations, and wavelength shifts caused by temperature variations.

Differences in measurement times between in situ collection times and satellite overpasses can contribute to disagreements between methods (maximum time difference was roughly half an hour). For example, mooring measurements were made once per hour on the hour whereas satellites passed over the mooring site at a particular time of day, e.g., on 21 July...
2001, the SeaWiFS image was collected at 13:24 EDT at the LEO-15 site. To assess the possible errors associated with differing measurement times, we employed the radiative transfer model, Hydrolight 4.1[14]. Rrs was computed for 13:00, 13:15, 13:30, 13:45, and 14:00 EDT assuming constant IOPs and Chl, wind speed of 5 m s⁻¹, 0% cloud cover, and optically deep waters. Solar angle was varied according to the time of day. Results show that a 30 (60) minute time difference can lead to 3% (4%) discrepancies with changes in solar angle.

We also evaluated Rrs for variable solar angle, IOPs, and Chl. Variations in IOPs and Chl can be attributed to temporal and/or spatial changes. The maximum hourly changes found in the 2001 Chl time series was 1.8 μg l⁻¹. For Hydrolight simulations, we assumed lower Chl and absorption (1.8 μg l⁻¹; 0.56 m⁻¹ at 412 nm) at 13:00 EDT and higher Chl and absorption at 14:00 EDT (3.6 μg l⁻¹; 0.81 m⁻¹ at 412 nm). Differences between Rrs at 13:00 and 14:00 EDT were -42%, -50%, -52%, -45%, -33%, and 9% for SeaWiFS wavelengths of 412, 443, 490, 510, 555, and 670 nm. Therefore, high temporal and spatial variability in IOPs and Chl can account for much of the observed discrepancies between satellite and in situ measured Rrs.

4.2 Chlorophyll concentration and inherent optical properties

The issues associated with high spatial variability, i.e., comparing a satellite pixel to in situ point measurements, are apparent in the comparisons of Chl derived from MODIS and measured in situ (Fig. 4 and Table 2). The MODIS-derived Chl is much greater in magnitude on 14 July 2001, when filaments of high Chl extended from the New Jersey coast, likely caused by local upwelling and advection [Fig. 4(a)]. These filaments are highly spatially (horizontally and vertically) variable and although mooring measurements indicate an increase in Chl during the time period of the filaments, the mooring values were not as high as the MODIS Chl estimates.

In general, though, the satellite Chl estimates derived using the standard NASA algorithms (OC4v4 for SeaWiFS and OC3m for MODIS) are quite good, within 20%, for ship-based filter pad measurements (both fluorometric and HPLC) for both sensors (Table 2). The shipboard errors are less than or near the 35% target accuracy level suggested by NASA [30]. The Chl estimates using the Stumpf algorithm (which was developed for a different region, the South Atlantic Bight and Gulf of Mexico) show larger errors (on the order of 50%) for both SeaWiFS and MODIS, when compared to the ship-based filter pad measurements. In comparison with the mooring Chl values, however, the Stumpf algorithm yielded much lower errors (0.5-21%) than the standard NASA OC4v4 and OC3m algorithms (70-110%). Recall that Rrs errors were larger for the mooring comparisons (Table 1), so the lower Chl errors for the Stumpf algorithm there may be a fortuitous result of the incorrect Rrs values at the blue wavelengths. Recent re-evaluation suggests that the actual global error in retrieved Chl values may even be closer to 50% [31], so our coastal estimates are quite reasonable. Other recent coastal Chl comparisons for SeaWiFS in Chesapeake Bay showed differences on the order of 100% between satellite and measured values [32]. In that case, satellite values overestimated the in situ values, and the authors suggested that strong absorption by CDOM and non-pigmented particulate matter, as well as remaining errors in the satellite-derived radiances were the reasons for the differences. In our analyses, the satellite images were processed with both the NIR- and 412-iteration techniques, whereas the Harding et al. [32] imagery was processed with only the NIR-iteration. So, even though the 412-iteration algorithm to account for absorbing aerosols still has some problems (“tail-up” of the Rrs spectra at blue wavelengths as discussed earlier) and might require additional modifications, it does seem to dramatically improve Chl retrievals in this region off coastal New Jersey.
Satellite-derived $a_{\text{app}}(\lambda)$ are consistently underestimated throughout the time series except a few comparisons at 440 nm (443 nm) using the GSM01 algorithm (Fig. 5 and Table 3). To some extent, the consistent underestimation is certainly related to the overestimate of the $R_\infty$ values at 412 nm due to the 412-iteration discussed earlier. Ladner et al. [33] compared
satellite-derived optical properties to in situ measurements in four different regions. They also found that the satellite values were generally lower than the in situ measurements, with errors (about 30-70%) comparable to what we report here, with some regional dependence. Based on the relative errors, the GSM01 algorithm performed the best, at all wavelengths for both SeaWiFS and MODIS.

Backscattering estimated from SeaWiFS was on average 19% higher than that measured in situ (Fig. 6; no coincident measurements with MODIS). Based on the model of Gould et al. [27] for the spectral shape of the scattering coefficient, and assuming that b and b' have roughly a similar spectral shape (not necessarily true), then we could expect the SeaWiFS-derived b at 555 nm to be approximately 4% higher than the HydroScat-measured b at 589 nm, based on just the wavelength difference (34 nm) between the two sensors. The temporal variability of SeaWiFS-derived IOPs (at wavelengths greater than 412 nm) is comparable to that of in situ values whereas temporal variability of MODIS-derived absorption does not match the trend of the in situ absorption coefficient. This is likely due to satellite pixel sizes and high horizontal spatial variability.

Although likely not as large as horizontal variability, differences in the depths of measurements contributed to discrepancies observed between satellite and in situ quantities. Chlorophyll fluorometers, ac-9s, and the HydroScat-6 were mounted at 5 m depth on the mooring whereas ocean color imagers provide surface measurements (a weighted-integral over one optical depth). Thus, the clearer the water, the greater the penetration of light and the deeper the satellite will see. For example, for water with a diffuse attenuation coefficient for downwelling irradiance (Kd) of 0.3 m⁻¹ at 532 nm [the actual Kd(532) at the mooring location on 1 August], the satellite will “see” to approximately 3.3m (1/Kd). So, the penetration depth of the satellite is shallower than the depth of the mooring; the satellite-retrieved optical properties will differ from the mooring measurements if the mixed layer is shallower than the depth of the mooring.

|                | R²  | Slope | y-intercept | 412 nm | 440 nm | 488 nm | 510 nm | 532 nm | 555 nm |
|----------------|-----|-------|-------------|--------|--------|--------|--------|--------|--------|
| Mooring vs. SeaWiFS |     |       |             |        |        |        |        |        |        |
| Arnone         | 0.90| 0.27  | 0.04        | -69.4  | -65.1  | -55.1  | -51.5  | -58.3  |
| GSM01          | 0.79| 0.57  | 0.002       | -52.6  | -22.6  | -50.4  | -42.9  | -46.8  |
| QAA            | 0.95| 0.36  | 0.02        | -62.7  | -60.7  | -52.5  | -51.4  | -65.6  |
| Mooring vs. MODIS |     |       |             |        |        |        |        |        |        |
| Arnone         | 0.82| 0.28  | 0.06        | -67.1  | -62.5  | -42.0  | -48.7  | -48.6  |
| GSM01          | 0.79| 0.62  | 0.02        | -48.9  | -14.6  | -41.8  | -34.7  | -35.4  |
| QAA            | 0.91| 0.34  | 0.02        | -65.4  | -63.7  | -49.5  | -60.4  | -64.4  |

+ = SeaWiFS wavelengths
- = MODIS wavelengths

Table 3. Linear regression results and average relative error (%) between satellite-derived (SeaWiFS and MODIS) and in situ measured (mooring and ship measurements) total minus water absorption coefficient, aₚ(λ).
Fig. 5. Time series of in situ mooring (solid blue lines and filled circles), and SeaWiFS- (open symbols) and MODIS-derived (filled symbols) $a_p$ at (a) 412 nm, (b) 440 nm (443 nm for SeaWiFS and MODIS) nm, (c) 488 nm (490 nm for SeaWiFS), and (d) 555 nm (551 nm for MODIS) wavelengths. In situ mooring (solid blue lines with filled circles) and (e) SeaWiFS-derived spectral absorption on 30 June 2001, and (f) MODIS-derived spectral absorption on 5 July 2001. Derivations using the Arnone, GSM01, and QAA algorithms are shown as green (SeaWiFS) and pink (MODIS) triangles, black (SeaWiFS) and orange (MODIS) diamonds, and red (SeaWiFS) and cyan (MODIS) squares.
5. Conclusions

We provide ground-truth measurements for two ocean color sensors, SeaWiFS and MODIS, at the HyCODE site off coastal New Jersey between 19 June and 6 August 2001. Comparisons are made between satellite and in situ remote sensing reflectance, chlorophyll concentration, spectral absorption coefficient, and backscattering coefficient, using multiple bio-optical algorithms. Discrepancies in \( R_a \) are attributed to inadequacies in the atmospheric correction for absorbing aerosols (blue wavelengths only) and changes in depths of the in situ mooring radiometers due to sea surface variations. High spatial and temporal variability of bio-optical properties coupled with differences in measurement techniques (pixel versus point) contribute to inconsistencies between remotely sensed and in situ Chl, \( a_{pg} (\lambda) \), and \( b_b(555) \).

For mooring/shipboard comparisons, we observed mean relative errors of 70.5%/-3.8% (SeaWiFS OC4v4), -21.4%/-49.3% (SeaWiFS Stumpf), 109.5%/13.4% (MODIS OC3m) and 0.5%/-48.9% (MODIS Stumpf) for Chl. For comparisons between satellite-derived and mooring measurements of \( a_{pg}(412) \), we found mean relative errors of -69.4% (-67.1%), -52.6% (-48.9%), and -62.7% (-65.4%) for the Arnone, GSM, and QAA algorithms for SeaWiFS (MODIS), respectively. Mean relative errors of 21.3%, 19.9%, and 16.5% were found between SeaWiFS-derived (Arnone, GSM, and QAA algorithms, respectively) and moored \( b_b(555) \) measurements. The errors in coastal retrievals for chlorophyll meet the NASA accuracy goals and are lower than errors reported in other coastal areas. The errors in the optical properties are comparable to errors reported in the literature for other coastal areas.

Further improvements between satellite and in situ optical data comparisons can be made with mooring instrumentation mounted closer to the surface ocean and improved satellite atmospheric corrections, particularly in hazier coastal regions like the New Jersey coast. Although not cost-effective, a network of ground-truth moorings within a 1-km grid would greatly reduce errors associated with high spatial variability. Relative errors can be slightly reduced by matching mooring measurement times with satellite overpass times. As optical databases expand, algorithms for deriving Chl and IOPs from satellite data are continually being developed and improved. The effects of highly variable water column constituents (CDOM, organic and inorganic particles) on algorithm performance in complex coastal areas such as the LEO-15 site must be understood.

Remote sensors, although valuable for synoptic- and large-scale horizontal coverage, require continual calibration and validation with complementary in situ measurements. Cloud
cover unpredictably reduces data availability, resulting in sporadic measurements in time and space. Importantly, satellites are unable to resolve vertical variability in the ocean, although work linking satellite imagery with vertical profiles and numerical model results is underway [34,35]. In situ methods are invaluable for depth dependent processes and can provide continuous, time series at higher spatial resolution than remote sensors. However, in situ methods are often limited in space and cannot provide synoptic coverage, e.g., moorings provide data at a single point and ships cannot cover an ocean basin in less than one month’s time. This emphasizes the importance of collecting interdisciplinary data at multiple time and space (horizontal and vertical) scales.

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