Validation of SeaWiFS chlorophyll $a$ in Massachusetts Bay
Kimberly J.W. Hyde$^{a,\ast}$, John E. O'Reilly$^a$, Candace A. Oviatt$^b$

$^a$NOAA, National Marine Fisheries Service, 28 Tarzwell Drive, Narragansett, RI 02886, USA
$^b$Graduate School of Oceanography, University of Rhode Island, South Ferry Road, Narragansett, RI 02886, USA

Received 10 August 2006; received in revised form 25 January 2007; accepted 5 February 2007
Available online 28 February 2007

Abstract

Massachusetts Bay, a semi-enclosed embayment ($50 \times 100$ km) in the Northwest Atlantic, is the focus of a monitoring program designed to measure the effects of relocating the Boston Harbor sewage outfall to a site 15 km offshore in Massachusetts Bay. The Massachusetts Water Resources Authority (MWRA) in situ monitoring program samples selected stations up to 17 times per year to observe seasonal changes in phytoplankton biomass and other water quality variables. We investigated the feasibility of augmenting the monitoring data with satellite ocean color data to increase the spatial and temporal resolution of quantitative phytoplankton measurements. In coastal regions such as Massachusetts Bay, ocean color remote sensing can be complicated by in-water constituents whose concentrations vary independently of phytoplankton and by inaccurate modeling of absorbing aerosols that tend to be concentrated near the coast. An evaluation of in situ and sea-viewing wide field-of-view sensor (SeaWiFS) measurements from 1998 to 2005 demonstrated that SeaWiFS overestimated chlorophyll $a$ mainly due to atmospheric correction errors that were amplified by absorption from elevated concentrations of chlorophyll $a$ and colored dissolved organic matter. Negative water-leaving radiances in the 412 nm band, an obvious artifact of inadequate atmospheric correction, were recorded in approximately 60–80% of the cloud-free images along the coast, while the remaining portions of the Bay only experience negative radiances 35–55% of the time with a clear nearshore to offshore decrease in frequency. Seasonally, the greatest occurrences of negative 412 nm radiances were in November and December and the lowest were recorded during the summer months. Concentrations of suspended solids in Massachusetts Bay were low compared with other coastal regions and did not have a significant impact on SeaWiFS chlorophyll $a$ measurements. A regional empirical algorithm was developed to correct the SeaWiFS data to agree with in situ observations. Monthly SeaWiFS composites illustrated the spatial extent of a bimodal seasonal pattern, including prominent spring and fall phytoplankton blooms; and the approximate 115 cloud-free scenes per year revealed interannual variations in the timing, magnitude and duration of phytoplankton blooms. Despite known artifacts of SeaWiFS in coastal regions, this study provided a viable chlorophyll $a$ product in Massachusetts Bay that significantly increased the spatial and temporal synoptic coverage of phytoplankton biomass, which can be used to gain a comprehensive ecosystem-wide understanding of phytoplankton dynamics at event, seasonal and interannual timescales. © 2007 Elsevier Ltd. All rights reserved.

Keywords: Ocean color remote sensing; Phytoplankton; Chlorophyll algorithm; SeaWiFS; Coastal remote sensing; Massachusetts Bay

1. Introduction

Coastal and estuarine ecosystems typically exhibit high temporal and spatial variability in
phytoplankton biomass that is often too difficult to characterize with a limited set of in situ shipboard measurements. Continuous monitoring of spatial and seasonal patterns of near-surface phytoplankton concentrations can only realistically be achieved by ocean color remote sensing which provides synoptic spatial and temporal chlorophyll a data not attainable by in situ sampling (Morel and Berthon, 1989; O’Reilly et al., 1998; Thomas et al., 2003; Harding et al., 2005). However, ocean color remote sensing in continental shelf and coastal regions such as Massachusetts Bay can be complicated by constituents in the water whose concentrations vary independently of phytoplankton abundance and by absorbing aerosols that tend to be concentrated near the coast (IOCCG, 2000; O’Reilly and Yoder, 2003; Schollaert et al., 2003).

The sea-viewing wide field-of-view sensor (SeaWiFS) on board the OrbView-2 spacecraft was specifically designed to estimate the phytoplankton pigment concentration in the oceans. It has been operational since September, 1997 and has provided global estimates of oceanic chlorophyll a and other bio-optical data that have increased the understanding of temporal variability of marine ecosystems and the role of oceanic photosynthesis and primary productivity in the Earth’s carbon budget and climate (Falkowski et al., 1998). SeaWiFS was designed to measure chlorophyll a concentrations in clear-water (Case 1) regions in the range of 0.01–64 mg m\(^{-3}\) to within 35% (Hooker and McClain, 2000; Lavender et al., 2004). Coastal regions and lakes often have more complex bio-optical properties compared to the open ocean and are thus classified as “Case 2” waters. Bio-optical complexity and inaccurate atmospheric modeling have created three challenges to ocean color remote sensing in coastal regions: (1) interference of the chlorophyll signal due to increased concentrations of optical constituents in the water that vary independently of phytoplankton biomass (Morel and Prieur, 1977; IOCCG, 2000); (2) failure of the atmospheric correction model due to increased turbidity in the water (Wang, 2000); and (3) failure of the atmospheric correction model due to absorbing aerosols in the atmosphere (O’Reilly and Yoder, 2003; Schollaert et al., 2003; Stumpf et al., 2003).

The overall impact of absorbing aerosols and additional in-water bio-optical constituents, such as colored dissolved organic matter (CDOM, also called gelbstoff, yellow substances, or gilvin) and total suspended solids or particulate matter (TSS), is to decrease the reflectance band ratio (\(R_{\text{max}}\)) used in the current SeaWiFS ocean chlorophyll 4 algorithm (OC4). This decrease of \(R_{\text{max}}\) ultimately causes an overestimation of chlorophyll a concentrations. OC4 is a modified cubic polynomial relating the ratio of the reflectance in the blue (wavelength = 443, 490 or 510 nm) and green (wavelength = 555 nm) bands to the chlorophyll a concentration:

\[
\text{Chl } a = 10.0^{0.366 - 3.067 \text{log} R_{\text{max}} + 1.930 \text{log}^2 R_{\text{max}} + 0.649 \text{log}^3 R_{\text{max}} - 1.532 R_{\text{max}}}, \tag{1a}
\]

where Chl a is the chlorophyll a concentration and \(R_{\text{max}}\) is the maximum band ratio determined in Eq. (1b) from the remote sensing reflectance (\(R_{\text{RS}}\)) ratios at the given wavelengths (O’Reilly et al., 1998, 2000).

\[
R_{\text{max}} = \log_{10} \left( \frac{R_{\text{RS}443}}{R_{\text{RS}555}} > \frac{R_{\text{RS}490}}{R_{\text{RS}555}} > \frac{R_{\text{RS}510}}{R_{\text{RS}555}} \right). \tag{1b}
\]

The maximum reflectance band ratio changes as a function of chlorophyll a concentration, where \(R_{\text{RS}443}/R_{\text{RS}555}\) is maximal from 0 to \(\sim 0.3 \text{ mg m}^{-3}\); \(R_{\text{RS}490}/R_{\text{RS}555}\) commonly dominates at chlorophyll a concentrations between 0.3 and \(\sim 1.5 \text{ mg m}^{-3}\); and when concentrations exceed \(\sim 1.5 \text{ mg m}^{-3}\), the \(R_{\text{RS}510}/R_{\text{RS}555}\) ratio is greatest (O’Reilly et al., 1998). Dissolved and suspended matter in productive and turbid coastal waters increase both absorption and scattering of light and influences the optical signal received by the satellite sensor (Morel and Prieur, 1977; IOCCG, 2000). Inaccurate modeling of aerosols during the atmospheric correction process will lower the remotely sensed reflectance ratio because more light at the top of the atmosphere (TOA) is attributed to the atmosphere, resulting in increased water-leaving radiances with increasing severity in the lower wavelengths (Gordon et al., 1997; O’Reilly and Yoder, 2003; Schollaert et al., 2003; Stumpf et al., 2003). In coastal waters this may cause negative water-leaving radiances in the blue bands and result in errors in the calculation of chlorophyll a (Stumpf et al., 2003). One advantage of using the OC4 algorithm is that at the higher concentrations of chlorophyll a expected in Massachusetts Bay the predominant \(R_{\text{max}}\) ratio of 510/555 is less affected by atmospheric correction errors due to absorbing aerosols (O’Reilly et al., 1998; Harding et al., 2005).

\[
C_{\text{RS}} = \frac{1}{R_{\text{RS}555}} \left( \frac{R_{\text{RS}490}}{R_{\text{RS}555}} > \frac{R_{\text{RS}510}}{R_{\text{RS}555}} \right).
\]

\[
C_{\text{C18/C19}} = \frac{1}{R_{\text{RS}555}} \left( \frac{R_{\text{RS}510}}{R_{\text{RS}555}} > \frac{R_{\text{RS}443}}{R_{\text{RS}555}} \right).
\]

\[
C_{\text{18/C19}} = \frac{1}{R_{\text{RS}555}} \left( \frac{R_{\text{RS}510}}{R_{\text{RS}555}} > \frac{R_{\text{RS}443}}{R_{\text{RS}555}} \right).
\]
Despite these known limitations in coastal remote sensing, numerous researchers have developed regional algorithms and models to estimate phytoplankton pigments as well as suspended particulate and color dissolved organic matter concentrations in coastal regions such as: the Bay of Biscay (Froidefond et al., 2002; Lavender et al., 2004), the Baltic Sea (Ohde et al., 2002; Darecki et al., 2003; Kowalczuk et al., 2005), coastal Ireland (Mitchelson et al., 1986; Darecki et al., 2003), the White Sea (Pozdnyakov et al., 2003), the Gulf of Naples (Tassan, 1994) and the Eastern Arabian Sea (Desa et al., 2001). In addition, refinements and improvements to the atmospheric correction process in the fourth and fifth SeaWiFS reprocessing yielded a reduction in the frequency of pixels with negative water-leaving radiances in the blue wavelength bands and have increased the accuracy of SeaWiFS in coastal regions (O’Reilly and Yoder, 2003).

The SeaWiFS sensor can be expected to provide up to 100 relatively cloud-free scenes per year in the Northwest Atlantic (Harding et al., 2005) and supplement the Massachusetts Water Resources Authority (MWRA) efforts to capture the seasonal fluctuations of phytoplankton biomass. The current SeaWiFS algorithm, OC4, is presumed to overestimate chlorophyll \( a \) concentrations in Massachusetts Bay; however, a thorough evaluation with an extensive dataset has not been performed. The objective of this study is to validate SeaWiFS chlorophyll \( a \) in Massachusetts Bay and to evaluate the impact of suspended solids and atmospheric correction errors to determine under what conditions SeaWiFS measurements are less accurate for the Massachusetts Bay region.

### 2. Methods

Massachusetts and Cape Cod Bays and the adjacent Boston Harbor are the locations of an intensive study conducted by the MWRA designed to assess the effects of relocating the Deer Island Water Treatment Plant sewage effluent discharge from the original discharge site in Boston Harbor to a location 15 km offshore in the Massachusetts Bay. Assessment of the existing conditions began in 1992, and continued monitoring is designed to study the impacts of the new outfall, which began discharging on September 6, 2000 (Albro et al., 1998; Libby et al., 2002). Monitoring data at 15 stations collected between 1998 and 2005 coincides with the first eight full years of SeaWiFS and were used to validate SeaWiFS products in Massachusetts Bay (Fig. 1).

#### 2.1. In situ measurements

Duplicate 25–400 mL chlorophyll \( a \) samples were vacuum-filtered on glass fiber filters (Whatman 47 mm-diameter GF/F filters). Two drops of a saturated solution of magnesium carbonate (MgCO\(_3\)) was added during filtration and the samples were frozen until analysis. Pigment samples were extracted by mechanical grinding followed by a 2–24 h steep in 90% acetone at \( 20^\circ C \). Samples collected in 2003 were extracted by soaking whole filters in 90% buffered acetone for 24 h prior to analysis. The extract was centrifuged and analyzed using a Turner Designs Fluorometer (Yentsch and Menzel, 1963; Arar and Collins, 1997). Laboratory calibration errors and degraded standards caused inaccurate chlorophyll \( a \) calculations of samples collected from 1998 to 2000 and in February and March 2003. Samples were accordingly corrected and qualified “use with caution” (Libby et al., 2001), however no significant difference was found if the data were eliminated from the SeaWiFS comparison analysis.

Total suspended solids were measured by vacuum filtering duplicate 300 mL aliquots of whole water samples through tared 0.4 \( \mu m \) pore size Nuclepore 47 mm-diameter membrane filters. Filters were dried in a desiccator for a minimum of 7 days, and then weighed using an ATI CAHN Model C-44 Top loading microbalance (Albro et al., 1998; Libby et al., 2002).

#### 2.2. Optically-weighted chlorophyll \( a \) concentration

For remote sensing purposes, the penetration depth of light in the sea is defined as the depth above which 90% of diffusely reflected irradiance originates (Gordon and McCluney, 1975). The penetration depth \( (Z_{90}) \) is less than 25% of the thickness of the euphotic depth \( (Z_{eu}) \), thus the pigment concentration estimated by the satellite sensor is not the concentration within the euphotic depth, but rather the concentration within the penetration depth. During the summer stratified
season, the subsurface chlorophyll maximum typically occurs within the euphotic zone, but below the penetration depth and may be partially or completely invisible to a remote sensor (Sathyendranath and Platt, 1989; Ballestero, 1999). To estimate the in situ chlorophyll concentration observed by the satellite, in situ chlorophyll a concentrations were optically-weighted to the penetration depth (Eq. (2)) (Gordon and Clark, 1980)

\[
\text{Chl}_{\text{wt}} = \frac{\int_0^\infty \text{Chl}(z)f(z)\,dz}{\int_0^\infty f(z)\,dz},
\]

where \(\text{Chl}_{\text{wt}}\) is the optically-weighted chlorophyll a concentration (mg m\(^{-3}\)), Chl (z) is the chlorophyll a concentration at depth z and \(f(z)\) is given by

\[
f(z) = \exp\left(-2 \int_0^z k_d(z')\,dz'\right),
\]

where \(k_d(z)\) is the attenuation coefficient for the penetration depth.

2.3. Satellite-derived observations

Individual daily merged local area coverage (MLAC) SeaWiFS images of the Northwest

Fig. 1. Location of the MWRA stations where chlorophyll a samples were collected. Data obtained from the Office of Geographic and Environmental Information (MassGIS), Commonwealth of Massachusetts Executive Office of Environmental Affairs (http://www.mass.gov/mgis/massgis.htm).
Atlantic were mapped at 1 km pixel resolution for the Massachusetts Bay coast using a Lambert conic conformal map projection. SeaWiFS MLAC consolidates all available LAC from a single orbit and overlapping scenes from multiple HRPT (high resolution picture transmission) stations are evaluated to select a single “best quality” scan and increase the signal to noise ratio. Chlorophyll $a$ was derived using SeaWiFS version 5.1 standard processing. Using the coordinates for each in situ sampling station, a $5 \times 5$ array of pixels was extracted from the images taken on the same day of the in situ chlorophyll $a$ sampling. 64% of the images were collected within 3 h of in situ sampling and 95% were within 5 h. The geometric means of chlorophyll $a$ arrays with eleven or more (40%) cloud-free pixels were calculated and compared to in situ chlorophyll $a$ samples. The geometric mean is the arithmetic average of the log-transformed data that is then untransformed. The geometric mean was selected rather than the arithmetic mean because chlorophyll $a$ concentrations are commonly log-normally distributed and the geometric mean has the advantage of reducing the influence of a small number of high or low values (outliers) on the mean (Campbell, 1995; Bricaud et al., 2002; Yoder et al., 2002; Yoder and Kennelly, 2003).

2.4. Environmental data

The Charles and Merrimack Rivers are the two principal freshwater sources influencing Massachusetts Bay. Daily stream flow records and long-term means were obtained from the United States Geological Survey for both rivers (http://waterdata.usgs.gov/nwis). The water gage for the Charles River is located on the Moody Street Bridge in Waltham, Massachusetts and the Merrimack gage is 335 m downstream of the Concord River in Lowell, Massachusetts. Daily precipitation is measured at locations in Middlesex County (42.3839—latitude, $-71.2147$—longitude) and Barnstable County (41.9758—latitude, $-70.0247$—longitude) by the National Atmospheric Deposition Program/National Trends Network (http://nadp.sws.uiuc.edu/).

3. Results and discussion

3.1. Chlorophyll $a$

In situ chlorophyll $a$ concentrations in Massachusetts Bay between January 1998 and December 2005 were log-normally distributed. The geometric mean of the in situ concentration for all depths sampled ($n = 6773$) was $1.5 \text{ mg m}^{-3}$. The minimum and maximum concentrations were 0.003–44 mg m$^{-3}$, respectively; however 98% of the chlorophyll $a$ measurements ranged from 0.11 to 13 mg m$^{-3}$ (Fig. 2). The shallowest chlorophyll $a$ sample for each profile was, on average, collected at 2 m below the surface and never greater than 4 m. In comparison, the penetration depth, or rather the maximum depth observed by the satellite sensor, ranged from 1 to greater than 15 m (mean $= 4.3 \text{ m}$), indicating that the shallowest measurement may not always be the best representation of the in situ chlorophyll $a$ concentration observed by the satellite sensor due to the possible presence of a sub-surface chlorophyll maximum.

Approximately three-quarters (73%) of the in situ profiles had a subsurface maximum chlorophyll $a$ concentration at an average depth of 15 m. However, the ratio between the maximum and the surface concentration was less than 1.5 in more than 50% of the subsurface chlorophyll maximum profiles. Furthermore, the mean concentrations of both the surface and optically-weighted penetration depth chlorophyll $a$ were similar (1.9 mg m$^{-3}$), yet slightly higher than the mean for all depths. Similarly, there was a strong relationship between the surface and optically-weighted chlorophyll $a$ concentrations (intercept = 0.009, slope = 0.986, $r^2 = 0.999$), suggesting that the weighted estimate was rarely influenced by a subsurface chlorophyll maximum. Despite the close relationship between the surface and optically-weighted chlorophyll $a$ concentrations, the optically-weighted value was...
used for all comparisons to SeaWiFS chlorophyll a in order to represent best the concentrations measured by the satellite sensor. Further references to in situ chlorophyll a refer to the optically-weighted chlorophyll a concentration.

There were over 400 match-ups between in situ samples and cloud-free SeaWiFS images taken within 12 h of the sample time from 1998 to 2005. The geometric mean SeaWiFS chlorophyll a concentration of the match-ups was 3.11 mg m\(^{-3}\) and was greater than the corresponding in situ mean concentration of 2.02 mg m\(^{-3}\). The SeaWiFS match-ups were compared to the optically-weighted in situ chlorophyll a concentration and statistically evaluated using a Type II reduced major axis linear regression (Laws and Archie, 1981; Press and Teukolsky, 1992) of the log\(_{10}\)-transformed data (Fig. 3). The match-up analysis showed a positive relationship between the SeaWiFS and in situ chlorophyll a, however SeaWiFS clearly overestimated chlorophyll a in Massachusetts Bay at lower concentrations (Fig. 3).

### 3.2. Possible sources of error

The SeaWiFS chlorophyll a match-up results were similar to those observed by Harding et al. (2005) who demonstrated that SeaWiFS overestimates chlorophyll a in Chesapeake Bay and the Mid Atlantic Bight due to in-water optical constituents and atmospheric correction errors. Overestimation errors in Chesapeake Bay decreased along the salinity gradient as the distance increased from the Susquehanna River, which is a large source of suspended solids and CDOM (Harding et al., 2005). Suspended solids, as well as terrigenous CDOM, are transported to coastal regions by riverine inputs. Unlike Chesapeake Bay, there are no major rivers directly discharging into Massachusetts Bay, but rather two indirect freshwater sources. The Gulf of Maine Rivers, dominated by the Merimack River, discharge roughly 1100 m\(^3\) s\(^{-1}\) and merge with the Gulf of Maine Coastal Current. The current flows south along the Maine and New Hampshire coasts and branches at Cape Ann, north of Massachusetts Bay. Much of the flow follows the topography southward past Stellwagen Bank and to the east of Cape Cod, however a weaker branch does enter Massachusetts Bay (Signell et al., 2000). Boston Harbor, fed by the Charles and other rivers, is a more localized freshwater source discharging approximately 41 m\(^3\) s\(^{-1}\), half of which was supplied by sewage outfalls prior to the relocation of the MWRA outfall on September 6, 2000 (Signell et al., 2000). Boston Harbor also acts as a long-term sink for fine grain sediments because of its restricted flushing and low-wave energy environment (Butman et al., 2002). As a result of the indirect nature of the freshwater inputs, surface suspended solid concentrations in Massachusetts Bay were low (mean=0.98 mg L\(^{-1}\), max = 4.8 mg L\(^{-1}\), Fig. 4) compared to other coastal regions such as, the Santa Barbara Channel (0–200 mg L\(^{-1}\)) (Warrick et al., 2004), San Francisco Bay (5–30 mg L\(^{-1}\)) (Cloern et al., 1989), East China Sea (100–1000 mg L\(^{-1}\)) (Deng and Li, 2003), and the northern Gulf of Mexico along the Louisiana coast (100–400 mg L\(^{-1}\)) (Myint and
There were only 32 SeaWiFS in situ match-ups when suspended solid concentrations were greater than 2 mg L\(^{-1}\) (Fig. 5). A Student’s \(t\)-statistic (Zar, 1999) of the slope and intercept showed no significant difference in the SeaWiFS to in situ chlorophyll \(a\) regression when the high TSS samples (>2 mg L\(^{-1}\)) were removed.

When concentrations of chlorophyll \(a\) and CDOM are high, water-leaving radiances \(L_{\text{wn}}\) in the 412 nm band approach zero and may even be slightly negative because of greater absorption of blue wavelengths by the in-water constituents. The mean \(L_{\text{wn}}\) (412) for the Massachusetts Bay region was 0.153 \((n = 8488\) images\), however 23% of the measured radiances were \(\leq 0\) (Fig. 6). Negative \(L_{\text{wn}}\) in the 412 nm band are also an indication of inaccurate SeaWiFS atmospheric correction because they occur when too much of the TOA signal is attributed to the atmosphere, due to inaccurate aerosol modeling or failure of the black pixel assumption (O’Reilly and Yoder, 2003; Schollaert et al., 2003). Thus, when the atmospheric portion is subtracted from the TOA signal, the result is reduced or negative values from the water and an overestimation of chlorophyll \(a\). Along the Massachusetts Bay coast (depth less than 25 m and within 7 km of the shore), negative water-leaving radiances were recorded in approximately 60–80% of the cloud-free images from 1998 to 2005 (Fig. 7). The remaining portions of the Bay only experienced negative radiances 35–55% of the time with a clear nearshore to offshore decrease in the frequency of negative radiances. Monthly composites of the 8-year study period revealed that the highest occurrences of negative 412 nm radiances were in November and December, while the lowest frequencies were during the summer months (Fig. 7).

This seasonality of the negative radiances and atmospheric correction errors is most likely to be explained by a combination of inaccurate atmospheric correction modeling and the presence of blue wavelength absorbers in the water, such as phytoplankton and CDOM. Measurements of CDOM absorption were not available for this study, however it can be assumed that CDOM concentrations fluctuate as a function of chlorophyll \(a\) concentration and/or river runoff (IOCCG, 2000; Twardowski and Donaghy, 2001). The absence of a direct freshwater source into Massachusetts Bay suggests that concentrations of the allochthonous CDOM, which is conservative and covaries with freshwater input and salinity, will be lower than other coastal ecosystems with direct freshwater flow such as Chesapeake Bay. The nonconservative portion of CDOM is a by-product of phytoplankton production and for remote sensing purposes is assumed to linearly vary with chlorophyll \(a\) (Twardowski and Donaghy, 2001).

A joint probability distribution of the monthly SeaWiFS chlorophyll \(a\) and percent frequency of negative 412 nm radiances explains a majority of the observed seasonality. All months demonstrated a positive relationship between the percent frequency of negative radiances and chlorophyll \(a\).
Fig. 7. The percent frequency of 8488 images collected from 1998 to 2005, and the monthly percent frequency when the water-leaving radiance in the 412 nm band is negative. A negative 412 nm radiance is an indication of a failure of the atmospheric correction algorithm. The greatest percentage of negative radiances was recorded along the coast (up to 80%) and decreased offshore. The total number of images for January = 718, February = 659, March = 723, April = 710, May = 711, June = 702, July = 724, August = 721, September = 714, October = 730, November = 665 and December = 713.
concentrations. From April through December the coefficient of determination ($R^2$) was greater than $0.70$ (Fig. 8). November and December had moderate concentrations of chlorophyll $a$ (mean greater than $1.6 \text{ mg m}^{-3}$), yet higher than average negative frequencies, indicating that a combination
of in-water absorbers and high solar zenith angles (approximately 57–65.6°) yielded negative frequencies up to 70% in some portions of Massachusetts Bay. Conversely, the probability distribution was more dispersed in January, February and March, when chlorophyll \(a\) concentrations and river flow were relatively low and variable, and the solar zenith angle was near its seasonal maximum.

The use of SeaWiFS’s OC4 maximum band ratio algorithm does have an advantage in that it consistently selected the 510:555 nm ratio because the average chlorophyll \(a\) concentration in Massachusetts Bay was greater than 1.5 mg m\(^{-3}\), thereby reducing the overestimation by not using the lower wavelength radiances that are more adversely affected by atmospheric correction errors. For the 8-year study period \(n = 8488\) images, the 510:555 nm ratio dominated the maximum band ratio for more than 75% of the time in a majority of the Massachusetts Bay region (Fig. 9(a)). The dominant band ratio shifted to 490:555 nm further offshore (Fig. 9(b)) and the 443:555 nm ratio rarely dominated in the Massachusetts Bay region (Fig. 9(c)).

### 3.3. SeaWiFS chlorophyll \(a\) correction

There were no specific instances when external parameters such as suspended solids were able to account for the overestimation of chlorophyll \(a\) by SeaWiFS. However, a localized empirical correction algorithm, based on the type II linear regression, was developed to correct regionally SeaWiFS chlorophyll \(a\) in Massachusetts Bay (Eq. (3)). The standard SeaWiFS chlorophyll \(a\) product (SeaWiFS\(_{(\text{chlorophyll})}\)) was corrected (SeaWiFS\(_{\text{corrected}}\)) using the slope \(b = 0.832\) and intercept \(a = 0.248\) from Fig. 3.

\[
\text{SeaWiFS}_{\text{corrected}} = 10 \left( \frac{\log_{10} \text{SeaWiFS}_{\text{chlorophyll}} - 0.248}{0.832} \right)
\]

(3)

The algorithm adjusts the slope and intercept of the regression, however the \(R^2\) associated with the

![Fig. 9. The percent of 8488 images when the maximum band ratio selected for the OC4 chlorophyll \(a\) algorithm was (a) 510/555, (b) 490/555, and (c) 443/555.](image-url)
scatter does not change (Fig. 10). The high uncertainty was partially due to the mismatch in sampling size between the in situ (<1 m^2) and satellite (~25 km^2) measurements and the small-scale, high-frequency variability in phytoplankton biomass common in Massachusetts Bay. The overall impact of applying the correction algorithm was to reduce the overestimated SeaWiFS chlorophyll a to concentrations typically observed in Massachusetts Bay (Figs. 10 and 11). The geometric mean of the SeaWiFS images for the 426 match-ups decreased from 3.11 (original data) to 2.11 mg m^{-3} (corrected data), which is similar to the corresponding optically-weighted in situ mean (2.02 mg m^{-3}).

3.4. Seasonal and interannual variations of chlorophyll a in Massachusetts Bay

SeaWiFS increased the spatial and temporal resolution in Massachusetts Bay over the MWRA sampling regime and the combination of in situ and remotely sensed data allowed for a more accurate and comprehensive assessment of phytoplankton dynamics. Spatially, chlorophyll a concentrations were greater along the coast and in Cape Cod Bay and decreased with distance offshore (Fig. 11). In addition, there was a high degree of interannual variability. The lowest mean concentration measured by SeaWiFS at the MWRA stations (Fig. 1) was observed in 2004 (1.14 mg m^{-3}), while the highest annual concentration for the region was in 2000 (2.10 mg m^{-3}), followed by 1999 (1.98 mg m^{-3}) and 2005 (1.81 mg m^{-3}). Seasonally, the 8-year monthly means of phytoplankton biomass exhibited a bimodal pattern similar to the seasonal cycle described by Cura (1991), Thomas et al. (2003) and Oviatt et al. (2007) with peak spring concentrations in April and fall maxima in October and November (Fig. 12, Table 1).

The sampling frequency increased from approximately 125 in situ measurements to nearly 1000 SeaWiFS measurements at the scale of a single station for the 8-year study period. The enhanced sampling revealed significant interannual variability in the magnitude, duration and timing of spring and fall phytoplankton blooms that were unresolved with in situ sampling (Fig. 13). Based on the in situ data, the phytoplankton patterns in 1998 were characterized as atypical due to the absence of a winter–spring bloom (Keller et al., 2001; Oviatt et al., 2007). However, our results based on SeaWiFS showed that a phytoplankton bloom occurred in April 1998, but it was much lower in both intensity and duration, relative to the winter–spring blooms observed in 1999, 2000, 2002, 2004 and 2005 (Fig. 13). Several high intensity, short duration blooms occurred between in situ measurements and were observed by SeaWiFS including a fall bloom in September, 1998, and late spring/early summer blooms in June, 2000 and 2003 (Fig. 13).
In addition, the increased SeaWiFS resolution unmasked rapidly varying chlorophyll $a$ concentrations, which indicate that the spring and fall bloom periods were not a single event as suggested by the in situ data, but rather a number of small pulses of increased phytoplankton biomass. These results were similar to findings of Flagg et al. (1994) who reported that short-term, synoptic-scale phytoplankton events were superimposed on the annual cycle and were often several times larger than those seen on a seasonal scale in the Mid-Atlantic Bight. Moreover, the small pulses of increased phytoplankton biomass with concentrations greater than 5 mg m$^{-3}$ were also observed during the summer months (June, August and September; Table 1). These previously unreported event-scale pulses characterized by SeaWiFS are

![Annual and monthly corrected SeaWiFS chlorophyll $a$ of Massachusetts Bay from 1998 to 2005. The black contour line represents 1 mg m$^{-3}$. Note the colorbar is a log$_{10}$ scale.](image)

Table 1

<table>
<thead>
<tr>
<th>Date</th>
<th>$N$</th>
<th>Mean</th>
<th>1%</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>99%</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>91</td>
<td>0.85</td>
<td>0.26</td>
<td>0.67</td>
<td>0.86</td>
<td>1.05</td>
<td>2.86</td>
</tr>
<tr>
<td>February</td>
<td>84</td>
<td>0.96</td>
<td>0.33</td>
<td>0.60</td>
<td>0.91</td>
<td>1.34</td>
<td>9.81</td>
</tr>
<tr>
<td>March</td>
<td>84</td>
<td>1.61</td>
<td>0.38</td>
<td>0.98</td>
<td>1.34</td>
<td>2.85</td>
<td>12.36</td>
</tr>
<tr>
<td>April</td>
<td>70</td>
<td>2.58</td>
<td>0.56</td>
<td>1.47</td>
<td>2.25</td>
<td>4.28</td>
<td>16.76</td>
</tr>
<tr>
<td>May</td>
<td>57</td>
<td>1.89</td>
<td>0.54</td>
<td>1.25</td>
<td>1.84</td>
<td>2.84</td>
<td>6.14</td>
</tr>
<tr>
<td>June</td>
<td>60</td>
<td>2.40</td>
<td>0.32</td>
<td>0.98</td>
<td>1.35</td>
<td>2.01</td>
<td>9.83</td>
</tr>
<tr>
<td>July</td>
<td>78</td>
<td>1.37</td>
<td>0.41</td>
<td>0.89</td>
<td>1.28</td>
<td>1.79</td>
<td>4.71</td>
</tr>
<tr>
<td>August</td>
<td>94</td>
<td>1.52</td>
<td>0.45</td>
<td>0.99</td>
<td>1.34</td>
<td>2.07</td>
<td>8.23</td>
</tr>
<tr>
<td>September</td>
<td>110</td>
<td>2.18</td>
<td>0.30</td>
<td>1.02</td>
<td>2.36</td>
<td>4.52</td>
<td>20.37</td>
</tr>
<tr>
<td>October</td>
<td>89</td>
<td>3.16</td>
<td>0.42</td>
<td>1.57</td>
<td>3.45</td>
<td>6.47</td>
<td>20.59</td>
</tr>
<tr>
<td>November</td>
<td>59</td>
<td>2.11</td>
<td>0.44</td>
<td>1.12</td>
<td>1.92</td>
<td>3.33</td>
<td>25.83</td>
</tr>
<tr>
<td>December</td>
<td>64</td>
<td>1.17</td>
<td>0.37</td>
<td>0.84</td>
<td>1.13</td>
<td>1.64</td>
<td>7.97</td>
</tr>
</tbody>
</table>

Station N04 is located to the northwest of the outfall (Fig. 1).
potentially significant to the ecology and water quality of this region.

4. Conclusion

The purpose of this study was to assess the accuracy of SeaWiFS chlorophyll \( a \) in Massachusetts Bay with respect to in situ measurements and to evaluate possible error sources associated with the overestimation of SeaWiFS in this coastal region. Coastal regions are economically important ecosystems that typically express high temporal and spatial variability in phytoplankton biomass and productivity that can easily be missed by in situ sampling programs. Ocean color remote sensors provide unprecedented synoptic coverage of chlorophyll \( a \) that has increased the understanding of the magnitude and seasonal cycling of phytoplankton biomass and production, which is critical for the comprehension of the general ecology of an ecosystem. However, complex bio-optical water properties and inaccurate modeling of the nearshore atmosphere often complicate the retrieval of accurate data from ocean color remote sensors in coastal regions. This study demonstrated that SeaWiFS overestimated chlorophyll \( a \) in the Massachusetts Bay region and provided a simple empirical correction scheme to adjust the SeaWiFS estimation. The corrected SeaWiFS accurately and reliably characterized the seasonal phytoplankton biomass in Massachusetts Bay revealing event, seasonal and interannual variability and established that remotely sensed data can be an important component of coastal monitoring programs.

Acknowledgments

The Massachusetts Water Resources Authority (MWRA) supported in situ data collection and manuscript preparation. Technical reports containing water-quality data are available at http://www.mwra.state.ma.us/harbor/enquad/trlist.html. We thank personnel at Battelle Ocean Sciences, Duxbury, Massachusetts and the Marine Ecosystem Research Laboratory, University of Rhode Island for data collection and support. All in situ data were used with permission from MWRA. SeaWiFS data support was also provided by Teresa Ducas,
NOAA—National Marine Fisheries Service, Narragansett, Rhode Island, and James Yoder, Maureen Kennelly and Colleen Mow, University of Rhode Island, Narragansett, Rhode Island. We also thank Chuck McClain, Gene Feldman and James Acker, NASA—Goddard Space Flight Center, for SeaWiFS technical support and advice.

References


Harding, J., Lawrence, W., Magnuson, A., Mallonee, M.E., 2005. SeaWiFS retrievals of chlorophyll in Chesapeake Bay and the mid-Atlantic bight. Estuarine, Coastal and Shelf Science 62 (1–2), 75–94.


layer: relationships reinvestigated in view of remote sensing applications. Limnology and Oceanography 34 (8), 1545–1562.


