Remote sensing of particle backscattering in Chesapeake Bay:  
A 6-year SeaWiFS retrospective view

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Abstract

Traditional field techniques to monitor water quality in large estuaries, such as boat-based surveys and autonomous moored sensors, generally provide limited spatial coverage. Satellite imagery potentially can be used to address both of these limitations. Here, we show that satellite-based observations are useful for inferring total-suspended-solids (TSS) concentrations in estuarine areas. A spectra-matching optimization algorithm was used to estimate the particle backscattering coefficient at 400 nm, \( b_{wp}(400) \), in Chesapeake Bay from Sea-viewing Wide-Field-of-view Sensor (SeaWiFS) satellite imagery. These estimated values of \( b_{wp}(400) \) were compared to in situ measurements of TSS for the study period of September 1997—December 2003. Contemporaneous SeaWiFS \( b_{wp}(400) \) values and TSS concentrations were positively correlated (\( N = 340, r^2 = 0.4, P < 0.0005 \)), and the satellite-derived \( b_{wp}(400) \) values served as a reasonable first-order approximation for synoptically mapping TSS. Overall, large-scale patterns of SeaWiFS \( b_{wp}(400) \) appeared to be consistent with expectations based on field observations and historical reports of TSS. Monthly averages indicated that SeaWiFS \( b_{wp}(400) \) was typically largest in winter (>0.049 m\(^{-1}\), November–February) and smallest in summer (<0.031 m\(^{-1}\), June–August), regardless of the amount of riverine discharge to the bay. The study period also included Hurricanes Floyd and Isabel, which caused large-scale turbidity events and changes in the water quality of the bay. These results demonstrate that this technique can provide frequent synoptic assessments of suspended solids concentrations in Chesapeake Bay and other coastal regions.

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Keywords: water quality; remote sensing; light backscattering; suspended particulate matter; ocean color; SeaWiFS; Chesapeake Bay

1. Introduction

The Chesapeake Bay is the largest estuary in the United States and is home to more than 3600 species of plants and animals. More than 15 million people live within its \( \sim 166,000 \) km\(^2\) watershed. It is also the site of one of the most ambitious ecosystem monitoring and restoration efforts to date (Langland and Cronin, 2003). The bay suffers from degraded water quality, loss of submerged aquatic vegetation (SAV), and depleted fisheries, among other problems. While restoration efforts have been underway for more than 20 years, these actions have not produced large-scale improvements in water quality and habitat (Chesapeake Bay Program, 2006). One challenge is routinely determining water quality in an accurate and timely fashion on a bay-wide scale.

Current assessments of bay water quality rely heavily on fixed, long-term monitoring stations (Boesch, 2000) that are sampled aperiodically. Some continuous monitoring stations have been added more recently (e.g., Maryland Department of Natural Resources, http://mddnr.chesapeakebay.net/eyesonthabay). This long-term, bay-wide monitoring program supplies important “status and trends” information to scientists, managers, and citizens, but still samples at spatial and temporal scales that cannot resolve many important estuarine processes (Johnson and Buchanan, 2002).
An optimal approach to estuarine characterization and monitoring would combine depth-resolved, automated, real-time in situ sensing with coincident synoptic satellite observations that are supplemented by relatively infrequent boat-based surveys (Boesch, 2000). Such a comprehensive program, however, is not without technical hurdles. Specific to remote sensing, optically shallow, submerged environments present the challenge of deconvolving radiance contributions from the atmosphere, water column, and sea floor. The conversion of at-sensor radiance values to meaningful water-quality parameters is not straightforward, especially in optically complex coastal waters (International Ocean-Colour Coordinating Group, 2000; Davis et al., 2002).

Recent technical advances and a growing need for spatially and temporally resolved coastal-zone information have led to efforts within the scientific-research and resource-management communities to develop and exploit ocean-color satellite capabilities (International Ocean-Colour Coordinating Group, 2000; Johnson and Buchanan, 2002). Satellite observations have been applied to study some Chesapeake Bay processes (e.g., sediment transport during floods, Stumpf, 1988; chlorophyll-α concentration in surface waters, Harding et al., 2005). Additional satellite-derived data products identified as being of particular interest to Chesapeake Bay restoration efforts include estimates of photosynthetically available radiation, diffuse light-attenuation coefficients, sea surface temperature, and concentrations of dissolved and particulate matter (Johnson and Buchanan, 2002). However, remote-sensing capabilities have not been routinely utilized by regulatory and research agencies participating in bay restoration, management, and monitoring (Johnson and Buchanan, 2002).

The objectives of this study were (a) to evaluate the feasibility of using estimated particle backscattering coefficients at 400 nm ($b_{\text{sp}}(400)$), derived from Sea-viewing Wide-Field-of-view Sensor (SeaWiFS) satellite imagery, as a proxy for total-suspended-solids (TSS) concentrations in Chesapeake Bay surface waters; and (b) to examine bay-wide SeaWiFS $b_{\text{sp}}$ distribution patterns and any associated seasonality. A spectra-matching optimization algorithm was applied to SeaWiFS remote-sensing reflectance data (six visible bands) to estimate $b_{\text{sp}}(400)$. Using this approach, SeaWiFS images spanning September 1997 to December 2003 were processed to provide a retrospective view of Chesapeake Bay water quality in terms of particle backscattering as a proxy for TSS concentrations.

2. Methods

2.1. Study area

The Chesapeake Bay (Fig. 1) is a large estuary on the Mid-Atlantic coast of the United States. Stretching over 300 km in length, the estuary has an average width of about 11 km (ranging from 6 to 56 km) and an average depth of about 7 m (Gurnett, 2000; Langland and Cronin, 2003). For the purposes of study design, data analysis, and reporting, the Chesapeake Bay is typically divided into a number of geographically defined segments (alphanumeric labels in Fig. 1; Chesapeake Bay Program, 2004). For more general purposes, the bay can be characterized in terms of three broad zones (Orth et al., 2003): (1) the Upper Bay, which includes the Northern Chesapeake Bay (CB1TF), Upper Chesapeake Bay (CB2OH), and Upper Central Chesapeake Bay (CB3MH) segments, as well as adjacent tributaries; (2) the Middle Bay, which includes the Middle Central Chesapeake Bay (CB4MH), Lower Central Chesapeake Bay (CB5MH), and Tangier Sound (TANMH) segments, plus adjacent tributaries; and (3) the Lower Bay, which includes the Western (CB6PH) and Eastern (CB7PH) Lower Bay, and mouth of the Chesapeake Bay (CB8PH) segments and adjacent tributaries. In general, the bay is oligohaline (salinity ($S$) < 10 psu) in its upper zone, mesohaline (10 psu ≤ $S$ ≤ 20 psu) in the upper middle zone, and polyhaline ($S$ > 20 psu) in its lower middle and lower bay zones (Harding and Perry, 1997).

Numerous rivers contribute to the estuary, but the three largest — the Susquehanna (at the very head of the estuary), Potomac (POT), and James (JMS) Rivers — account for approximately 85% of the total riverine input. Significant interannual variability is observed in freshwater discharge to the bay. The study period (September 1997–December 2003) includes two wet years (1998, 2003, i.e., discharge rates in the uppermost quartile of long-term rates) and three dry years (1999, 2001, 2002, i.e., discharge rates in the lowest quartile). The remaining years (1997, 2000) were considered normal relative to long-term trends (http://md.water.usgs.gov/monthly/bay.html).

2.2. Data sources

In situ water-quality data were obtained from the Chesapeake Bay Program (CBP) Water Quality Database (http://www.chesapeakebay.net/data/index.htm; RJO Enterprises Inc., 1998). Since 1984, approximately 50 fixed monitoring stations throughout the bay have been visited and sampled for approximately 20 different measures of water quality, including Secchi depth and concentrations of TSS and chlorophyll-a (Chesapeake Bay Program, 1996). For the TSS measurements, 500 mL of water was filtered under vacuum through a pre-washed, dried, and weighed GF/F filter (0.7-μm pore size, 47-mm diameter). Smaller volumes were filtered when high concentrations of particulates were present. After the sample filter was washed and excess water was removed under suction, the filter was stored for a maximum of seven days at 4 °C or cooler. The sample filter was then dried in a 104 °C (± 1 °C) oven for at least 1 h, cooled in a desiccator, and weighed. The cycle of drying, cooling, and re-weighing was repeated until no significant change in weight (≤0.5 mg) was observed between successive weighings. The detection limit for the TSS analyses was 2 mg L⁻¹, and the practical range of application was 2 to 20,000 mg L⁻¹ (Chesapeake Bay Program, 1996).

Satellite data were obtained from the SeaWiFS ocean-color sensor, which measures radiance at eight spectral bands centered at 412, 443, 490, 510, 555, 670, 765, and 865 nm.
Nominal spatial resolution is \(\sim 1\) km/pixel (nadir view), and the revisit time for this latitude is \(\sim 1\) day. SeaWiFS raw data were downlinked and processed in near real-time at a ground station at the University of South Florida. For the study period, image pixels that were associated with any of the following conditions were excluded from further analysis: cloud cover, atmospheric correction failure, large sun zenith or viewing angle, and several other satellite data processing artifacts, such as stray light contamination. For valid pixels, at-sensor radiance data were converted to normalized water-leaving radiances \(L_{WN}\;\text{(Morel and Mueller, 2003)}\) with standard NASA SeaWiFS processing algorithms (SeaDAS version 4.4). The normalization was meant to provide a temporally consistent time series regardless of the differences in atmospheric effects, solar illumination, and viewing geometry.

### 2.3. Estimation of particle backscattering coefficients

SeaWiFS \(L_{WN}\) values were converted to provisional water-quality indices using a spectra-matching optimization algorithm (Lee et al., 1999; Hu et al., 2003). In this algorithm, values for a set of optical parameters (e.g., absorption, backscattering, etc.) are used to generate reflectance spectra, based on a semi-analytical model and assumed absorption spectral shapes for phytoplankton pigments, colored dissolved organic matter (CDOM), and detrital particles (including TSS). Given

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Fig. 1. Chesapeake Bay site map, including Chesapeake Bay Program 2003 segmentation scheme. Segments represent regions with similar natural characteristics. Figure courtesy of Chesapeake Bay Program GIS Team.
that CDOM and detrital particles have similar absorption spectral shapes (both decrease exponentially with wavelength), they typically are combined together and referred to as colored dissolved and detrital organic matter (CDM). As such, there are four unknowns in the algorithm: the phytoplankton absorption coefficient at 443 nm ($a_{bp}(443)$), the CDM absorption coefficient at 443 nm ($a_{CDM}(443)$), the particulate backscattering coefficient at 400 nm ($b_{bp}(400)$), and the spectral slope of backscattering ($\eta$ in Eq. (1) below). Values of $a_{bp}(443)$ were assumed to be the same as in Lee et al. (1999). Since CDOM absorption in coastal waters is typically 0.014–0.018 nm$^{-1}$ and that of detrital absorption is lower, $a_{CDM}$ was assumed to be 0.015 nm$^{-1}$. For each satellite pixel, $\eta$ was empirically derived, and the three remaining unknowns were allowed to vary until the predicted spectrum (from the six visible bands) best matched the SeaWiFS spectrum. This type of non-linear search for a match has been computationally expensive in the past, and previously represented a major hurdle for operational data processing. However, with improved computer hardware and efficient coding of the spectra-matching optimization algorithm, one scene covering the entire bay can now be processed in 1–2 min.

The parameter emphasized in this paper is the particle-associated backscattering coefficient at 400 nm, $b_{bp}(400)$. The choice of the reference wavelength (400 nm) is arbitrary given the fact that $b_{bp}$ at other wavelengths can be derived mathematically as

$$b_{bp}(\lambda) = b_{bp}(400) \left(\frac{400}{\lambda}\right)^{\eta} \quad (1)$$

where $\lambda$ is the wavelength (in nanometers) and $\eta$ is the power law exponent describing the spectral variability of $b_{bp}$. A band ratio from the $L_{WN}$ spectrum, based on observations at 443 and 555 nm, was used to empirically derive $\eta$ (Lee et al., 1999), which typically ranged from 0.5 for coastal waters to 2.2 for offshore waters.

Given the lack of in situ $b_{bp}(400)$ measurements, we examined the relationship between the SeaWiFS-derived $b_{bp}(400)$ values and in situ observations of surface TSS collected within 2 h of the satellite pass. The in situ TSS data were obtained from the CBP Water Quality Database. Within the study period, we found 340 matching pairs in the Middle and Lower Bay Zones; no match-ups were located in the Upper Bay Zone. Around each monitoring station, a 3 x 3 pixel region was extracted from the SeaWiFS $b_{bp}(400)$ data, and the median value was compared to the corresponding TSS value. The median was used to help minimize errors due to satellite sensor and/or algorithm noise (Hu et al., 2001).

To reveal spatial patterns in the magnitude and variability of SeaWiFS $b_{bp}(400)$ throughout the bay, mean values and corresponding coefficients of variation (CV) were computed on a per-pixel-basis for the entire data set. Defined as the ratio of the standard deviation to the mean (Zar, 1999), the CV is a dimensionless, relative measure of dispersion, indicating the consistency of values in a series. The magnitude of the standard deviation tends to increase or decrease proportionately with similar changes in the mean. Normalizing the standard deviation by the mean removes its impact on the variability.

2.4. Comparison of in situ TSS measurements to the SeaWiFS-derived $b_{bp}(400)$

Both the in situ TSS and SeaWiFS-derived $b_{bp}(400)$ data were logarithmically (base-10) transformed prior to comparison. A least squares regression was used to examine the relationship between them.

2.5. Flow rate classification

Estimates of monthly river flow into Chesapeake Bay (1951–2003) were obtained from the U.S. Geological Survey (Bue, 1968; updated and corrected values are available at http://md.water.usgs.gov/publications/ofr-68-Bue10/table9.html) and from recent USGS Monthly Water Conditions Reports (http://md.water.usgs.gov/monthly/index.html). To construct monthly time series for ‘low’, ‘normal’, and ‘high’ flow conditions, rates of monthly flow to the bay from 1951 to 1996 were first used to compute a long-term monthly mean and corresponding 25th and 75th percentiles for each month of the year. For the 1997–2003 study period, all months with flow rates lower than the 25th percentile were designated as ‘low-flow’ and those with flow rates exceeding the 75th percentile as ‘high-flow.’ All remaining months were considered to have a ‘normal’ flow rate (Table 1). Using these classifications, maps of monthly mean SeaWiFS $b_{bp}(400)$ values were created for ‘low’, ‘normal’ and ‘high’ flow years. Between 13 and 111 SeaWiFS images were averaged to generate the maps (Table 2). A number of factors, such as cloud cover, failure of the atmospheric correction algorithm, large sun or viewing angle, and other satellite data processing artifacts, such as stray light contamination, affected the number of images available for a given month. Finally, the maps were assembled in calendar-order to create time series for nominal ‘low’, ‘normal’, and ‘high’ flow years.

3. Results and discussion

3.1. Signal contribution from the water column versus the sea bottom

In optically shallow waters, the water-leaving radiance includes contributions from the water column and from the sea floor. To examine whether bottom “contamination” of the signal might introduce confounding effects in our data set, the CBP Water Quality Database was examined for occurrences when the Secchi disk was visible on the sea floor (i.e., optically shallow water). Instances were found in the St. Mary’s area of the lower Potomac River and at one station in the lower York River. No optically shallow water was found in the main stem of the bay. Bottom reflectance may have contributed to the high SeaWiFS $b_{bp}(400)$ values in the upper Pocomoke
Sound and in some areas of Tangier Sound. We concluded that, in general, the Chesapeake Bay is optically deep.

### 3.2. Comparison of satellite-derived and in situ data

Histograms of the SeaWiFS $b_{bp}(400)$ and in situ TSS data exhibited positively skewed distributions (Fig. 2). Surface TSS ranged from 2 to 45 mg L$^{-1}$, with a mean of 7.6 mg L$^{-1}$ and a median of 6.1 mg L$^{-1}$. The tail of higher values (TSS > 20 mg L$^{-1}$) is largely due to measurements made in the Lower Bay (segments CB6PH and CG7PH) on November 17–18, 1997. On those dates, TSS values in the Lower Bay were approximately 3 times above normal levels. In the Middle Bay zone to the north, TSS values were somewhat higher (~ 1.5×) than long-term observations. Additional isolated observations from the Lower Bay on October 14, 1998 and August 1, 2001 account for the remainder of the high TSS measurements. These observations are consistent with the SeaWiFS true-color image and $b_{bp}(400)$ map from 17 November 1997 (Fig. 3). The SeaWiFS data show turbid, highly scattering, particle-rich waters in the Lower Bay and coastal shelf areas, with clearer conditions in the Middle Bay.

SeaWiFS $b_{bp}(400)$ varied from 0.011 m$^{-1}$ to 0.13 m$^{-1}$, with a mean of 0.034 m$^{-1}$ and a median of 0.030 m$^{-1}$. In general, SeaWiFS $b_{bp}(400)$ in Chesapeake Bay surface waters increases with increasing TSS levels (Fig. 4), following this relationship:

$$\log_{10}(\text{SeaWiFS } b_{bp}(400)) = 0.516 \cdot \log_{10}(\text{TSS}) - 1.92$$

which may be rewritten as

$$\text{SeaWiFS } b_{bp}(400) = 0.0119 \cdot \text{TSS}^{0.516}$$

where ($2 < \text{TSS} < 50 \text{ mg L}^{-1}$)

with a coefficient of determination ($r^2$) of 0.40 and a standard error of regression equal to 0.138 m$^{-1}$. While the regression relation explains only 40% of the variance in SeaWiFS $b_{bp}$, analysis of variance testing did reject the null hypothesis of a zero slope ($P < 0.0005$), indicating a meaningful correlation between TSS and SeaWiFS $b_{bp}$.

Several factors limit the degree of correlation. First, it is important to consider the spatial scale disparity between satellite measurements and water bottle samples. Measurements of TSS give the concentration of suspended solids in a 500-mL bottle of bay water collected near the air/sea interface. Depending on spatial heterogeneity, this concentration may or may not be representative of the larger water mass in that area. SeaWiFS samples over an area of about 1 km$^2$ and should not be expected to exactly match a 500-mL point sample. Hu et al. (2004) showed that in situ bio-optical properties were used to estimate $b_{bp}(400)$.

### Table 1

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### Table 2

Number of SeaWiFS high-resolution images (~ 1 km per pixel) used to generate the monthly averages. The inflow designations in Table 1 were used to select the images for creating the monthly composites shown in Figs. 6–8

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is the dependence of SeaWiFS $b_{bp}(400)$ on particulate size, shape, and population composition (Jerlov, 1968; Van De Hulst, 1981). For example, Woodruff et al. (1999) documented how storm re-suspension of bottom fines altered the relationship between TSS and optical properties (in their case, the diffuse attenuation coefficient and satellite reflectance).

Furthermore, the parameterizations (e.g., spectral shapes of phytoplankton and CDOM absorption) in the spectra-matching optimization model may have some uncertainties because they are generalized and not specific to Chesapeake Bay. Finally, there may be some unidentified uncertainties in the in situ TSS data.

Numerous empirical algorithms have been developed to help derive synoptic maps of total suspended matter in coastal zones from satellite images (e.g., Stumpf and Pennock, 1989; Miller and McKe, 2004; Binding et al., 2005; Bowers and Binding, 2006). These techniques, however, also have limitations. In particular, single-waveband algorithms are vulnerable to significant errors due to variability in particle size, shape, and composition. Reflectance ratios of near-infrared to green wavebands have been shown to be more robust, but only for relatively turbid waters since remote-sensing reflectance is nearly zero for near-infrared wavelengths when TSS is $<50$ mg L$^{-1}$ (Doxaran et al., 2002).

One of the appealing factors of the semi-analytical algorithm of Lee et al. (1999) is its use of meaningful physical parameters, such as pigment concentration and the coefficients of absorption and backscattering. In particular, information from all six visible bands is used to derive $b_{bp}(400)$, as opposed to one or two bands in the traditional empirical approaches. Doing so helps minimize the effect of noise and other errors in any single band. For example, at pixels where water-leaving radiance at 412 nm is negative, as a result of overcorrection of atmospheric radiance, the algorithm uses the remaining five bands to estimate $b_{bp}(400)$. Efforts to relate remote-sensing reflectance at either 555 nm or 670 nm to TSS produced less satisfactory results than using SeaWiFS $b_{bp}(400)$ (results not shown here).

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**Figure 2.** Histograms of (A) TSS values and (B) SeaWiFS $b_{bp}(400)$ values included in the match-up data set.

**Figure 3.** Synoptic view of the Chesapeake Bay for 17 November 1997. (A) True-color SeaWiFS image based on arbitrarily-stretched red, green, and blue SeaWiFS channels. (B) SeaWiFS-derived $b_{bp}(400)$. 
segment of the Potomac River where mean SeaWiFS $b_{bp}(400)$ values are also high (segment POTMH), as well as in the upper bay (segments CB3MH and CB2OH). Low CVs in the Tangier/Pocomoke Sounds areas suggest that the persistently high SeaWiFS $b_{bp}(400)$ values observed in this region may be attributable in part to a persistent signal contribution from the bottom. Relatively low variability is also observed at the mouth of the York River and in parts of the western bay where typically low SeaWiFS $b_{bp}(400)$ values occur.

These SeaWiFS $b_{bp}(400)$ patterns are generally consistent with previously reported large-scale, time-averaged patterns of turbidity, surface TSS, and light attenuation in Chesapeake Bay. A prominent feature in the northern main stem of the bay and larger tidal tributaries is an Estuarine Turbidity Maximum (ETM). This region functions as a sediment “reservoir” where fine-grained particulates are accumulated and are occasionally re-suspended and re-deposited (Schubel and Carter, 1976; Langland and Cronin, 2003). The ETM is an area characterized by high concentrations of suspended sediment and reduced light availability. Based on measurements of turbidity and salinity, the general location of the Chesapeake Bay ETM is at the boundary of segments CB1TF and CB2OH (Langland and Cronin, 2003). TSS concentrations averaged spatially over each CBP segment are large and variable in this region. High SeaWiFS $b_{bp}(400)$ values are consistent with these observations.

Each of the tributary systems typically has its own ETM zone near the upstream limits of saltwater intrusion (Langland and Cronin, 2003), but the location of these zones is generally upstream of the tributary areas that can be resolved in SeaWiFS imagery. For example, the Potomac River and James River ETMs are in segments POTOH and JMSOH, upriver of $b_{bp}(400)$ data available from satellite imagery with 1 km spatial resolution.

Field measurements also indicate a number of areas of relatively high turbidity adjacent to the ETM zones and in a few other areas around the bay. Almost the entire Lower Bay Zone (segments CB6PH, CB7PH, and CB8PH) has relatively high turbidity (Langland and Cronin, 2003). Particulate matter accumulation in the Lower Bay has been linked to tidal re-suspension of sediments (Schubel and Carter, 1976), convergent circulation, and low flushing rates (Hood et al., 1999).

Other areas of relatively high turbidity are mapped in Tangier Sound (segment TANMH) and adjacent tributaries and in a small area within northern Pocomoke Sound (segment POCMH) (Langland and Cronin, 2003). Segment-averaged surface TSS and light-attenuation observations also show a peak in the eastern shore embayment CHOMH1, and especially in TANMH and POCMH. The mean SeaWiFS $b_{bp}(400)$ values show similar patterns (Fig. 5A). These high TSS values are likely due to active shoreline erosion.

3.4. Monthly averages of SeaWiFS $b_{bp}(400)$ under low, normal, and high riverine streamflow

Discerning general temporal patterns for any given year is challenging since the observed month-to-month variability...
includes the effect of seasonal influences, as well as interannual variability — most notably in terms of riverine inflow to the bay. To investigate how riverine streamflow affects turbidity, we created a monthly time series of SeaWiFS $b_{400}$ maps for nominal ‘low,’ ‘normal,’ and ‘high’ flow years. Each month from September 1997 to December 2003 was designated as ‘low,’ ‘normal,’ or ‘high,’ relative to long-term average streamflow patterns (Table 1; for details, see Methods — Flow rate classification). Note that April never qualified as a ‘high’ flow month within the study period. The maps were grouped into 12-month time series for each flow category (Figs. 6—8).

From a bay-wide perspective, December and January are associated with the largest SeaWiFS $b_{400}$ values (>0.06 m$^{-1}$). During ‘low-flow’ years (Fig. 6), SeaWiFS $b_{400}$ was relatively low (~ 0.02 m$^{-1}$), and clear shelf waters (~ 0.002 m$^{-1}$) were found near the bay mouth from approximately June to December. Normal years (Fig. 7) exhibited similar patterns. For a theoretical ‘high’ flow year, large SeaWiFS $b_{400}$ values (>0.05 m$^{-1}$) persisted for most of the year, diminishing only during the summer (Fig. 8). In general, as river discharge increased, low-backscattering shelf waters were only found offshore. Binding et al. (2005) observed a similar seasonal cycle in particle backscattering signal for the Irish Sea. They attributed the winter peak in backscattering to reduced phytoplankton populations and increased wind stirring, which led to particle disaggregation. Similar factors are relevant to the Chesapeake Bay. For example, some of the elevated winter SeaWiFS $b_{400}$ values were likely associated with winter frontal passage and sediment re-suspension.

With respect to the ETM zone of the Upper Bay, SeaWiFS $b_{400}$ in the ETM zone of the Upper Bay was highest during April, likely due to the spring freshet. The high SeaWiFS $b_{400}$ zones of the James and Potomac Rivers were also most pronounced during April. During a ‘high-flow’ year, SeaWiFS $b_{400}$ exceeded 0.09 m$^{-1}$ over much of the Upper Bay for most of the year (Fig. 8). Under such conditions, September appeared to be a time of unusually high SeaWiFS $b_{400}$. This canonical ‘wet September’ was strongly influenced by Hurricane Floyd (September 1999) and Hurricane Isabel (September 2003) (see below).

The patterns observed in the images are generally consistent with reports of bay conditions during the transition from the ‘low-flow’ years of 2001 and 2002 to the ‘high-flow’ year of 2003. The earlier years saw an increase in water clarity and a concomitant increase in acreage of SAV (Orth et al., 2003). Dramatic declines in SAV acreage were reported for 2003 and attributed to high rates of precipitation, which increased nutrient input, phytoplankton growth, and sediment concentrations (Maryland Department of Natural Resources, 2003; Orth et al., 2004). Similar patterns of improving water clarity with decreasing inflow and sediment input were also reported for the transition from the ‘high-flow’ months of early 1998 to the drought conditions of late 1998 (Chesapeake Bay Program, 1999).

3.5. Hurricanes Floyd and Isabel

Among the monthly composites of SeaWiFS $b_{400}$, we found that 1999 and 2003 stood out as having unusually particle-rich Septembers. These two years included the passage of Hurricane Floyd (1999; Fig. 9A) and Hurricane Isabel (2003; Fig. 9B).

According to U.S. Drought Monitor indices (http://www.drought.unl.edu/dm/monitor.html), almost the entire
Fig. 6. Seasonal cycle of SeaWiFS $b_{op}(400)$ in Chesapeake Bay under ‘low-flow’ conditions.
Fig. 7. Seasonal cycle of SeaWiFS \( b_{\text{app}}(400) \) in Chesapeake Bay under ‘normal’ conditions.
Fig. 8. Seasonal cycle of SeaWiFS $b_{bp}(400)$ in Chesapeake Bay under 'high-flow' conditions.
Chesapeake Bay watershed experienced severe to extreme drought conditions as of 31 August 1999. During the first week of September, Hurricane Dennis brought tropical storm conditions and significant rainfall to some areas of the watershed. On September 12 (Fig. 10A), SeaWiFS $b_{bp}(400)$ values in the bay were relatively low — approximately 0.022 m$^{-1}$ or lower over much of the bay. On September 15, Hurricane Floyd made landfall near Cape Fear, North Carolina, as a Category 2 hurricane, and proceeded on a north-northeasterly track, crossing the Chesapeake Bay mouth before exiting to sea and skirting northward along the mid-Atlantic coastline (Fig. 9A; Bales et al., 2000). In the first post-storm image sufficiently cloud-free (17 September, Fig. 10B), SeaWiFS $b_{bp}(400)$ values were markedly increased bay-wide, indicating that bay waters were particle-laden. Areas of highest SeaWiFS $b_{bp}(400)$ were found in the upper estuary, the Potomac River, Tangier Sound, and the mouth of Chesapeake Bay. This distribution of SeaWiFS $b_{bp}(400)$ strongly resembles those for December and January in a ‘high’ flow year (Fig. 8). Six days later (23 September, Fig. 10C), SeaWiFS $b_{bp}(400)$ values returned to approximately pre-storm conditions in the lower Potomac River and western Middle Bay, but remained elevated in the Lower Bay. This pattern is consistent with patterns of precipitation associated with Hurricane Floyd. Within the Chesapeake Bay watershed, maximum values of total precipitation (41–53 cm) occurred near the mouths of the James (JMS) and York (YRK) Rivers in the southwest quadrant of the lower bay (NOAA Climate Prediction Center, 1999).

Almost exactly four years later, Hurricane Isabel struck the Chesapeake Bay region. Preceding the storm (September 16), SeaWiFS $b_{bp}(400)$ values were generally lowest near the western shore, increasing eastward with maximum values in the Tangier Sound and bay mouth areas (Fig. 10D). On September 18, 2003, Hurricane Isabel made landfall near Drum Inlet, North Carolina, as a Category 2 hurricane, and proceeded on a northerly track up the mid-Atlantic seaboard (Fig. 9B; NOAA National Climatic Data Center, 2003). In the first post-storm image sufficiently free of cloud cover (September 19), SeaWiFS $b_{bp}(400)$ values were markedly increased bay-wide (Fig. 10E), indicating that bay waters were particle-laden. The overall spatial distribution of SeaWiFS $b_{bp}(400)$ is rather different from that observed in the wake of Hurricane Floyd, with elevated values occurring bay-wide. The lowest values were observed near the mouth of the Potomac River. One probable explanation for this difference relates to the paths traversed by each storm. Hurricane Floyd exhibited a typical northeasterly passage across the mouth of the bay, while Isabel took a northwesterly overland track to the west of the bay (Fig. 9A,B). The landward passage of Isabel aligned its strong southeast-to-southerly winds with the approximate north—south orientation of the bay. As a result, water was driven into the bay, and turbulent mixing homogenized the...
normally stratified water column (Li et al., 2006). The strong vertical mixing would have re-suspended bottom sediments, producing the SeaWiFS $b_{bp}(400)$ distribution shown in Fig. 10E. Over the subsequent week, as suspended solids settled out of the water column, SeaWiFS $b_{bp}(400)$ conditions returned approximately to their pre-storm state (Fig. 10F). These results are consistent with field observations of a temporary, substantial decrease in water clarity in tidal portions of Chesapeake Bay during and immediately after the storm. Sediment re-suspension and shoreline erosion, associated with storm surge and wave effects, were the most significant causal forces (Maryland Department of Natural Resources, 2003).

4. Summary and conclusions

SeaWiFS satellite data were used in a bio-optical inversion algorithm to estimate the optical backscattering coefficient (SeaWiFS $b_{bp}(400)$) for surface waters of the Chesapeake Bay. These estimates were in first-order agreement with contemporaneous concentrations of TSS. Time series of bay-wide SeaWiFS $b_{bp}(400)$ maps revealed patterns consistent with historical suspended solids data. The largest values of SeaWiFS $b_{bp}(400)$ were observed in the vicinity of the Chesapeake Bay ETM zone at the boundary of segments CB1TF and CB2OH, as well as in Pocomoke Sound and in the James and Potomac Rivers just downstream of their tributary ETM zones. Values of SeaWiFS $b_{bp}(400)$ were most highly variable in the middle Potomac River and Upper Bay Zone.

To investigate the large-scale impact of river discharge on turbidity, a monthly time series of bay-wide SeaWiFS $b_{bp}(400)$ maps was created for nominal ‘low’, ‘normal’, and ‘high’ flow years. High particle-associated backscatter was consistently observed during winter months, regardless of the flow scenario. Under ‘normal’ conditions, high SeaWiFS $b_{bp}(400)$ values also occurred in April, typically the time of the spring freshet, especially in the Upper Bay Zone and areas of the James and Potomac Rivers.

Fig. 10. Hurricane impacts on SeaWiFS $b_{bp}(400)$ for the Chesapeake Bay. (A–C) Before and after Hurricane Floyd, September 1999. (D–F) Before and after Hurricane Isabel, September 2003.
During ‘low-flow’ years, SeaWiFS $b_{bp}(400)$ values generally were smaller, and the diminished riverine discharge allowed clear shelf waters to move further inshore.

To study the effects of short-term, large-scale events, such as hurricanes, daily imagery was more appropriate than monthly averages. Daily image data collected before and after Hurricanes Floyd and Isabel illustrated a dramatic increase in SeaWiFS $b_{bp}(400)$ shortly after passage of the storms. The characteristics of the spatial SeaWiFS $b_{bp}(400)$ distributions differed according to conditions specific to each storm. Bay waters cleared significantly within 6–8 days after passage of each hurricane.

Technical challenges (e.g., improved atmospheric correction and accurate parameterization in the bio-optical algorithm) remain to be resolved in order to derive the most accurate water-quality indices for coastal and estuarine waters. Nevertheless, current qualitative or semi-quantitative views can provide an important complement to existing monitoring methods. Synoptic, frequent coverage and rapid processing ensure timely information delivery — qualities critical for coastal-management concerns. We encourage further investigations to realize the full potential of these techniques to aid estuarine monitoring programs.

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References


Harding, L.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.


