# Physical and biogeochemical controls on light attenuation in a eutrophic, back-barrier estuary

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#### 9 Abstract

10 Light attenuation is a critical parameter governing the ecological function of shallow 11 estuaries. In these systems primary production is often dominated by benthic macroalgae and seagrass; thus light penetration to the bed is of primary importance. We quantified light 12 13 attenuation in three seagrass meadows in Barnegat Bay, New Jersey, a shallow eutrophic 14 back-barrier estuary; two of the sites were located within designated Ecologically Sensitive 15 Areas (ESAs). We sequentially deployed instrumentation measuring photosynthetically 16 active radiation, chlorophyll-a (chl-a) fluorescence, dissolved organic matter fluorescence 17 (fDOM; a proxy for colored DOM absorbance), turbidity, pressure, and water velocity at 10 18 min intervals over three week periods at each site. At the southernmost site, where sediment 19 availability was highest, light attenuation was highest and dominated by turbidity and to a 20 lesser extent chl-a and CDOM. At the central site, chl-a dominated followed by turbidity and 21 CDOM, and at the northernmost site turbidity and CDOM contributed equally to light 22 attenuation. At a given site, the temporal variability of light attenuation exceeded the 23 difference in median light attenuation at the three sites, indicating the need for continuous 24 high-temporal resolution measurements. Vessel wakes, anecdotally implicated in increasing 25 sediment resuspension, did not contribute to local resuspension within the seagrass beds, 26 though frequent vessel wakes were observed in the channels. With regards to light attenuation 27 and water clarity, physical and biogeochemical variables appear to outweigh any regulation of boat traffic within the ESAs. 28

#### 1 **1 Introduction**

2 Back-barrier estuaries, especially along the Atlantic coast of the United States, are typically 3 shallow systems colonized by benthic primary producers (Ziegler and Benner, 1998; 4 Meyercordt et al., 1999; McGlathery et al., 2001). Prior to urbanization and agricultural 5 influence in the watersheds, many systems were characterized by high densities of seagrass 6 and relatively low light attenuation. Subsequent nutrient loading resulting from industrial and 7 agricultural development has led to a gradual decline in seagrass density as eutrophication 8 created water-column algal blooms and overgrowth of benthic algae (Burkholder et al., 2007). 9 Both of these algal succession processes reduce light penetration to seagrass colonies. 10 Evaluating the resiliency of remaining seagrass colonies requires understanding the relative importance of the mechanisms controlling light attenuation in the water column. 11

12 There are generally four major factors that reduce light penetration in the water column: the water itself (a function of depth), non-algal particulate material (i.e. suspended sediment), 13 phytoplankton biomass, and colored dissolved organic matter (CDOM) (Kirk, 1994). 14 Generally proxies are used to estimate these quantities in-situ: turbidity, chlorophyll-a 15 16 fluorescence, and fluorescing DOM (fDOM). In estuaries, depth is governed by geomorphology and tidal elevations, therefore light attenuation caused by water is maximized 17 18 in the deepest channels at high tide, and minimized over shoals at low tide. Suspended-19 sediment concentrations are typically controlled by supply from external sources or local 20 resuspension from the sediment bed (Schoellhamer, 2002). Supply is a function of tidal advection (or riverine input) from a non-local repository, while local resuspension can be 21 22 instigated by tidal currents or wave action (Ganju et al., 2004). Chlorophyll-a concentrations 23 represent the abundance of phytoplankton in the water column, which is a function of nutrient 24 loading, residence time, advection, grazing by zooplankton, and other factors (Phlips et al., 2002; Howarth and Marino, 2006; Glibert et al., 2007). Estuaries with high nutrient loading 25 and long residence time tend to have the highest chlorophyll-a concentrations; locations 26 within the estuary far from the nutrient source may experience elevated concentrations due to 27 28 tidal advection. CDOM is typically associated with a terrestrial end member, leading to an inverse correlation between salinity and CDOM; concentrations may also be elevated in areas 29 draining marsh plains (Downing et al., 2009) and terrestrial watersheds (Spencer et al., 2013). 30

Instrument limitations typically preclude high temporal resolution (~1 h) of these parameters
 over extended periods (i.e. spring-neap cycle). Light and other optical sensors are prone to

rapid biofouling and it is logistically difficult to occupy multiple stations within an estuary. 1 2 Several studies have quantified the spatial and temporal variability of light attenuation in estuaries, though the spatial and temporal scales vary widely. Philps et al. (1995) sampled 3 4 monthly at 17 stations within Florida Bay for one year and described spatial variability in 5 light attenuation due to variability in non-algal turbidity and phytoplankton concentrations. Christian and Sheng (2003) conducted synoptic sampling over a 3-mo period in the Indian 6 7 River Lagoon and found that non-algal particulates dominated light attenuation. Both of these 8 studies used non-autonomous light sensors and laboratory determination of chlorophyll-a and 9 suspended sediment, thereby limiting temporal resolution. However, with a combination of 10 high-frequency point observations and modeling, Lawson et al. (2007) investigated the 11 influence of suspended sediment on light attenuation in a coastal lagoon and determined that 12 infrequent point monitoring was inadequate for characterizing light dynamics for benthic 13 flora.

14 The Barnegat Bay-Little Egg Harbor estuary (BBLEH) is a back-barrier estuary on the New 15 Jersey coast (Fig. 1). BBLEH is connected to the Atlantic Ocean via three inlets and is characterized by extensive shallows and maintained navigation channels. The shallows of 16 17 BBLEH are colonized by seagrass beds of *Zostera marina* and *Ruppia maritima*, depending on salinity conditions, with the salt-tolerant Z. marina mostly in the southern portion of the 18 19 system (Kennish et al., 2013). The influence of the Toms River (and other freshwater sources) 20 lowers salinity in the northern portion of the system, leading to a shift towards R. maritima. 21 Seagrass meadows rely on adequate light conditions to maintain productivity and their 22 presence in estuarine systems; changes in light attenuation, sediment quality, and water 23 quality can threaten the persistence of seagrasses. In BBLEH, eutrophication due to 24 anthropogenic nutrient loading has led to decreased water clarity, increased macroalgal 25 proliferation, and frequent hypoxia (Kennish et al., 2007; Kennish et al., 2011). Concurrently, 26 decreases in areal seagrass meadow coverage have been observed using a combination of 27 remote sensing and field surveys (Lathrop et al., 2006). Within BBLEH, several Ecologically 28 Sensitive Areas (ESAs) have been designated to lessen the effect of both vessel wakes and 29 propeller scars. Many of the ESAs are centered on seagrass meadows, while other wellcolonized areas are not within a protected zone. In this study, we aim to quantify the 30 31 constituents and mechanisms governing light attenuation within seagrass meadows in BBLEH 32 with high temporal resolution at multiple sites. We first detail the observational methods and 33 results of the time-series analysis. We then discuss the spatiotemporal variability of light

attenuation, assign relative contributions from different constituents, address the possible role of vessel wakes and wind-waves on sediment resuspension, and discuss the role of sediment availability on spatial differences in light attenuation. Finally, we compare the differences in light and wave climate between ESAs and non-ESAs, and high-vessel-traffic areas vs. lowvessel-traffic areas.

6

#### 7 2 Methods

#### 8 2.1 Field observations

9 We developed a shallow-water platform designed to measure light attenuation and attenuating constituents in the bottom half of a 1 m water column. The platform consisted of an RBR 10 11 DWave recorder, a pair of WetLabs ECO-PARSB self-wiping photosynthetically active 12 radiation (PAR, 400-700 nm) sensors; a YSI EXO multisonde measuring temperature, salinity, turbidity, chlorophyll-a fluorescence, fluorescing dissolved organic matter (fDOM, a 13 14 proxy for CDOM), pH, and depth; and a Nortek Aquadopp-HR 1 MHz current profiler. All 15 instruments except for the upper PAR sensor were mounted at 0.15 meters above the bed (mab) on a weighted fiberglass grate approximately 1 m x 0.5 m. The lower PAR sensor was 16 recessed inside a PVC tube protruding from the bottom of the frame, intended to penetrate 17 18 into the bed. At two sites this required a water-jet apparatus to fluidize the sediment bed and 19 facilitate penetration; turbidity plumes typically subsided within 1 h. The upper PAR sensor was mounted at 0.45 mab to provide an estimate of light attenuation  $K_{dPAR}$  over the PAR 20

21 spectrum (400-700 nm), calculated as:

22 
$$K_{dPAR} = -\frac{1}{dz} \ln(PAR_{lower}/PAR_{upper})$$
(1)

23 where dz is the distance between the two PAR sensors (0.3 m in this case). Light attenuation 24 was calculated only between the hours of 1030 and 1530, when the angle of the sun relative to 25 the deployment location was closest to 0 degrees (for the June-September period). A second 26 instrument package consisted of an RBR-D|Wave and a WetLabs ECO-NTUSB to measure 27 turbidity; this package was deployed in the navigation channel closest to each site. The platform was attached to vertical structures with the sensors approximately 1.5 m below the 28 29 water surface at mid-tide. All sensors sampled at intervals between 5-10 min, except for the 30 wave recorders which sampled continuously at 6 Hz. Significant wave height and period were 1 calculated using zero-upcrossing statistics over 20 min windows; peak parameters were

2 estimated with a 20 sec window. We identified vessel wakes by comparing the ratio of peak

3 significant wave height over short time windows (20 s) with the wave height over longer time

4 windows (20 min); this technique highlights infrequent increases in wave height that are most

5 likely caused by passing vessels. Spectral density estimates for turbidity, chlorophyll-a, and

6 fDOM were made using the WAFO toolbox (Brodtkorb et al., 2000).

7 We sequentially occupied three shoal/channel sites during the 25 June 2013 – 13 September

8 2013 period (Fig. 1). From south to north, Little Egg Island (LEI<sub>sh</sub>) and the Route 72 bridge

9 (LEI<sub>chan</sub>) were occupied from 25 June – 15 July 2013; Tice's Shoal (TS<sub>sh</sub>) and ICWW marker

10 28 (TS<sub>chan</sub>) were occupied from 16 July – 13 August 2013; and Lavalette (LVL<sub>sh</sub>) and ICWW

11 marker 40 (LVL<sub>chan</sub>) were occupied from 14 August -12 September 2013. Depths were 0.9 m

12 at site  $\text{LEI}_{sh}$ , 0.8 m at site  $\text{TS}_{sh}$ , and 0.6 m at site  $\text{LVL}_{sh}$ . Depths at channel sites varied but

13 instruments were maintained at a depth of 1.5 m below surface at mid-tide.

14 As mentioned above, portions of Barnegat Bay are designated as ESAs, and boaters are

15 encouraged to avoid these areas to minimize damage to seagrass and benthic habitats.

16 Nonetheless, some ESAs experience substantial recreational vessel traffic. Shoal sites were

- 17 chosen to coincide with one of three archetypes: an ESA with minimal vessel traffic (site
- 18 LEI<sub>sh</sub>), an ESA with substantial vessel traffic (site  $TS_{sh}$ ), and a non-ESA with substantial
- 19 vessel traffic (site  $LVL_{sh}$ ). At all three sites, we chose areas with seagrass coverage but
- 20 deployed the platform on bare patches of the bed within the meadow. Bare patches were
- 21 typically 10 m<sup>2</sup>, but surrounded on all sides by vegetation. Kennish et al. (2013) documented
- 22 seasonal and spatial characteristics of seagrass meadows in Barnegat Bay. We averaged
- values from the June-September time period, and summed biomass and areal coverage of all
- 24 species. Northern locations are dominated by *Ruppia* with total dry biomass of 9  $g/m^2$  and
- 25 24% areal coverage, central locations are dominated by Zostera with total dry biomass of 14
- $26 ext{ g/m}^2$  and 32% areal coverage, and southern locations are entirely *Zostera* with total dry
- 27 biomass of  $10 \text{ g/m}^2$  and 26% areal coverage.

#### 28 **2.2** Estimation of light attenuation contributions

29 Preisendorfer (1976) linked  $K_{dPAR}$  with the inherent optical properties (IOPs) including

30 absorption (a), scattering (b), and/or backscattering ( $b_b$ ) coefficients. As measuring scattering

31 accurately remains operationally difficult, Lee et al. (2005) introduced a semi-analytical

1 formulation based only on absorption and backscattering. Gallegos et al. (2011) adopted this

2 approach and adapted it for spectral irradiance to take the form:

3 
$$K_d(\lambda) = (1 + 0.005 \,\theta_0) \,a(\lambda) + 4.18 \left(1 - 0.52 \,e^{-10.8 \,a(\lambda)}\right) b_b(\lambda)$$
 (2)

4 where  $\theta_0$  is the solar incidence angle in degrees, and  $K_{dPAR}(\lambda)$ ,  $a(\lambda)$  and  $b_b(\lambda)$  are the spectral 5 attenuation, absorption and backscattering at frequency  $\lambda$ .

6 In this study, we use the Gallegos et al. (2011) formulation that computes the quantities 7 needed to form spectral attenuation in terms of suspended and dissolved constituents including the effects of water, CDOM, phytoplankton, and non-algal particulates (NAP. e.g., 8 9 detritus, minerals, bacteria). We include absorption by four components: (1) absorption by 10 water was assumed to follow the spectral characteristics of pure water; (2) CDOM absorption was taken proportional to fDOM concentration, with a negative spectral slope (Bricaud et al., 11 1981) set to  $s_{e}=0.0177 \text{ nm}^{-1}$  (within the range of values measured by Gallegos et al., 2011); 12 (3) phytoplankton absorption was proportional to chlorophyll-a concentration and with the 13 14 spectrum shape normalized by the absorption peak at 675 nm (initial value for peak absorption was taken as  $a_{\phi,675}=0.0235 \text{ m}^2 \text{ (mg Chl-a)}^{-1}$ , within the range provided by Bricaud 15 16 et al., 1995); and (4) non-algal absorption was taken as proportional to the total suspended 17 solids (TSS) concentration with a spectral shape (Bowers and Binding, 2006) that included a baseline of  $c_{x1}$ =0.0024 m<sup>2</sup> g<sup>-1</sup> (Biber et al., 2008), an absorption cross-section of  $c_{x2}$ =0.04 m<sup>2</sup> 18  $g^{-1}$  (Bowers and Binding, 2006), and a spectral slope of  $s_r=0.009$  (Boss et al., 2001). The 19 20 backscattering ratio of water was set at 0.5, while CDOM is considered nonscattering 21 (Mobley and Stramski, 1997), and the particulate effective backscattering ratio was initially 22 set at 0.015. The composition of NAP in most environments is largely unknown and rapidly 23 changing resulting in a large variability in the relationship between TSS, absorption and 24 backscattering. While Gallegos et al. (2011) introduced a range of values depending on the 25 different components of the NAP pool, we chose a constant set of parameters that represented 26 averaged conditions; ultimately the relationship between fDOM and CDOM absorbance 27 appeared to be variable (see below). These parameters were varied to obtain the best 28 agreement between observations and the model.

#### 1 **2.3 Sediment sampling methods**

2 Bed sediment samples were collected from the estuarine floor using the mini-SEABOSS 3 system (Valentine et al., 2000), which uses a modified Van Veen sediment grab to collect 0.1 4  $m^2$  undisturbed seafloor sample. Samples in water less than 1 m depth (adjacent to the 5 deployment sites) were collected with a hand-held shovel. The upper 2 cm of the recovered 6 sediment was sampled with a scoop and bagged for textural analysis. Approximately 50 g of 7 wet sample were wet sieved through a 0.062 mm sieve to separate the coarse and fine 8 fractions. Coarse fractions (sand and gravel) were oven-dried, weighed and dry-sieved. Fine 9 fractions (silt and clay) were analyzed using a Coulter Counter Multisizer 3. The combination 10 of both techniques allows for the weight percentages of grain sizes from -5 to 11 phi to be 11 determined. The sediment classification and frequency percentages were calculated using 12 GSSTAT software (Poppe et al., 2004), which is based on the methods of Folk (1974) and 13 Collias et al. (1963). Most sampling locations were optimized to groundtruth boat-based 14 acoustic backscatter data rather than to characterize the sites at which light attenuation was 15 measured, and were therefore depth-limited. At sites LVL<sub>sh</sub> and TS<sub>sh</sub>, there were several samples within 2 km of the instrumentation, and a single sample adjacent to each deployment 16 17 site. At site LEH<sub>sh</sub>, other than the deployment-adjacent sample, the closest sediment samples 18 were approximately 5 km away.

19 3 Results

## 3.1 Temporal variability of light attenuation, constituents, and physical forcing

We discuss the characteristics of the time-series at all shoal sites from south to north, 22 23 beginning with site LEI<sub>sh</sub>. Maximum tidal range was about 0.75 m during spring tides (Fig. 24 2), though water velocity rarely exceeded 0.20 m/s. PAR was successfully measured at the 25 upper sensor, but the lower sensor unexpectedly failed after 5 days, which precludes the direct 26 measurement of  $K_{dPAR}$  over the entire record. We used Eq. 2 to reconstruct  $K_{dPAR}$  for the remainder of the time period; details of the application of Eq. 2 are given at the end of this 27 section.  $K_{dPAR}$  exceeded 7 m<sup>-1</sup> during periods with high turbidity. Turbidity exceeded 50 NTU 28 29 on several days, due to M<sub>2</sub> periodic (12.42 h) tidal advection and diurnal wind-wave 30 resuspension (Figs. 2, 3, 4). Chl-a demonstrated a diurnal signal (Figs. 2, 4), with troughs 31 during peak daylight (and peaks during lowest light); this is a characteristic signature of non-

photochemical quenching (NPQ) whereby chlorophyll fluorescence is reduced at high levels 1 2 of irradiance (Fig. 5; Maxwell and Johnson, 2000; Lawrenz and Richardson, 2011). Given the long residence time in Barnegat Bay (Defne and Ganju, 2014), it is most likely that NPO is 3 4 responsible for these changes rather than tidal advection or daily changes in phytoplankton 5 concentration. The concentration of fDOM was relatively low and constant (Fig. 2) showing a stable relationship with salinity (Fig. 6). Prior work has demonstrated the interference of 6 turbidity with fDOM measurement (Downing et al., 2012); we found low correlation 7 8  $(r^2=0.08)$  between fDOM and turbidity at this site. Significant wave height approached 0.1 m, 9 peaking daily during periods of winds from the south (Fig. 3); peak wave height was 0.14 m. 10 This led to a concurrent increase in turbidity during wave events. Wave period ranged from 11 1.4 to 2.4 s; peak wave periods over 4 s were observed and attributed to vessel passage due to 12 their anomalous nature (not shown). At the channel site, wave heights were almost three times 13 greater (not shown), but out of phase with wind speed. Wave heights in the channel peaked during times with ostensibly more vessel traffic (weekends, early afternoon). We explore the 14 wave characteristics and their relationship to vessel passage at this site further in the 15 16 Discussion section.

17 At site TS<sub>sh</sub>, maximum tidal range was less than 0.40 m, and water velocity was less than 0.20 m/s with substantial subtidal variability (Fig. 2). The reduction in tide range and larger 18 19 influence of subtidal processes on hydrodynamics in northern Barnegat Bay corroborates prior studies (Chant, 2001; Defne and Ganju, 2014). PAR was successfully measured at both 20 sensors during the entirety of the deployment.  $K_{dPAR}$  peaked over 3 m<sup>-1</sup> during a frontal 21 22 passage on 25 July 2013; strong winds from the north led to a wind-wave sediment 23 resuspension event, and increased river runoff from the Toms River decreased salinity and 24 raised fDOM levels. Apart from the duration of this event, turbidity was less than 20 NTU. Chl-a again demonstrated a diurnal signal (Fig. 4), with troughs during peak daylight (and 25 peaks during lowest light); non-photochemical quenching was again suspected (Fig. 5). The 26 concentration of fDOM was higher than site LEI<sub>sh</sub>, with a peak during the event of 25 July 27 28 2013 (Fig. 2); the relationship with salinity strayed slightly from the relationship at site  $LEI_{sh}$ , 29 suggesting a different source of fDOM (Fig. 6). Significant wave height was less than 0.1 m, peaking during periods of strongest winds (Fig. 3); peak wave height was 0.17 m. Wave 30 31 period ranged from 1.4 to 3.5 s; peak wave periods over 5 s were observed regularly (not 32 shown). At the channel site, wave heights were over 0.3 m (not shown).

The northernmost site LVL<sub>sh</sub> had a tidal range of less than 0.40 m, with velocities exceeding 1 2 0.3 m/s during meteorological events (Fig. 2). PAR was successfully measured at both sensors during all but the last week of the deployment.  $K_{dPAR}$  peaked at over 3.0 m<sup>-1</sup> during another 3 frontal passage on 1 September 2013; strong winds from the south led to a wind-wave 4 5 sediment resuspension event with turbidity exceeding 20 NTU. Apart from the duration of this event, turbidity was less than 20 NTU. Non-photochemical quenching was again 6 7 observed in the chl-a time-series (Fig. 5). The concentration of fDOM was higher than site  $TS_{sh}$ , but relatively constant (Fig. 2). The relationship with salinity was markedly different 8 9 than the other sites, suggesting yet another source of fDOM (Fig. 6). Significant wave height 10 was less than 0.05 m, peaking during the frontal passage of 1 September 2013 (Fig. 3); peak 11 wave height was 0.07 m. Wave period ranged from 1.0 to 4.0 s; peak wave periods over 6 s 12 were observed regularly (not shown). At the channel site, wave heights were over 0.1 m (not 13 shown). We discuss the diminished sediment resuspension response to wave forcing at sites 14  $LVL_{sh}$  and  $TS_{sh}$  in the following section.

#### 15 **3.2** Spatial variability of median measurements

The median values of physical forcings, light attenuation, and constituents demonstrate a 16 17 large spatial gradient of external forcings and water quality in Barnegat Bay (Table 1). While 18 tidal velocity was relatively similar over all shoal sites, median wave height was minimized at 19 the northern site LVL<sub>sh</sub>, where limited fetch likely contributes to reduced wave heights. The 20 south-to-north salinity gradient is caused by substantially higher river outflow from northern tributaries such as the Toms and Metedeconk Rivers. This transport, coupled with higher 21 22 nutrient loading in the north (Kennish et al., 2007) likely explains the increased chl-a and 23 fDOM in the northern bay. However, light attenuation is maximized in the southern bay at site LEI<sub>sh</sub> due to elevated turbidity. Both fDOM and chl-a were minimized at this site, due to 24 25 reduced freshwater and nutrient loading. Measurements at the continuously occupied site Mantoloking indicate that the sequential nature of our deployments did not complicate 26 interpretation of these patterns: turbidity was relatively constant throughout the summer, 27 28 while neither fDOM nor chl-a increased as summer progressed, while there was an increase spatially as sites were occupied from south-to-north). 29

#### 1 **3.3 Sediment composition**

2 Samples were collected at 9 locations near sites LVL<sub>sh</sub> and TS<sub>sh</sub>, and 12 locations southwest 3 of LEI<sub>sh</sub>, as well as one sample adjacent to each deployment site (Fig. 7). Grain-size analyses 4 revealed a coarsening of sediment from south to north (Table 2). Samples collected adjacent 5 to site LEI<sub>sh</sub> had over double the clay percentage of the other sites and less sand. Median 6 particle diameter  $D_{50}$  at site LEI<sub>sh</sub> was in the medium silt range, while  $D_{50}$  was in the very 7 fine sand and coarse silt range at sites  $TS_{sh}$  and  $LVL_{sh}$ , respectively. Sites  $TS_{sh}$  and  $LVL_{sh}$ both reside on the landward side of the barrier island, which has historically been subjected to 8 9 overwash events (Donnelly et al., 2007). Overwash processes deposit sand on the landward 10 side of the barrier island into the estuary leading to coarser deposits in these areas (Oertel, 11 1985). Conversely, site LEI<sub>sh</sub> is on the landward side of the estuary adjacent to the mainland, 12 which is fringed by extensive marsh. These marshes represent a local source of fine sediment that can be released during marsh collapse under wave forcing (Mariotti and Fagherazzi, 13 14 2013; Ganju et al., 2013).

15

#### 16 4 Discussion

#### 17 **4.1** Relative contributions to light attenuation

18 The application of Eq. 2 allows for estimating the relative contributions of turbidity, chl-a, 19 and CDOM to light attenuation at each site (Table 3). Turbidity dominated the light 20 attenuation at site LEI<sub>sh</sub>, while chl-a was dominant at site TS<sub>sh</sub>; CDOM was important at site 21 LVL<sub>sh</sub> (though secondary to turbidity) due to its proximity to freshwater sources such as the 22 Toms River. These results suggest that physical processes (sediment resuspension and advection) are dominant at sites LEIsh and LVLsh, while water-quality processes (nutrient 23 loading and phytoplankton proliferation) are more important at site TS<sub>sh</sub>. This is supported by 24 25 the residence time calculations of Defne and Ganju (2014) that demonstrate areas between sites TS<sub>sh</sub> and LVL<sub>sh</sub> are poorly flushed, leading to less dilution of estuarine waters by 26 27 seawater and enhancing phytoplankton proliferation.

Before implementing the light model, we removed the effect of non-photochemical quenching (Fig. 4) by eliminating chl-a measurements during periods when PAR exceeded 50  $\mu$ E/m<sup>2</sup>/s and filling the gaps using linear interpolation. We selected an initial slope of fDOM fluorescence to CDOM absorbance based on measurements from several estuaries (Chen et

1 al., 2008). We then applied the model with the default parameters noted above (Table 4), and 2 compared modeled  $K_{dPAR}$  to the field measurements at each site. We modified three parameters selectively based on correlations between residual error and the different 3 4 constituents to obtain the highest correlation and lowest error (Fig. 8). Attempts at a standard 5 multiple linear regression model led to spurious results in some cases (e.g. inverse 6 relationship between fDOM and  $K_{dPAR}$  at site LVL<sub>sh</sub>). The variability in the fDOM vs. salinity 7 relationship supports the possibility that the source and optical properties of colored organic 8 matter varies spatially in Barnegat Bay; Oestreich et al. (2014) demonstrated large spatial variability in CDOM absorbance potential per unit fluorescence, as a function of source. 9 10 Spectral slope within Barnegat Bay varied by approximately 15%, resulting in calculated changes to  $K_{dPAR}$  of less than 4%. Additionally, variability in turbidity and organic content of 11 12 suspended sediment also suggests that particulate backscattering ratio may be spatially 13 variable; suspended-sediment samples demonstrated organic content ranging from 13% at site 14 LEI to 60% at site LVL. The backscattering ratio change from 0.015 to 0.025 at LEI<sub>sh</sub> is within the range (0.0024 to 0.06, Loisel et al., 2007 and Snyder et al., 2008) provided by 15 Gallegos et al. (2011). While scattering by organic particles is strongly in the forward 16 17 direction (smaller value of  $b_{b(part)}$ ), mineral particles, having larger refraction indices, scatter a 18 greater fraction of light in the backward direction (larger  $b_{b(part)}$ ). The dependency of 19 backscattering on particle size results in smaller modifications of  $b_{b(part)}$  than the refraction 20 index differences between organic and mineral particles (Gallegos et al., 2011). Thus a larger 21 backscattering ratio was expected in the areas with higher turbidity (site LEI). Finally, marked 22 variability in phytoplankton community composition suggests that chlorophyll absorbance at 23 specific wavelengths may be variable (Ren, 2013). The chlorophyll-specific absorption coefficients of natural phytoplankton ( $a_{\phi,675}$ ) exhibit substantial variability (Bricaud et al., 24 25 1995) with higher values for oligotrophic waters and smaller coefficients for eutrophic environments, which is consistent with the lower absorption coefficient chosen for LVLsh 26 27 (highest chl-a concentration).

At the lower end of the comparison between observed and modeled  $K_{dPAR}$  (i.e. modeled  $K_{dPAR}$ </br>29<1.6), we find reduced sensitivity of the model to changes in observed turbidity, chl-a, and</td>30fDOM. This could be due to changes in either particle characteristics or other effects that31would be more obvious at low attenuation, such as interference from surface waves. It is also32possible that the model parameterization for the three attenuating substances fails at the low33end because the parameters (Table 4) are not static. We are also assuming that constituent 1 concentrations are uniform between the two PAR sensors; changes in vertical gradients 2 between quiescent and energetic periods could also alter the agreement. We chose to optimize 3 the relationship for high  $K_{dPAR}$ , but could have alternatively selected parameters to optimize 4 for agreement at the low end.

#### 5 **4.2** Temporal and spatial variability in light attenuation

Many prior studies and current estuarine monitoring protocols utilize infrequent (e.g. daily or 6 7 weekly) sampling for water quality parameters including light attenuation (or secchi depth as 8 a proxy). We found that temporal variability in light attenuation at each site was much larger 9 than the difference between the median values at the three sites. At site LEI<sub>sh</sub>, maximum  $K_{dPAR}$  was over 7 m<sup>-1</sup> during a wind event, which caused increased turbidity; during quiescent 10 periods  $K_{dPAR}$  decreased to 1.2 m<sup>-1</sup>. At site TS<sub>sh</sub>, a storm/runoff event raised  $K_{dPAR}$  to a peak 11 value of 2.8 m<sup>-1</sup>; the minimum value was 0.8 m<sup>-1</sup>. Another wind event led to a peak  $K_{dPAR}$  of 12  $2.9 \text{ m}^{-1}$  at site LVL<sub>sh</sub>, while the minimum value was under 1.0 m<sup>-1</sup>. Daily or weekly sampling 13 14 would not capture this variability and sampling during a peak or minimum event (more likely, as sampling is biased towards calm conditions) may skew the resulting interpretation of light 15 penetration. We find that daily sampling at a set time (8:00 am local time, in this case) 16 17 resulted in mean light attenuation errors ranging from 2% at site TS to 17% at site LEI. Sites 18 with large temporal variability in constituents, like turbidity, will likely have the largest 19 increases in error as sampling interval is lengthened. While it is cost-prohibitive to monitor 20 light attenuation continuously at multiple sites, spatial and temporal patterns deduced from 21 infrequent measurements should be interpreted with care or supplemented by more complete measurements (e.g. proxy measurements or modeling). 22

23 Spatially, the increased light attenuation in the south is mainly forced by turbidity. Regular 24 resuspension and advection events on tidal and diurnal timescales (Figs. 2, 3, 6) increase 25 turbidity and light attenuation at site LEI<sub>sh</sub> throughout the deployment. Moving northward, 26 light attenuation is governed increasingly by biogeochemical components, congruent with the longer residence time and decreased flushing in the northern bay (Defne and Ganju, 2014). 27 28 The northern bay is also subjected to elevated nutrient loads from the more developed 29 watershed (Kennish et al., 2007). Conversely, the southern portion of the bay is fringed by 30 wetlands, which represent a large source of fine sediment through shoreline erosion (see below). This pattern suggests a south-to-north gradient in light attenuation that is forced by a 31 32 south-to-north gradient in physical forcing, sediment availability, and nutrient loading.

## 4.3 Sediment transport on the shoals: resuspension mechanisms and fine sediment supply

3 Sediment sampling confirmed a greater abundance of clay-sized material in the southern bay, 4 suggesting an increased likelihood of resuspension under wave forcing. We computed wave-5 current combined bed shear stresses (Madsen, 1994) at the three shoal sites and found varying 6 resuspension responses to bed stress. At sites LEI<sub>sh</sub> and TS<sub>sh</sub>, turbidity responded linearly 7 with stress; but turbidity was nearly 5 times larger at site LEI<sub>sh</sub> for a given stress (Fig. 9). This 8 confirms a larger repository of erodible material at the site, likely due to supply from adjacent 9 wetlands. Samples closest to site TS<sub>sh</sub> indicate that the bed is nearly all sand-sized material, 10 which would only be resuspended at the highest stresses (Fig. 9). At site LVL<sub>sh</sub>, the weak 11 correlation and diminished resuspension response suggests a limited pool of erodible material. 12 The secondary spectral density peak at the M<sub>2</sub> tidal period at LEI<sub>sh</sub> (Fig. 4) raises the 13 possibility that sediment advection from a far-field source may be important, and that local 14 resuspension is not dominant. Waves accounted for 56% of the calculated shear stress at site 15  $LEI_{sh}$ , 64% at site  $TS_{sh}$ , and 45% at site  $LVL_{sh}$ .

16 Turbidity measurements at all channel/shoal-paired sites show that longitudinal (north-south) 17 variability was larger than lateral (channel-shoal) variability (Table 5). Median and extreme 18 (99%) values of turbidity were similar between paired sites; correlation was highest in the 19 south (where forcing was consistent) and lower in the north where episodic events dominated. 20 Estuarine shoals are typically subjected to greater wind-wave resuspension than channels, but the channels are the conduit for subsequent advection of suspended sediment. Given the 21 22 dominance of shoals in Barnegat Bay, it is not surprising that channels adjacent to shoals are 23 influenced by shoal processes. As discussed above however, the longitudinal variability in 24 sediment source and availability explains the large longitudinal gradient in turbidity and light attenuation. From a sampling point-of-view, it appears that dense longitudinal sampling is 25 26 more critical than lateral sampling, at least for turbidity and suspended-sediment 27 concentration. The role of submerged aquatic vegetation in shoal resuspension processes can 28 be substantial. Seagrass canopies can alter the velocity profile (Lacy and Wyllie-Echeverria, 2011) and dampen waves (Fonseca and Cahalan, 1992). While we did not quantify the effect 29 of seagrass meadows on these processes, it is possible that differences in vegetative density 30 31 and areal coverage could modify the response of the seabed to a given resuspension event.

#### 1 **4.4** Role of vessel wakes in sediment resuspension

2 Due to the frequent resuspension and advection events at site LEI<sub>sh</sub> (relative to the northern sites), we focused our analysis of vessel-induced sediment resuspension on this site. At the 3 4 shoal site the ratio of 20 s significant wave height to 20 min significant wave height hovered 5 about 1, indicating almost no local vessel wakes, while the ratio fluctuated widely at the 6 channel site (Fig. 10). Turbidity between the channel and shoal was well-correlated with 7 similar medians and extreme values (Table 5); however correlation between wave height and wind speed is weak at the channel site  $(r^2=0.03)$  but strong at the shoal site  $(r^2=0.44)$ . 8 9 Similarly, correlation between turbidity and wave height at the channel site is extremely low  $(r^2 < 0.01)$  while it is high at the shoal site  $(r^2=0.52)$ . This suggests that local resuspension 10 from wind-waves is responsible for increased turbidity at the shoal site, and that advection 11 12 from shoals is responsible for increases in turbidity at the channel site. It also suggests that the 13 shoal site is representative of a broader area; i.e. diurnal winds over the entire southern bay 14 increase turbidity throughout the area allowing for advection into the channels. Wave heights 15 in the channel tended to peak in the late afternoon (local time) though the peak of wake occurrence varied, while wave heights over the shoal peaked during the period of maximum 16 17 winds. We also estimated wave heights over the shoals with a fetch-limited, shallow water approximation (USACE, 1984) and with a SWAN (Booij et al., 1999) wave model of 18 19 Barnegat Bay forced with steady winds in the northerly direction. These simulations show 20 that the observed winds are more than capable of causing the observed waves, without 21 invoking vessel wakes (Fig. 11). However, given the separation between the sites it is likely 22 that vessel wakes in the channel are attenuated rapidly as they encounter the channel-shoal 23 transition. At these locations it is possible that turbidity is locally enhanced, but this is not 24 reflected in either channel or shoal measurements.

#### **4.5** Influence of regulation, ESA status, and vessel traffic on light attenuation

Increased population in the Barnegat Bay region has led to concerns about the effect of recreational boating on estuarine ecological function (EPA, 2007). In response to these concerns, Environmentally Sensitive Areas (ESAs) were established to ostensibly protect seagrass-colonized shoals from scarring and sediment resuspension due to vessel traffic (NJDEP, 2012). We occupied three distinct vegetated shoal habitats in Barnegat Bay, each representing a different combination of protection and anthropogenic exposure (Lathrop and Haag, 2011): 1) a protected ESA near an area with lower coastal development and vessel

1 harborage (site LEI<sub>sh</sub>); 2) a protected ESA with relatively high recreational vessel traffic (site 2  $TS_{sh}$ ); and 3) an unprotected site with relatively high recreational vessel traffic (ste LVL<sub>sh</sub>). Our results show that physical variables (wind-wave resuspension, sediment availability) 3 outweigh both protection and potential vessel traffic in terms of light attenuation over 4 5 seagrass meadows. Site LEI<sub>sh</sub> is designated for protection, yet light attenuation is maximized at that site due to wind-waves and sediment resuspension. Both of these parameters are 6 7 outside the sphere of regulation and suggest that a future decrease in light attenuation to 8 seagrass meadows at this site is unlikely (in lieu of a long-term depletion of sediment supply). 9 It should be noted that protection does decrease the likelihood of propeller scarring, 10 something this study does not address. The light attenuation and constituent measurements 11 provide an estimate of what gains can be made through reduction of anthropogenic nutrient 12 loads. Sites TS<sub>sh</sub> and LVL<sub>sh</sub> stand to benefit the most from mitigation of eutrophication as 13 phytoplankton concentrations may decrease with nutrient loading reductions. This will also 14 diminish the proliferation of macroalgae, which compete with seagrass and have been 15 implicated in seagrass loss.

16

#### 17 **5 Conclusions**

18 Understanding the temporal and spatial variability of light attenuation is critical for 19 establishing potential success of seagrass community restoration and estimating the recovery 20 of estuaries from eutrophication. We quantified light attenuation and dissolved and particulate 21 light inhibitors with high-temporal resolution in three seagrass meadows of Barnegat Bay, 22 New Jersey. We found a strong south-to-north gradient in light attenuation that is mainly 23 forced by turbidity and sediment supply in the southern part of the bay. Regular wind-wave resuspension, infrequent storms, and runoff events all contributed to sizable temporal 24 fluctuations in light attenuation at all shoal sites. Individual storms were capable of doubling 25 light attenuation over periods longer than 1 d through wind-wave resuspension and increased 26 27 river flow. Changing patterns of storm intensity and frequency may have a long-term effect on the light climate in back-barrier estuaries. Wave heights and turbidity over the shoals 28 29 appeared to be the result of wind rather than vessel traffic. Light attenuation was lowest in the 30 most trafficked areas of the estuary, indicating that direct impact of vessel wakes on light 31 attenuation is minimal. Spatial and temporal data of this type are necessary for modeling the 32 response of seagrass communities to sea-level rise, storms, and nutrient loading. Numerical models of hydrodynamics, sediment transport, and ecology can be constrained with these
measurements and used to guide restoration and habitat characterization.

3

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14

#### 15 Author Contributions

16 N.K.G. designed the time-series experiment and analyzed the time-series data, A.L.A. 17 implemented the light model, and J.L.M. designed the sediment sampling program and 18 analyzed the surficial sediment data. All authors contributed to the drafting of the manuscript.

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1Table 1. RMS values of velocity (absolute value), and median values of wave height, salinity,2light attenuation  $K_{dPAR}$ ) and attenuating constituents from three sites and reference site3Mantoloking. Value in parentheses at Mantoloking covers the same temporal overlap of the4study sites.

	LEI <sub>sh</sub>	TS <sub>sh</sub>	LVL <sub>sh</sub>	Mantoloking
RMS velocity (m/s)	0.06	0.05	0.07	N/A
Wave height (m)	0.02	0.02	0.01	N/A
Salinity (psu)	28	26	18	N/A
$K_{dPAR} (\mathrm{m}^{-1})$	2.7 (1.9) <sup>a</sup>	1.4	1.4	N/A
Chl-a (RFU) <sup>b</sup>	12	21	24	9 (8, 4, 13)
fDOM (qsu) <sup>c</sup>	10	19	39	0.6 (1, 2, 0.2)
Turbidity (NTU)	12	6	6	6 (7, 7, 6)

<sup>a</sup>First value is from period with complete PAR data (26-30 June 2013), second value is
reconstructed data for entire period (26 June – 16 July 2013) using Eq. 2

7 <sup>b</sup>Chl-a values at Mantoloking are reported in ug/L.

8 <sup>c</sup>fDOM values at Mantoloking are reported as CDOM in mg/L.

1 Table 2. Sediment grain-size results for combined samples collected near deployment sites

	Parameter	LEI	TS	LVL
	% sand	43	62	55
	% silt	39	31	38
	% clay	18	7	7
	D <sub>50</sub> (mm)	0.028	0.084	0.056
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4				
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2 with mini-SEABOSS grab sampler.

1 Table 3. Contributions to light attenuation from three constituents. The effect of water depth

	Constituent	LEI <sub>sh</sub>	$TS_{sh}$	LVL <sub>sh</sub>
	Chl-a	17%	44%	22%
	CDOM	14%	21%	36%
	Turbidity	69%	35%	42%
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4				
5				
6				
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2 is removed from these calculations.

Table 4. Parameters used for light model of Gallegos et al. (2011), Eq. 2:  $s_g$  = spectral slope of CDOM;  $a_{\phi,675}$  = chlorophyll peak absorption;  $c_{x1}$  = baseline non-algal absorption;  $c_{x2}$  = non-algal absorption cross-section;  $s_x$  = non-algal spectral slope;  $b_{b(water)}$  = backscattering by water molecules;  $b_{b(part)}$  = backscattering by particulates.

Parameter	LEI <sub>sh</sub>	TS <sub>sh</sub>	LVL <sub>sh</sub>	
$s_g (\mathrm{nm}^{-1})^{\mathrm{a}}$	0.0177	0.0177	0.0177	
$a_{\phi,675} (\mathrm{m^2  mg^{-1}})$	0.0235	0.0235	0.0130	
$c_{x1} (m^2 g^{-1})^b$	0.0024	0.0024	0.0024	
$c_{x2} (\mathrm{m}^2 \mathrm{g}^{-1})^{\mathrm{c}}$	0.04	0.04	0.04	
$s_x (\mathrm{nm}^{-1})^{\mathrm{d}}$	0.009	0.009	0.009	
$b_{b(\text{water})}$	0.5	0.5	0.5	
$b_{b(\text{part})}$	0.025	0.015	0.015	

<sup>6</sup> <sup>a</sup>Gallegos et al., 2011; <sup>b</sup>Biber et al., 2008; <sup>c</sup>Bowers and Binding, 2006; <sup>d</sup>Boss et al., 2001.

- -

	Statistic	LEI <sub>sh</sub>	LEI <sub>chan</sub>	$TS_{sh}$	$TS_{chan}$	$LVL_{sh}$	LVL <sub>chan</sub>
	$r^2$	0.38		0.30		0.24	
	50% (NTU)	12	13	5.7	6.0	6.2	6.9
	99% (NTU)	54	47	14	22	18	14
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1 Table 5. Statistics and correlation of turbidity between channel and shoal at three sites.

Figure 1. Map of Barnegat Bay, on the New Jersey Atlantic coast. Shoal sites are marked with
 a star; channel sites are marked with a circle. Estuarine bathymetry is from recent USGS
 mapping (unpublished).

4 Figure 2. Time-series of water level, photosynthetically active radiation (PAR), light 5 attenuation over the PAR spectrum ( $K_{dPAR}$ ), turbidity, chlorophyll-a fluorescence (Chl-a), and 6 fluorescing dissolved organic matter (fDOM) for each site, starting from the south on the left. 7 Grey trace in bottom three panels are reference values from site Mantoloking.

8 Figure 3. Time-series of north-south winds (positive winds from the south), water level,
9 significant wave height at shoal sites, and turbidity for each site, starting from the south on the
10 left.

Figure 4. Spectral density of turbidity, chlorophyll-a, and fDOM time-series from three shoal sites. Dashed lines correspond to M<sub>2</sub> tidal period (0.5175 days) and the diurnal period (1 d). Note the difference in y-axis scaling at LEI<sub>sh</sub> in comparison to the other two sites.

Figure 5. Relationship between binned near-surface irradiance in the PAR spectrum (400-700 nm) and measured chlorophyll-a fluorescence. Bounds are one standard deviation of measured fluorescence within each bin. Fluorescence decreases with irradiance at all shoal sites, indicating substantial non-photochemical quenching (NPQ) of fluorescence.

Figure 6. Relationship between salinity and fDOM at three shoal sites, with linear regressions
for each population. The three sites appear distinct, suggesting variability in the nature of the
fDOM source.

Figure 7. Surficial sediment composition adjacent to deployment sites. A higher abundance of clay sized sediment is available near site LEI as compared to the other sites.

Figure 8. Agreement between observed  $K_{dPAR}$  over the PAR spectrum and the spectral attenuation model of Gallegos (2011).

Figure 9. Relationship between wave-current combined shear stress and turbidity at three shoal sites; darker symbols are instantaneous data binned and averaged in 0.01 Pa intervals. Site LEI<sub>sh</sub> demonstrates enhanced resuspension as compared to other sites under similar stress conditions; surficial sediment distribution indicates a higher abundance of fine material in the southern part of the system.

- 1 Figure 10. Example of a single day of significant wave height (H<sub>sig</sub>) data from sites LEI<sub>chan</sub>
- 2 and LEI<sub>sh</sub>, and the ratio of 20-s window significant wave height  $(H_{sig20})$  to 1200-s window
- 3 significant wave height ( $H_{sig1200}$ ). The latter metric is used to identify vessel wakes, which are
- 4 observed frequently at site LEI<sub>chan</sub>, but seldom at site LEI<sub>sh</sub>.
- 5 Figure 11. Measured and modeled wave-height response to wind at site  $LEI_{sh}$ ; the USACE
- 6 formulation neglects spatial variation in bathymetry, the SWAN model does not include the
- 7 influence of tidal currents and assumes a constant, uniform wind field.















% Clay



74°18'W

74°15'W







