PARTICULATE BULK REFRACTIVE INDEX DISTRIBUTIONS IN COASTAL REGIONS AS DETERMINED FROM BACKSCATTERING RATIO MEASUREMENTS

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INTRODUCTION

The particulate bulk refractive index of different water masses may be used to estimate the relative amounts of suspended organic and inorganic particles within the water column. Phytoplankton cells have refractive index values (~1.015 - 1.075) (Aas 1996, Ackleson & Spinrad 1988, Carder et al. 1972) that are typically lower than that of inorganic mineral particles (~1.15 - 1.20) (Jerlov 1976, Lide 1997). The lower refractive index of living phytoplankton is a product of their high water content (Aas 1996) and one of the reasons that phytoplankton weakly backscatter light (Bricaud et al. 1983). Thus, the backscattering ratio (the proportion of particulate backscattering to total particulate scattering) for phytoplankton dominated waters are normally lower than those of waters where suspended inorganic minerals and detritus dominate (Stramski & Morel 1990).

A model based on Mie theory (Twardowski et al. 2001) was used to determine bulk particulate refractive index from readily obtainable in-situ optical measurements. Bulk refractive index was estimated using the backscattering ratio and the slope of spectral beam attenuation. The only required in-situ optical measurements for the model were the particulate backscattering coefficient, the total particulate scattering coefficient, and the particulate attenuation coefficient. These measurements were made using a ship-deployed profiler in several different shallow coastal regions around the United States to examine the relative amounts of organic and inorganic particles in waters with varying bottom sediments and hydrodynamics.

METHODS

In-situ optical and hydrographic measurements were made using a ship-deployed vertical profiler that contained a Seabird SBE25 CTD, dissolved oxygen sensor, WETlabs Eco-VSF (3 angle backscattering sensor at 532nm) and two WETlabs ac-9's (in-situ absorption and attenuation sensor at nine different wavelengths). One ac9 measured absorption and attenuation in the dissolved and particulate fractions, a_{pg} and c_{pg}, respectively, and the second ac9 had a 0.2 µm pre-filter on its water intakes to measure the dissolved fraction of absorption. By subtraction, this allowed the particulate absorption and attenuation coefficients to be obtained. Particulate scattering coefficients were obtained by subtracting particulate absorption from particulate attenuation. The ac-9s were calibrated before each cruise. The methods used for ac-9 calibration and corrections for temperature, salinity and scattering errors are described in Twardowski et al. (1999). Particulate backscattering coefficients from the Eco-VSF data where calculated using the methods of Moore et al. (2000). Chlorophyll *a* concentration (*Chl*) was estimated using a relationship developed by C. Roesler (Bigelow Laboratories, personal communication) where:

$$Chl\ (\mu\text{g/L}) = (\ a_{\text{pg}}(676) - a_{\text{pg}}(650)\ )\ /\ 0.014$$

The model (Twardowski et al. 2001) used to estimate particulate bulk refractive index ($\hat{n}_p(\widetilde{b}_{bp}, \gamma)$) as a function of the particulate backscattering ratio ($\widetilde{b}_{bp}$) and the hyperbolic slope of the particulate attenuation spectra (γ) is given below:

$$\hat{n}_p(\widetilde{b}_{bp}, \gamma) = 1 + \widetilde{b}_{bp}^{\ 0.5377+0.4867\ (\gamma)2}\ [1.4676 + 2.2950(\gamma)^2 + 2.3113\ (\gamma)^4].$$

After initial processing and correction of the data sets, all data were binned to 1 meter intervals and the final optical calculations completed, except for one very shallow field site (< 3 m) that was binned to 10 cm intervals.

RESULTS

Field data were collected at the following sites around the coastal USA (see Table 1): East Sound, WA, Pensacola Bay, FL, the Gulf of Mexico off the coast of Pensacola, FL, the Gulf of Mexico south of Terrebonne Bay, LA, Narragansett Bay, RI and Rhode Island Sound. Representative profiles from each site are presented in Figure 1.

Table 1. Field sites sampled and characteristics.

Site, lat/long	**time of year**	**type**	**average bottom depth (m)**	**nominal sediment type**	**typical productivity around sample time**
East Sound, WA (48.64 N, 122.88W)	May	stratified fjord	30	fine mud, rocky	high
Pensacola Bay, FL (30.34 N, 87.16 W)	Sept.	partially mixed estuary	5	fine mud	medium
Gulf of Mexico off the coast of Pensacola, FL (30.28 N, 87.25 W)	Sept.	shelf	20	sandy	low
Gulf of Mexico south of Terrebonne Bay, LA (28.61 N, 90.42 W)	April	shelf	25	sand, fine mud	low
Narragansett Bay, RI (41.66 N, 71.38 W)	April	well mixed estuary	8	fine mud, rocky	high
Rhode Island Sound, mouth of Narragansett Bay (41.44 N, 71.41 W)	June	estuarine/ shelf	28	fine mud, rocky	medium

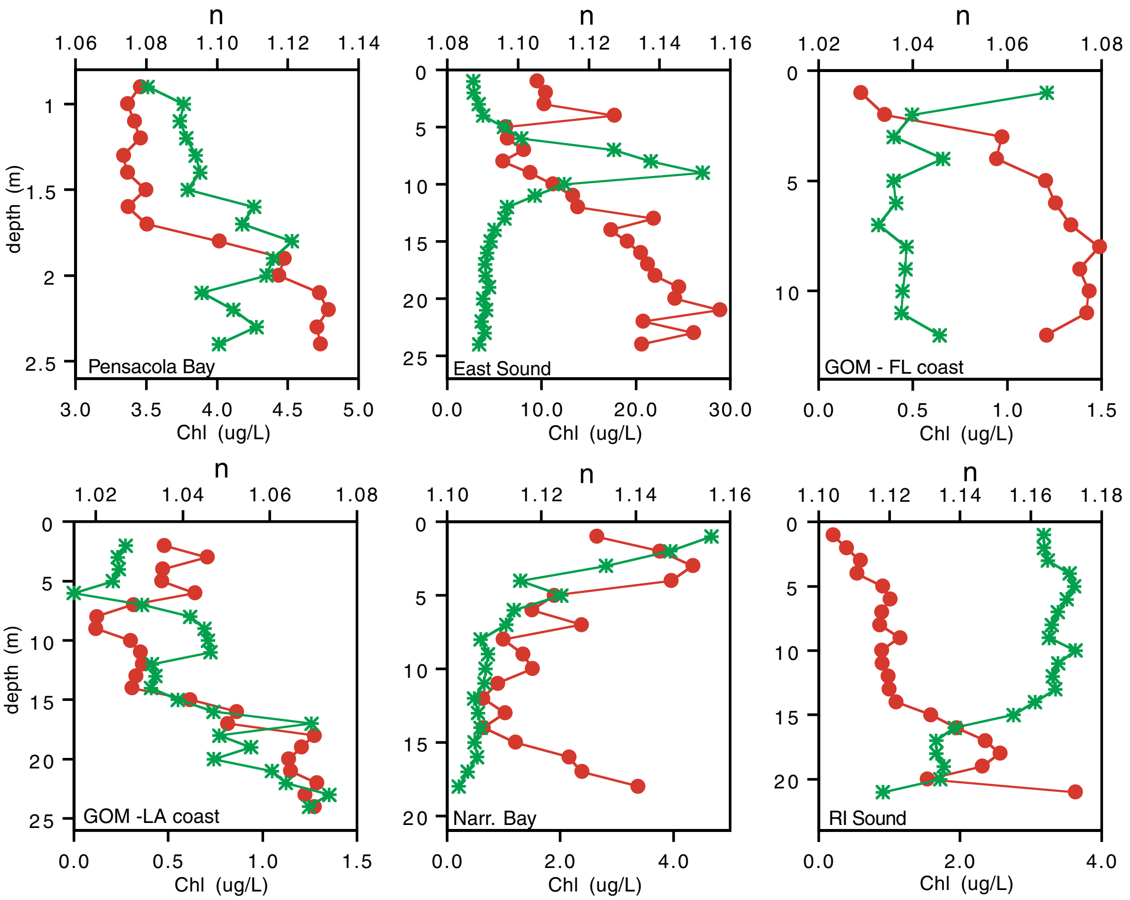

Figure 1. Bulk refractive index, n (red symbols) and chlorophyll concentration, Chl (µg/L) (green symbols) as a function of depth for the six field sites examined (Note different scales).

DISCUSSION

Bulk refractive index estimates where generally found to increase near bottom sediments and decrease in surface waters with high levels of phytoplankton, as evidenced by chlorophyll concentrations. The increase in bulk refractive index near the bottom was expected in these shallow coastal sites where resuspension of bottom sediments is common. At most sites, the lowest bulk refractive indices in the water column generally occurred at the same depth as chlorophyll peaks. It appears that the estimated bulk refractive index values fell within a realistic range and had reasonable vertical distributions.

The mean magnitude of refractive index values through the water column appeared to be related to distance from shore, where the closer to shore, the higher the mean refractive indices. This is apparent in comparing the near shore sites (East Sound, Narragansett Bay, RI Sound, and Pensacola Bay) with the coastal Gulf of Mexico sites, which were a few kilometers (off Pensacola, FL) and approximately 50 km (off LA) from shore, respectively. This observation is consistent with near shore sites experiencing a greater degree of sediment resuspension due to tidal and land boundary effects.

Both of the coastal Rhode Island sites had high overall refractive index values. These sites tend to be well-mixed and this is reflected in the apparent high percentage of resuspended inorganic particles throughout the water column. Gravimetric analyses for organic and inorganic particulate material in recently collected samples near the mouth of Narragansett Bay confirm this fact, with inorganic material comprising about 60% of total particulate mass (M. Twardowski, unpubl. data).

The lowest refractive index values (and chlorophyll concentrations) were found at the Gulf of Mexico sites. Both of these sites appeared to have coarse sand bottom sediments mixed with some fine mud. The low refractive index values may be a function of low resuspension, as mentioned above, or that the larger sandy sediments do not stay in suspension as long as the smaller fine grained particles at other sites. Thus, even though phytoplankton abundance was low, phytoplankton appeared to nonetheless dominate the particle population in these regions.

The East Sound, WA site had moderate to high refractive index values similar to the Rhode Island sites, even though it also had the highest phytoplankton abundance. At this time of year, this site is normally stratified and resuspension of inorganic bottom sediments may not be the driving force behind the overall high refractive index values of the water column. Detrital particles and marine snow have been found, however, in high abundance within the water column of East Sound (Alldredge et al. 2002). If these particles had relatively low water content, approximately 40% or less, and were in high abundance relative to phytoplankton during the sampling period, then it is possible these condensed organic particles could account for the observed levels.

Another possibility for the elevated refractive indices in East Sound could be the presence of extremely fine glacial silt suspended in the water column. The waters of East Sound have a strong influence from the Fraser River, approximately 40 km to the north. Fraser River plumes contain glacial silt remnant from the Cascade Mountain range which gives these plumes a characteristically strong remote sensing reflectance signal (Fig. 2). It may be possible that the very fine silt remains suspended in these waters long enough to be present in detectable amounts in East Sound.

The data presented here provide evidence to the usefulness of the backscattering ratio as an indicator of bulk particle composition. The discrimination between particulate organic and inorganic material seems particularly well suited for studies of sediment resuspension in coastal regions. It is clear, however, that increased validation efforts are required at this time to more thoroughly characterize the model's performance.

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Figure 2. Image of suspended sediment concentration in the Strait of Georgia, around the San Juan Islands (containing East Sound), Puget sound to the southeast, and the surrounding region. Suspended sediment is derived from bands 1 and 2 of the NOAA 14 satellite. The very bright signal associated with the Fraser River plume and surrounding regions is from glacial silt. Image courtesy of the Institute of Ocean Sciences, British Columbia, Canada. Recorded July 19, 1997 (see http://www.pac.dfo-mpo.gc.ca/sci/satelliteimages/noaaimages.htm).