

Why Should We Measure Optical Backscattering

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INTRODUCTION

In recent years commercial sensors for *in situ* determinations of optical backscattering coefficient, b_b , have become available. The small size and low power requirements of these sensors permit deployment from small sensing platforms such as autonomous underwater vehicles, in addition to standard profiling packages. Given their rapid sampling time (sub second) they can collect data with high temporal and spatial resolution (sub meter).

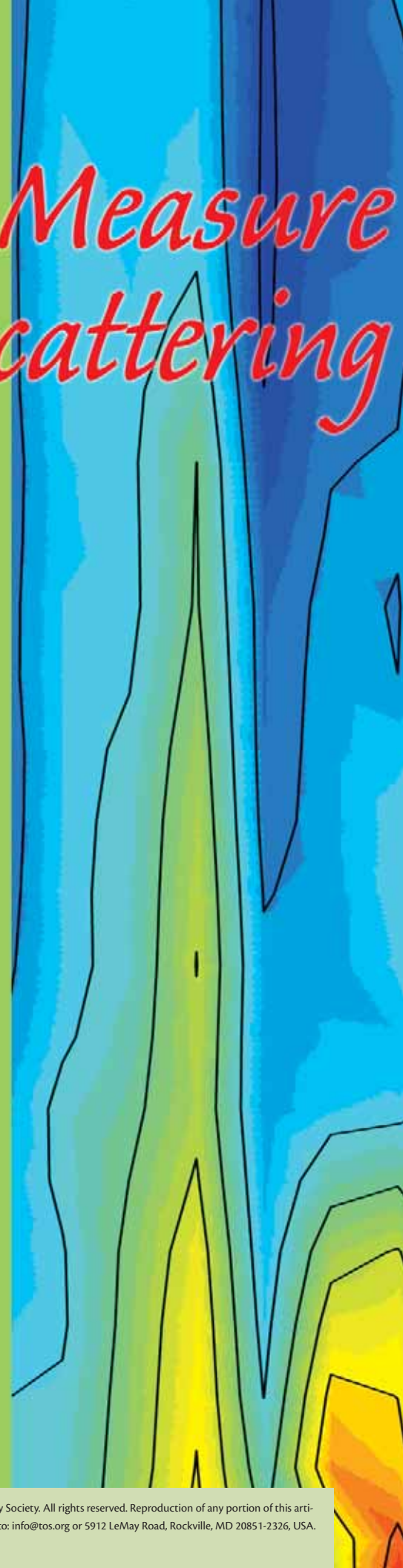
While these are attractive features of any sensor they do not answer the question: why should oceanographers measure b_b ?

The short answer is that b_b carries useful information about seawater constituents that scatter light. The potential to derive information about the abundance and the types of suspended marine particles, which play different roles in ocean ecosystems and biogeochemical cycling, is particularly attractive. To first order, the b_b coefficient is a proxy for particle abundance but it also depends significantly on particle size distribution and particle composition, for example, on relative proportions of small and larger particles or on whether the particles are organic or inorganic. Most importantly, however, the spectral reflectance of the ocean (known as ocean color) is, to first order, pro-

portional to b_b . The measurements of ocean color from remote optical sensors on satellites provide a unique capability to monitor surface ocean properties (e.g., chlorophyll concentration and biological primary productivity) over extended spatial and temporal scales. Measurements and fundamental understanding of b_b are required for understanding and successful applications of remotely sensed ocean color.

WHAT IS OPTICAL BACKSCATTERING?

When a photon of light propagates in water and interacts with a “particle” (varying from water molecules to fish) it can either be absorbed, be redirected (scattered), or continue to propagate in the same direction (un-attenuated). The optical backscattering coefficient (b_b) refers to all the photons that have been redirected in the backward directions (Figure 1). Specifically, b_b is defined as the fraction of incident light that is scattered in the backward direction per unit distance traveled by the photons. Its units are inverse meter (m^{-1}). For a given distance of water, r , the fraction of incident light beam that is lost to backscattering equals: $\exp(-b_b r)$. The sum of the backscattering coefficient, b_b , and the forward scattering coefficient, b_p , yields the total scattering coefficient, b .



the Coefficient?

THE POTENTIAL TO DERIVE INFORMATION ABOUT THE ABUNDANCE AND THE TYPES OF SUSPENDED MARINE PARTICLES, WHICH PLAY DIFFERENT ROLES IN OCEAN ECOSYSTEMS AND BIOGEOCHEMICAL CYCLING, IS PARTICULARLY ATTRACTIVE.

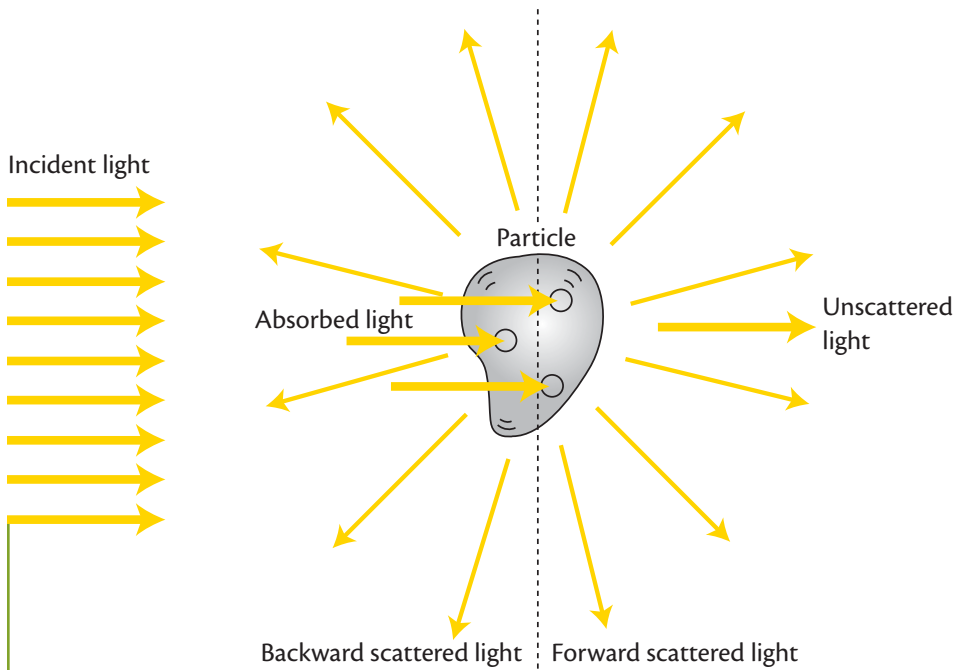
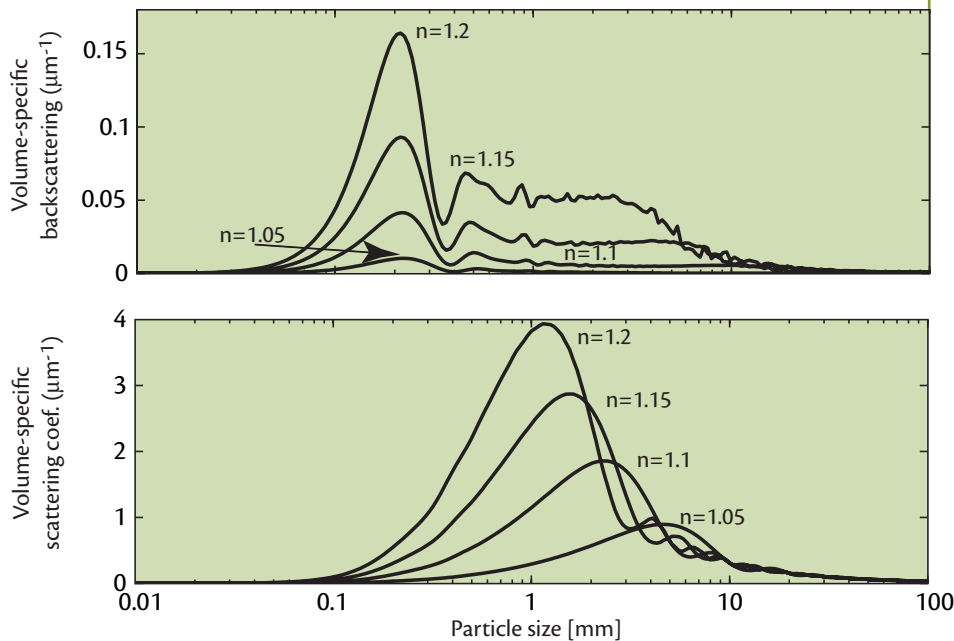


Figure 1. In this cartoon we show how attenuation of light occurs through the process of absorption and scattering. Scattered light is divided into the light scattered in the backward and forward directions relative to the direction of the un-attenuated beam. Scientists measure backscattering, or b_b , of the ocean because it provides information on the abundance and distribution of suspended particles, which play an important role in ocean ecosystems and biogeochemical cycling. In addition, the ocean's color, which is monitored by satellites, is proportional to the backscattered light.

Figure 2. This figure illustrates that different optical properties, such as total scattering and backscattering, respond differently to particle characteristics such as size and composition. The particle volume-specific backscattering coefficient (top panel) and volume-specific scattering coefficient (bottom panel) at 660 nm as a function of the size of particles for non-absorbing particles with different real indices of refraction relative to water (n); $n=1.05$ is similar to the index of refraction of water-laden organic particles such as phytoplankton, while $n>1.15$ characterize most inorganic particles in the ocean. These plots were derived from Mie theory, which assumes the particle to be homogeneous and spherical. The particle volume-specific backscattering (scattering) coefficient for a given particle diameter, shown in this figure, is equivalent to the ratio of the backscattering (scattering) cross section of a single particle at that diameter (which is obtained from the Mie theory) to the particle volume.



WHAT CONTRIBUTES TO THE BACKSCATTERING COEFFICIENT?

Many water constituents contribute to b_b : water molecules, salts and other dissolved materials, organic and inorganic particles, and bubbles (for an extensive account see Stramski et al., 2004). The process of scattering is additive; the magnitude of b_b is the simple sum of the contribution from each of these constituents.

For the simple case in which there is only one kind of scattering material in water, the measured backscattering, minus the known backscattering contribution by pure water, is linearly proportional to the concentration of this material (as long as the mixture is dilute enough that multiple scattering events can be ignored and absorption along the path is negligible or accounted for). This is the basis of using optical instruments to provide proxies for suspended matter concentration.

Beside concentration, the important characteristics of a particle that affect the magnitude of backscattering are its size, index of refraction, shape, and structure. The index of refraction is dependent on particle composition and is the ratio of the speed of light in the surrounding waters to its speed within the particle. As a general rule: (i) the further the index of refraction of the particle is from the value for the surrounding media the higher the backscattering coefficient, (ii)

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for a given number of particles, the larger the particle, the larger the backscattering coefficient, and (iii) the smaller the particle the more it backscatters relative to total scattering.

Much of the understanding of the backscattering coefficient and its dependence on particle properties has come from theoretical studies; unfortunately theoretical solutions are available only for a restrictive set of particles. Most widely used is the Mie theory, which provides the solution for the interaction of light with homogeneous and spherical particles. Solutions for layered spheres (e.g., bubbles coated with organic material) and simple non-spherical particles (spheroids, cylinders) are also available and have been sparsely applied to the study of oceanic particles.

Examples of theoretical solutions are provided in Figure 2. The volume- (or mass) specific backscattering coefficient of homogeneous, non-absorbing, spherical particles is shown to be a strong function of the size of the particles and the particle composition (which determines its index of refraction). This means that packaging the same amount of material (that is the same constant total volume of particles per given volume of water) into different sized particles can lead to very different b_b .

Comparing the primary sensitivity of the total and backward scattering coefficients, we find that while the total scattering is most sensitive to micron-sized particles, the backscattering of homogeneous spherical particles is relatively more responsive to sub-micrometer particles (Figure 2; Stramski and Kiefer, 1991). The difference between the backscattering and scattering dependence on particle composition and size suggests that scattering and backscattering can be used together to obtain information about some

particle characteristics. Indeed the backscattering ratio (b_b/b) can be used to infer information about the primary contributors to scattering in the water.

The differences in sensitivities of total particulate scattering and particulate backscattering to size distribution and composition of particulate assemblages provide a means to study and classify particles. Assuming the particles obey a simple monotonic size distribution, the backscattering ratio is found to be largely a function of index of refraction (i.e., composition) and to a lesser degree the steepness of the size distribution (relative contribution of small particles to the total particulate population¹; Twardowski et al., 2001). For water molecules and particles very small compared to the wavelength of light, the forward scattering coefficient equals b_b , and thus the backscattering ratio is one half. In contrast, phytoplankton-dominated ocean waters tend to have backscattering ratios of about one half of a percent, while suspension of inorganic sediment have backscattering ratios of a few percent.

HOW DO WE MEASURE BACKSCATTERING IN SITU?

In the past half of century only a few prototype instruments have been deployed to measure the angular distribution of scattering in the oceans. Analysis of these measurements and Mie theory calculations has shown that in order to estimate the backscattering coefficient in the ocean, it is suf-

ficient to measure scattered light in a very limited number of angles chosen between about 100 and 155 degrees (Oishi, 1999; Maffione and Dana, 1997; Boss and Pegau, 2001). This has resulted in commercially available instrumentation for *in situ* measurements of the backscattering coefficient that use angular measurements of scattered light utilizing one to three selected angles in the backward direction (manufactured by Hydro-Optics, Biology, & Instrumentation Laboratories [HOBI Labs], Tucson, Arizona; and WET Labs Inc., Philomath, Oregon; e.g., Figure 3).

Calibration of these sensors to obtain the backscattering coefficient can be done either by using spherical beads of known optical properties (and Mie theory) or measuring the scattering properties of a plate of known reflectivity. Good agreement was found in a recent comparison of b_b estimated by commercial sensors and the b_b estimated using a prototype instrument that measures the scattering of light at high angular resolution in the backward direction; the root-mean-square difference between them was found to be less than 10 percent (Boss et al., 2004).

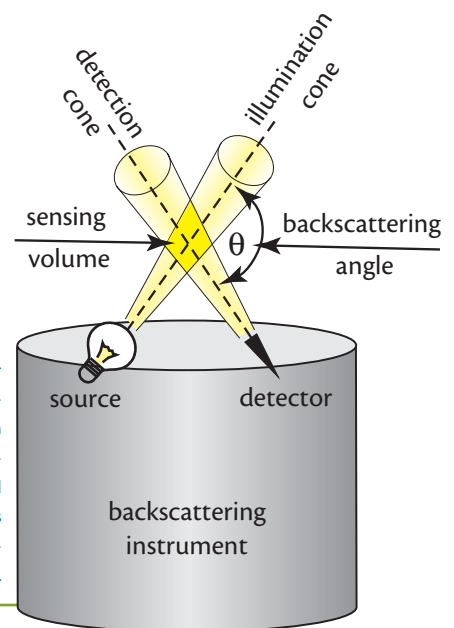


Figure 3. This schematic of a single-angle backscattering sensor shows a detector and source embedded within a flat-faced instrument. The light backscattered near the angle, θ , emanates from the volume created by the intersection of the illumination and detection cones. The simple design of such sensors makes them ideal for deployment from small sensing platforms such as autonomous underwater vehicles and floats. The flat-face design can accommodate simple anti bio-fouling devices such as copper shutters.

¹Note that the above assumes a simplified size distribution, which applies to all the particles impacting the ratio. Unfortunately, at this time, very little is known about the distribution of sub-micron size particles that may affect the interpretation of this ratio.

LINK BETWEEN THE BACKSCATTERING COEFFICIENT, OCEAN BIOGEOCHEMISTRY, AND OCEAN COLOR

To a first order, due to the large range of particle concentration within a water body, the backscattering coefficient responds to changes in the total concentration of particles in the water. Therefore the backscattering coefficient may serve as a proxy for the amount of suspended matter in water. For example, it has been demonstrated that the backscattering coefficient correlates with particulate organic carbon (POC) in the Southern Ocean and the Arabian Sea (Stramski et al., 1999; Balch et al., 2001). Infrared backscattering is one of the U.S. Environmental Protection Agency's approved methods to quantify the turbidity of water associated with suspended particles (e.g., the OBS sensor of D&A Instruments).

The spectral reflectance of the ocean surface (ocean color) is roughly proportional to the backscattering coefficient and inversely proportional to the absorption coefficient. Only those photons that are scattered predominantly at backward directions within the surface layers of the ocean have a chance to leave the ocean and be subsequently detected by optical sensors that view the ocean from satellites or aircraft. This is why backscattering is so important to remote sensing of the ocean. Consequently, any fundamental understanding of ocean color and its use to estimate in-water biogeochemical constituents (such as chlorophyll and particulate organic carbon concentrations) requires understanding of the sources of variability in the backscattering coefficient and accuracy and precision in its measurement in the ocean.

EXAMPLE: THE BACKSCATTERING COEFFICIENT AT LEO 15

An eight-day time series of backscattering profiles (~400) from the Long-term Environmental Observatory at 15 m (LEO 15), located on the shelf off Tuckerton, New

Jersey, are used to illustrate the utility of the backscattering coefficient. The observations were taken during periods with a highly stratified water column (7/29 and

8/4-5/2001) as well as during a less-stratified water-column period (7/30-8/3/2001; Figure 4). During stratified conditions, two distinct layers of water were present with a deep,

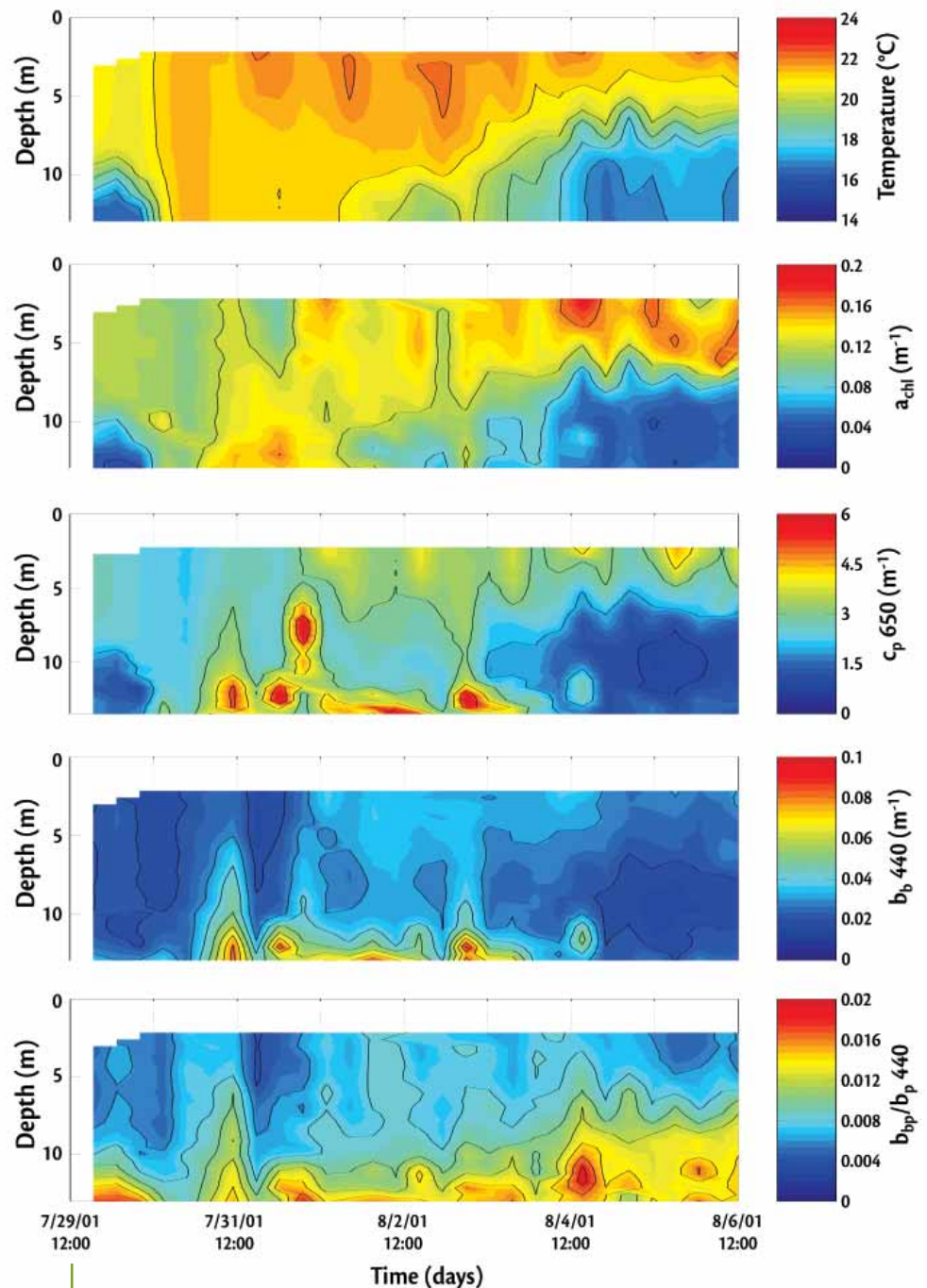


Figure 4. Eight-day time series of water temperature, chlorophyll absorption (based on the 676 nm absorption line height), beam attenuation coefficient at 650 nm (c_p , 650), particulate backscattering coefficient at 440 nm (b_{bp} , 440), and the particulate backscattering ratio (b_{bp}/b_p , 440; the ratio of particulate backscattering to particulate scattering) at 440 nm. All of these data were collected by the LEO-15 profiling mooring. Periods of a highly stratified water column (7/29 and 8/4-5/2001) are characterized by relatively low backscattering while a less-stratified period (7/30-8/3/2001) exhibit higher backscattering, in particular near the bottom due to sediment resuspension. The backscattering ratio is high near the bottom and low near the surface throughout the time series suggesting that high index of refraction sediments dominate near the bottom while low index of refraction phytoplankton dominate near the surface. This time series illustrates the added information that backscattering measurements provide to more traditional optical and hydrographical measurements.

3-5 m thick cold layer and a surface layer that was warmer and had a relatively higher chlorophyll *a* concentration (based on the absorption line height at 676 nm). In general, the particulate beam attenuation coefficient at 650 nm (which is dominated by total scattering) is well correlated with the chlorophyll absorption, except near the bottom during the non-stratified period when large values of beam attenuation occurred. This elevated bottom signal is likely due to sediment resuspension from the bottom. Note that the distribution of the backscattering coefficient is different than that of the beam attenuation coefficient. In the backscattering signal, the surface phytoplankton bloom (evident by the high chlorophyll absorption) after August 3rd (during the stratified water column period) is barely noticeable, while sediment resuspension dominates backscattering distribution during the non-stratified period.

The particulate backscattering ratio increases from 0.5 percent in warm waters with high chlorophyll absorption to 2 percent in turbid waters near the bottom (Figure 4). This is consistent with a change of the particulate population, dominated by phytoplankton at the surface, while dominated by highly refractive suspended inorganic particles near the bottom.

FUTURE DIRECTIONS

There is still much scientists need to learn about b_b . There is currently no consensus over which particles dominate b_b and its variability in the ocean (see Stramski et al., 2004 for a recent review). A major impediment is the paucity of measurements of b_b for specific marine particles. The deviation of oceanic particles from being spherical and homogeneous puts into question some of the quantitative prediction of Mie theory, particularly regarding prediction of b_b (e.g., Bohren and Singham, 1991). We are also constrained by the limited quantitative information on particulate size distribu-

tions for sub-micrometer particles, which is needed for an understanding of scattering sources and variability.

The interplay of spectral absorption and backscattering within the upper ocean results in the ocean color, which is observed from above the ocean. Scattering and absorption at a given wavelength are not independent (a photon absorbed is not scattered). These spectral relationships between backscattering and absorption are only now becoming evident with the combined measurements of spectral total attenuation, absorption, and backscattering. To understand ocean color or derive biological and geochemical properties from ocean color signatures, this gap in understanding the interplay between backscattering and absorption processes must be overcome.

CONCLUSIONS

The backscattering coefficient has a place in the arena of relatively simple, well-defined, and routine optical measurements with links to both ocean particulate biogeochemistry and ocean color. Because the measurement of backscattered light at a few angles in the back direction can be done with source and detector(s) occupying the same plane (Figure 3), and with relatively little distance between them, the overall size of backscattering sensors can be small, which enhances sensor deployment options by including small autonomous Lagrangian platforms such as gliders and profiling floats (Rudnick and Perry, 2003). The flat-face design enables the sensors to be equipped with copper shutters that prevent bio-fouling during long-term deployments.

Given that the information content of backscattering is important for particulate characterization and understanding of ocean color, we conclude with the recommendation that backscattering sensors, with at least a few spectral bands, be included as standard sensors on the international oceanographic fleet and in-water observatories.

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