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Estimating Particle Size in the Ocean from High-frequency Variability in In-situ Optics

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The Recipient shall include a list of any Subject Inventions required to be disclosed during the preceding year in the performance report, technical report, or renewal proposal. A complete list (or a negative statement) for the entire award period shall be included in the summary of research.

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SUMMARY OF RESEARCH

During this 3-year NESSF fellowship and seven-month no-cost extension, I published two papers as first author (Briggs et al. 2011; Briggs et al. 2013) and two papers as a co-author (Alkire et al. 2012; Cetinic et al. 2012). I am also co-author on one submitted paper and have worked on five additional papers that are in preparation (two as first author). I have given talks at four international oceanographic conferences: The 2012 and 2014 Ocean Sciences Meetings in Salt Lake City and Honolulu, the 2012 Ocean Optics meeting in Glasgow, Scotland, and the 2013 Liège Colloquium in Liège, Belgium. I also gave a 45-minute seminar at the *Laboratoire d'Oceanographie Villefranche-sur-mer* in France. In 2013, I received the University of Maine's NSFA Graduate Research Excellence Award in recognition of the research conducted under the NESSF fellowship. In addition to my research-related accomplishments, I successfully completed five graduate-level classes (paid for with NESSF funding) and passed my qualifying exams to ascend to PhD candidacy.

My research focused on advancing methods for estimating two important oceanographic quantities – particle size and primary productivity (PP) – from autonomous platforms. The aim of my research is to pave the way for much greater global coverage of size and productivity estimates, both for direct application to ecological and biogeochemical studies and to validate and perhaps calibrate the growing number of global ocean color-based particle size and PP inversions.

Particle size method

Size is a fundamental characteristic of particles in the ocean, critical to biological and chemical properties such as trophic level, movement speed, metabolic rates, and nutrient uptake rates, as well as physical properties such as sinking rate. Through these properties, particle size influences not only the physical marine environment (e.g. sediment transport) and ocean ecology, but also the global climate system through large, fast-sinking, organic particles (marine snow) that sequester carbon in the deep ocean. The study of marine particle size is therefore of great relevance to the broad NASA Earth Science goals of both identifying current changes and predicting future changes in the global earth system. In line with these goals, several methods have been developed to estimate marine particle size (Loisel et al. 2006; Kostadinov et al. 2009) or phytoplankton size (Uitz et al. 2006; Hirata et al. 2008; Mouw & Yoder 2010) from ocean color measurements. These algorithms have so far been tested primarily against HPLC phytoplankton pigment data from water samples. Not only is the global HPLC dataset limited in its spatial and temporal coverage, it is also not a direct measure of phytoplankton size and tells us nothing about non-algal particles and large phytoplankton aggregates. The particle size inversion I developed under this NESSF funding has the potential to address these problems, because it is autonomous (capable of greatly expanded spatial and temporal coverage), and because it can identify both mean phytoplankton size (from fluorescence measurements) and mean particle size (from backscattering or beam attenuation measurements.

I refer to this particle size method as the VMR inversion, because it is based on the relationship of the variance-to-mean ratio (VMR) of an optical measurement of particles and the optical signal per particle. The VMR inversion builds on the method of Shifrin (1988), and takes advantage of the random fluctuations in a series of optical measurements of particles in suspension caused by particles entering and leaving the sensor's sample volume. My work on the VMR method falls into three parts: 1) theoretical derivation, 2) lab testing, and 3) field testing and application. Parts 1 and 2 have been published (Briggs et al. 2013), and part 3 is in preparation and early results have been presented in two international conferences.

1. Theoretical derivation

Based on the assumption that particles are randomly distributed in space and moving through a discrete sample volume, fluctuations in the number of particles of a given size class in the volume can be described by a Poisson distribution. It is a property of a Poisson distribution that the variance equals the mean (VMR = 1). If we define the optical signal returned by a sensor at a given time as the product of the number of particles in its sample volume and the signal per particle, we can see that the mean signal scales with the signal per particle, but the signal variance scales with the square of the signal per particle. Thus, the VMR of the optical signal scales linearly with the signal per particle but is not affected by the particle concentration. This relationship is fully and formally derived in (Briggs et al. 2013) and expanded to accommodate multiple size classes. In the presence of multiple size classes, the VMR inversion yields a weighted mean signal per particle Possible biases are also discussed, including electronic noise and nonrandom distribution of particles. Uncertainties involved in converting mean optical signal per particle into mean particle size are also discussed, including the role of sensor sample volume and particulate optical properties.

2. Laboratory testing

The VMR inversion was applied to particulate optical beam attenuation (c_p) data and particulate optical backscattering (b_{bp}) data from a laboratory clay aggregation experiment and tested against independent particle size data from a LISST laser diffraction sensor (Sequoia Scientific, Inc.). VMR inverted mean particle size estimates were biased high when particlhies were <10μm, but performed well in the 10-80 μm range (mean bias 17-38%; relative RMSE 10-24%). For mean particles sizes in the 80-200 μm range, validation data were not available, but VMR mean size estimates were well correlated with particle clearance rates (r^2 = 0.75-0.93), as expected, given the relationship between size and settling rate. Details of the laboratory validation can be found in (Briggs et al. 2013).

3. Field testing and application

The VMR inversion was applied to in-situ fluorescence and backscattering data from ships and autonomous gliders deployed in the Iceland Basin in spring 2008 as part of the North Atlantic Bloom 2008 project. A preliminary analysis of these data indicate that the chlorophyll fluorescence VMR is able to distinguish large diatom communities from small phytoplankton communities. Furthermore, the optical backscattering VMR appears to correctly identify the timing of an aggregation event that triggered rapid sinking flux to at least 900 m (Briggs et al. 2011). I intend to submit these results for publication within 6 months.

Primary productivity method

Primary productivity (PP), the rate of organic carbon production via (in the surface ocean) photosynthesis, is another fundamental measurement for the fields of marine ecology and biogeochemistry. PP sets the limit on the carbon available for the entire food web, as well as for long-term sequestration. Several satellite ocean color-based PP algorithms have been developed, but global performance of these algorithms is inconsistent, with root mean squared errors ranging from a factor of 1.25 to a factor of 2.5, depending on ocean region (Saba et al. 2011). As with particle size, further PP model development is limited in part by the sparse spatial and temporal coverage of in situ PP measurements. Again, accurate autonomous PP estimates would therefore be highly valuable.

Under the support of this NESSF fellowship, I have tested a method for estimating PP from diel cycles in dissolved O_2 and/or optical beam attenuation, measured by an autonomous Lagrangian mixed-layer float. The method is similar to that of past studies of O_2 and beam attenuation diel cycles (Hamme et al. 2012; Caffrey 2003; Siegel et al. 1989; Claustre et al. 2008), relying on the assumption that the difference between daytime and nighttime rates of change is due entirely to PP. To my knowledge, however, our analysis is the first application of the diel cycles PP method to autonomous, Lagrangian float data, and the first comparison of both O_2 and beam attenuation diel cycles with independent PP estimates made on the same temporal and spatial scale. Preliminary results show that both diel cycles methods are well correlated with each other ($r^2 = 0.77$), and agree with ^{14}C-based PP estimates throughout most of the bloom, excluding a period of silica limitation. I have presented these results at conferences in Liège in 2013 and Honolulu in 2014 and plan to submit for publication within 2 months.

Conclusions

I have used the three years of NESSF support to develop and test methods for autonomous measurements of particle size and primary productivity, two important ecological and biogeochemical parameters. Results so far are encouraging regarding the eventual use of these methods to measure size and PP on a global scale, driving both direct improvements of our understanding of the ocean carbon cycle and validation and calibration of global satellite products.

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