The Influence Of Bubbles On The Backscattering Of Spectral Irradiance In The Upper Ocean.

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LONG-TERM GOALS

The complexity of the oceanic optical environment has suggested that a high degree of spectral resolution will be required to diagnose components of optical variability, and to predict the performance of sensor and weapon systems. For this new hyperspectral approach to be successful, accurate interpretations of the biological and physical processes responsible for variations in the reflectance of the ocean are crucial. Based on extensive theoretical calculations and limited field data, we hypothesize that a large component of optical variability in the upper ocean is the result of variations in the number, the size distribution, and the organic coatings of air bubble populations. The strongest effects relate to the backscattering coefficient, which in turn is directly responsible for the magnitude and spectral distribution of water-leaving radiances detected from air and space-borne hyperspectral imaging radiometers.

OBJECTIVES

We have proposed to test the following hypotheses within the HyCODE program:

a.) In the visible domain, there is no significant difference in total scattering between clean bubbles, and bubbles coated with organic film ("dirty bubbles").

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b.) Given the bubble number density ($\sim 10^5$-$\sim 10^7$) that has typically been reported from measurements in the sea, the bubble population significantly influences the scattering process in the ocean, especially in oligotrophic waters.

c.) By virtue of the refringent characteristics (m=0.75), bubbles have a backscattering efficiency at least one order of magnitude higher than backscattering reported for planktonic organisms. Backscattering from coated bubble populations is likely to be one of the largest of the missing terms in constructing the observed total backscattering coefficient in the sea.

d.) Through enhanced backscattering over the whole visible domain, the bubbles will influence the hyperspectral remote sensing of ocean color in 1) atmospheric correction, and 2) optical and biological properties derived from remotely measured radiances. For high bubble concentrations, such as injected during storms or from ship wakes, the ocean color will tend to be greener due to bubbles, and the chlorophyll concentration and attenuation depths would, therefore, be overestimated and underestimated respectively.

APPROACH

The proposed program of work is focused on evaluating the hypotheses presented above (see Zhang et al. 1998).   The proposed work is highly interdisciplinary, and we have brought together a unique team to address these questions, including an optical oceanographer (Lewis), the world's expert on oceanic bubble dynamics (Johnson), and a world-class shallow-water acoustic oceanographer who has strong expertise in the high frequency (1-5 MHz) systems needed to determine the bubble population distribution at sea (Hay). All have strong track records with ONR in a variety of programs.

A primary focus for the work is sea-going observations of the optical properties as influenced by bubble populations.   This work is/has taken place at the LEO-15 site in conjunction with two field experiments – HyCode 2000 and HyCode 2001.   For this work, we have developed and successfully deployed a device which measures the upwelling hyperspectral radiance and downwelling irradiance fields with the same spectral resolution as that specified for the Coastal Ocean Imaging Spectrometer (NEMO/COIS). The instrument was calibrated and characterized to the highest accuracy using our extensive calibration facilities, which are used by ourselves, the Navy, NASA and NIST for the highest precision calibration of ocean optical instruments. The facilities are within a 200 m^2 , Class 10000 clean room, and include the highest accuracy spectrophotometer available, 10 meters of optical bench assemblies with precision translational and rotational elements, NIST-certified source and reflectance standards, and advanced optical and electronic metrological instruments.   The hyperspectral observations at the surface have been combined with novel acoustic observations (multi kilo- and mega-Hertz scatterance measurements), optical observations (an imaging bubble camera system), and other chemical/physical measurement systems (gas tension, CTD, meterologogy).   In addition to the surface measurements, the vertical distribution of hyperspectral reflectances was determined with a profiling device, and a new device for the direct measurement of the volume scattering function was deployed. This device uses a new and unique prism and lens design coupled with a precision rotator to measure the full phase function. Finally, for the HyCode 2001 experiment, an above-water hyperspectral radiance sensor with a restricted field of view (3 degrees) was deployed that viewed the sea surface at a zenith angle of 40 degrees from the vertical, and a relative (to the sun) azimuth of 90 degrees.   Another radiance sensor viewed the sky at the same azimuth, and at the complementary angle. This sensor, along with a hyperspectral irradiance sensor looking upward, allowed estimation of the contributions to the reflectance from both water leaving radiance, and specular reflection. This sensor was deployed in support of aircraft overflights.

Both "natural" (e.g. wind/wave entrained) bubbles, and bubbles generated by ship wakes have been investigated.

WORK COMPLETED

We have successfully completed the following tasks this fiscal year:

1.   We have completed revisions and augmentations of an analysis of the effect of variation in the volume scattering function induced by the injection of bubbles in ship wakes on the underwater radiance field, and on the emergent hyperspectral radiance from the ocean surface.   The manuscript from this effort has been submitted to Applied Optics (Zhang et al. 2003).   We have complemented the theoretical analysis with direct experimental evidence from work done at LEO (Case II), and in the Equatorial Pacific (Case I), and have included an analysis based on remote observations using PHILLS2.

2.   A manuscript, has been published describing a new device to measure the volume scattering function, and a presentation of the first volume scattering measurements made at sea for the last 20 years (Lee and Lewis 2003, Zhang et al. 2002).   Data from this instrument has been widely used by others for theoretical and practical applications (e.g. Mobley et al. 2002, Boss and Pegau 2001).

3.   We have continued to exploit our work dealing with the expected volume scattering by natural bubbles, and their effect on the backscattered radiation from the sea surface.   Code and VSF data have been provided to the Navy (Stennis Space Center, and NSWC).   Applications to remote sensings and heat budgets have been investigated.

4.   Work has been completed, and a manuscript prepared for publication dealing with the mapping of coastal optical environments using the REMUS autonomous underwater vehicle (Brown et al. 2002, 2003).

5.   We have completed other other papers for submission/publication including those dealing with meso-scale and basin-scale predictions of bio-optical properties (Shallenberg et al., 2002, McClain et al. 2002, Miller et al., 2002, Lewis 2002, Lewis et al., 2003).

6.   We have, with Tom Dickey and Grace Chang, completed an analysis of the various components necessary for a global ocean observing system (Dickey et al. 2003).

7.   All optical data from HyCode 2000 and HyCode 2001 has been prepared and submitted to the WOODS database, to the NASA SeaBASS, and to the database held by UCSB on behalf of the ONR HyCode program.

RESULTS

a. *Influence of Bubbles on Ocean Optical Properties.*   With respect to theoretical development, we have shown clearly the influence of bubble populations on the volume scattering function; as a general statement, the VSF is enhanced in the backward direction, and several diagnostic broad peaks were identified.   However, these characteristic peaks (at ca. 80 degrees), due to total internal scattering, are eliminated if a large population of sub-micron bubbles exist.   These theoretical predictions have been scattering coefficient, the bubble VSF enhances the water-leaving radiance over that associated Petzold functions.   Injection of bubbles as a result of ship wakes significantly alters the water-leaving radiances, particularly in open, 'blue-water' regions, a result that has been confirmed by direct measurement in the Equatorial Pacific and at the HyCode LEO-15 field site (Zhang et al. 2003).   The

bubbles injected into the water by a vessel traveling at an assumed 10 knots increase the reflectance; this effect is indistinguishable after ~1 km behind the vessel in coastal waters.   In addition, bubbles in coastal waters are often generated as a result of sediment processes, and we have further elucidated this process (Beaudreau et al. 2002a,b; Gardiner et al. 2002a,b; Johnson et al. 2002).   Furthermore, we have established methods and interpretations of dissolved gases in the upper ocean more generally (McNeil et al. 2002, Emerson et al. 2002).

b. Variations in the Volume Scattering Function (VSF) in the upper ocean.   We have made the first measurements of natural variability in the volume scattering function of the upper ocean, and have analyzed these data extensively; a manuscript was published this year (Lee and Lewis 2003).   Others have made use of these data (Zhang et al. 2002a, Mobley et al. 2002).   Mobley's quote nicely summarizes our collective conclusions: "*using the correct particle phase function is just as necessary for accurate prediction of underwater light fields as is using correct absorptioand scattering coefficients*".

c. Basin-scale and meso-scale variations in upper ocean optical properties; sources and consequences.   We have investigated and reviewed the sources of variability in mesoscale eddy biological dynamics and conclude that they often dominate in the oligotrophic ocean gyres (Lewis 2002, Lewis et al. 2003).   We have established the bases for prediction of biological processes in the Equatorial Oceans based on satellite observation of oceanic optical properties (McClain et al. 2002), and conclude that variations in the optical processes of the upper ocean have a first order influence on the physical dynamics and mixed layer formation of the upper ocean (McClain et al. 2002, Murtugudde et al. 2002, Miller et al. 2002).

d. Prediction of species composition.   We have developed novel methods for evaluation of species composition on upper ocean optical properties (Ciotti et al. 1999, 2002).

e. Hyperspectral Detection, Classification and Identification of Vessels at Sea.   As a part of a related effort, we have developed and have now revised, highly successful methods for the identification of individual vessels based on their hyperspectral reflectances (Sildam and Lewis, 2002).
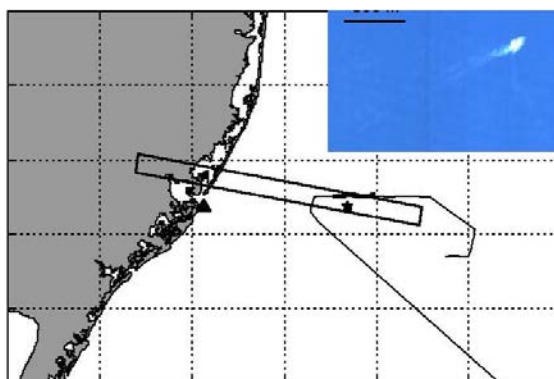

Figure 1: Vessel wake observed form the airborne hyperspectral imaging system PHILLS-2 during the HyCode 2001 field experiment off the coast of New Jersey. The map shows the aircraft flightline as a solid rectangle, and the surface ship cruise track as a light line. The inset is a flase color image of the vessel and wake taken from PHILLS-2 (Zhang et al. 2003).
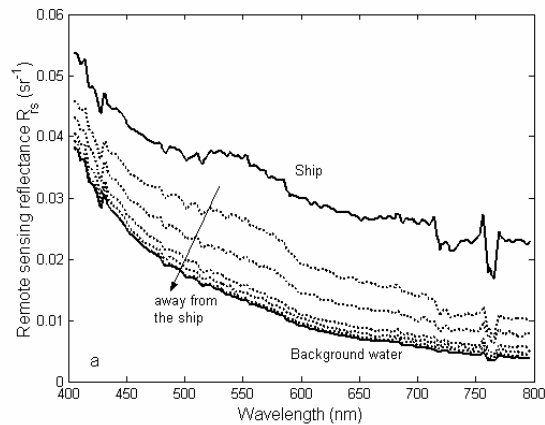
Figure 2. The reflectance spectra derived from the airborne sensor PHILLS-2 for the ship wake above. From the top to the bottom, the reflectance within the ship wakes (dotted lines) decreased with increasing distance away from the ship; it was the same as the background after ~1 km.

IMPACT/APPLICATIONS

The results derived with the VSF have addressed a long standing uncertainty in the factors responsible for variation in the backscattering coefficient in the ocean, a result of fundamental importance for remote sensing of the hyperspectral reflectance of the ocean (e.g. Mobley et al. 2001).

Our work on optical variability has resulted in this process now being included in virtually all new models of the physical dynamics of the upper ocean. Climate researchers are now using our estimates of bubble scattering to estimate wind-dependent variations in ocean albedo, which may be responsible for large scale climate changes such as glaciation. Finally, a wide variety of coastal observation systems are presently in design or construction, which will rely on algorithms and approaches developed by our group for the non-intrusive monitoring of coastal ocean processes based on optical variations.

TRANSITIONS

We are actively working with others (particularly OSU, Sequoia and FERI) to provide VSF and hyperspectral observations for a more complete understanding of the inherent optical properties, and their influence on the hyperspectral reflectance of the ocean. Data and code have been provided to the Navy (NRL and NSWC).

The development of hyperspectral profiling devices during the HyCode program has resulted in commercial sale of numerous systems by Satlantic to a wide variety of customers.

The hyperspectral profiling device was deployed during this fiscal year by Dr. Alan Weidemann (NRL/SSC) and ourselves in an effort to provide system validation off Miami for a new laser bathymetric system (SHOALS).

RELATED PROJECTS

We have had a related program supported by the Canadian Space Agency to collect a library of hyperspectral reflectances of ships and background harbor waters (Completed).   We work closely with John Cullen at Dalhousie University on a variety of optical programs (see OP32).

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