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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14. ABSTRACT
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.

15. SUBJECT TERMS

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b.) Given the bubble number density (~10^5-~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 radiance and downwelling irradiance fields with the same spectral resolution as that specified for the Coastal Ocean Imaging Spectrometer (NEMO/COIS). The instrument will be 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 will be 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 will be determined with a profiling device, and a new device for the direct measurement of the volume scattering function will be deployed. This device uses a new and unique prism and lens design coupled with a precision rotator to measure the full phase function.

WORK COMPLETED

We have successfully completed the following tasks during this fiscal year:

1. We have completed and have submitted for publication, a theoretical analysis of the volume scattering function based on a wide range of bubble populations with differing organic coatings and compared these with direct measurements of the volume scattering function of laboratory-derived bubble populations (Zhang et al. 2001a). Bubble formation has been analyzed, and related to gas observations (Beaudreau et al. 2001a,b Emerson et al. 2001, Gardiner et al. 2001a,b; Johnson et al. 2001; McNeil et al. 2001).

2. We have completed and have submitted for publication, 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 (Zhang et al. 2001b).

3. We have completed a description of 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 (Li and Lewis 2001, Zhang et al. 2001a). Data from this instrument has been widely used by others for theoretical and practical applications (e.g. Mobley et al. 2001).

4. We have completed many other papers for submission/publication including those dealing with a.) meso-scale and basin-scale predictions of bio-optical properties and their influence on biological and physical processes (Turk et al. 2001a,b,c; Lewis 2001, McClain et al. 2001, Murtugudde et al. 2001) b.) the prediction of species composition based on optical signatures (Ciotti et al. 2000, 2001).

5. We have participated in the LEO-15 HyCode 2001 Field experiment onboard the R/V Endeavor during July/August, 2001. In that experiment, we:
    a. Completed, tested and successfully deployed a new surface drifting buoy array, which carried the following instruments as a payload (Figure 1): i.) Hyperspectral upward looking irradiance sensor (in air); ii.) Hyperspectral downward looking radiance sensor just below the surface; iii.) A new bubble imaging camera which viewed the same volume as probed by the hyperspectral sensors; iv.) Multi- and high frequency acoustic backscatter sensor; v.) a device to measure gas pressure; vi) differential GPS; vii.) meteorological instrumentation suite (winds, humidity, solar radiation, air/sea temp); viii) a CTD and ix.) an electronic compass/tilt sensor suite. The data system for the buoy is interfaced cabled network which allows remote data logging and control of all systems.
    b. The Marine Hydrophysical Institute completed revisions to their new volume scattering device (Li and Lewis, 2001) and successfully deployed this device onboard the R/V Endeavor (Figure 2; not funded under this contract, but supplied for evaluation).
    c. Completed and successfully deployed a new profiling hyperspectral radiometer, which provides observations of the hyperspectral upwelling radiance and downwelling irradiance over the waveband 350-800 nm at a spectral resolution of 3.3 nm.

6. All optical data from HyCode 2000 has been prepared and submitted to the WOODS database, 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

Figure 1. Deployment of the Optical/Acoustic Drifting Buoy off the R/V Endeavor near New Jersey Coast, July, 2001. The package contains optical, acoustic and chemical measurement systems designed to examine the influence of bubble clouds on upper ocean hyperspectral reflectance.

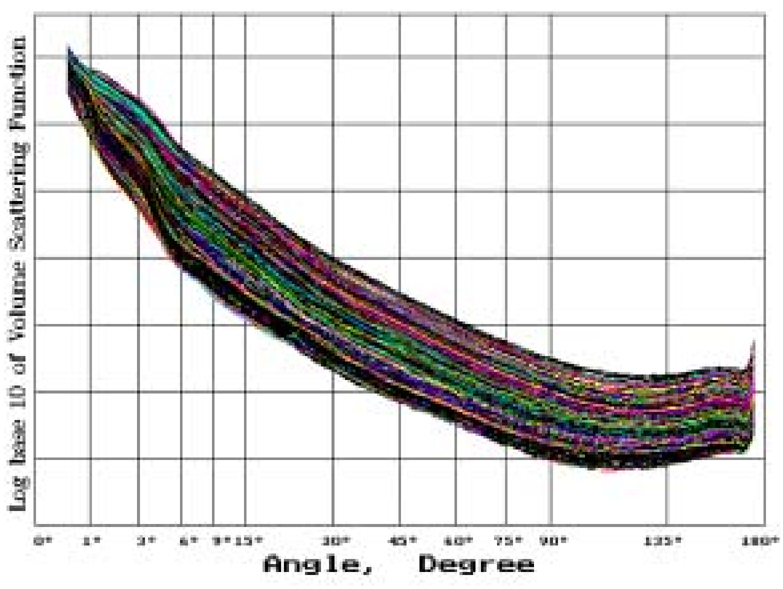

Figure 2. Variations in the Volume Scattering Function during the HyCode 2001 experiment. The data consist of over 800 independent observations in waters extending from the Gulf Stream to the coast of New Jersey.

identified. These theoretical predictions have been confirmed by direct measurement of laboratory-derived bubbles (Zhang et al. 2001a). For a given total scattering coefficient, the bubble VSF enhances the water-leaving radiance over that associated with 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 at the HyCode LEO-15 field site (Zhang et al. 2001b). 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. 2001a,b; Gardiner et al. 2001a,b; Johnson et al. 2001). Furthermore, we have established methods and interpretations of dissolved gases in the upper ocean more generally (McNeil et al. 2001, Emerson et al. 2001).

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 (Li and Lewis 2001, Zhang et al. 2001b; see Figure 2), as have others (e.g. Mobley et al. 2001). 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 absorption and scattering coefficients*".

b.) Basin-scale and meso-scale variations in upper ocean optical properties; sources and consequences. We have, for the first time, established predictive capability in large-scale biological processes based on use of TOPEX/Poseidon altimetric observations to establish the depth of the thermocline, and algorithms for estimation of biological productivity based on this (Turk et al. 2001a,b,c). 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 2001). 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. 2001), 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. 2001, Murtugudde et al. 2001).

c.) Prediction of species composition. We have developed novel methods for evaluation of species composition on upper ocean optical properties (Ciotti et al. 1999, 2000, 2001).

d.) Hyperspectral Detection, Classification and Identification of Vessels at Sea. As a part of a related effort, we have developed highly successful methods for the identification of individual vessels based on their hyperspectral reflectances (Sildam and Lewis, 2001).

IMPACT/APPLICATIONS

The results derived with the VSF have addressed a 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 and Sequoia) 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. We have made several open and classified presentations of the initial efforts under this program to audiences within the US DOD surveillance community.

RELATED PROJECTS

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

REFERENCES

Boudreau, B.P., B.S. Gardiner and B.D. Johnson 2001a. Rate of growth of isolated bubbles in sediments with a distributed source of methane. *Limnol. Oceanogr.*, 46, 616-622.

Boudreau, B.P., B.S. Gardiner and B.D. Johnson 2001b. Erratum: Rate of growth of isolated bubbles in sediments with a distributed source of methane. *Limnol. Oceanogr., in press.*

Ciotti, A., J.J. Cullen, and M.R. Lewis. 1999. A semi-analytical model of the influence of phytoplankton community structure on the relationship between light attenuation and ocean color. *J Geophys. Res.,* 104: 1559-1578.

Ciotti, A.M., J.J. Cullen and M.R. Lewis 2000. Analyses of the influence of different cell sizes of phytoplankton on relationships between apparent optical properties. *Oceans from Space,* Venice 2000.

Ciotti, A.M., M.R. Lewis and J.J. Cullen. 2001. Assessment of the relationships between dominant cell size in natural phytoplankton communities and the spectral shape of the absorption coefficient. *Limnol. Oceanogr., in press.*

Emerson, Steve, Charles Stump, Bruce Johnson and Dave Karl. 2001. In-situ determination of oxygen and nitrogen concentrations in the upper ocean; submitted to *Deep Sea Research*; May 2001.

Gardiner, B.S., B.P. Boudreau and B.D. Johnson. 2001a. Growth of disk shaped bubbles in sediments by fracture; submitted to *Geochim. Cosmochim. Acta*. August 2001.

Gardiner, B.S., B.P. Boudreau and B.D. Johnson. 2001b. Diffusion-limited growth of a disc-shaped bubble; submitted to the *International Journal of Heat and Mass Transfer*. August 2001

Johnson, B.D., B.P. Boudreau, B.S. Gardiner and R. Maass. 2001. Mechanical Response of Sediments to Bubble Growth; submitted to *J. Mar. Geol*. Jan. 2001.

Lewis, M.R. 2001. Variability of plankton and plankton processes on the mesoscale. *In*, Phytoplankton Productivity: Carbon Assimilation in Marine and Freshwater Ecosystems. (P. J. le B. Williams, D. N. Thomas and C. S. Reynolds (eds.) Blackwell, London, *in press*.

Li, M., and M.R. Lewis. 2001. Measurement of the optical volume scattering function (VSF) in the ocean. Submitted, *J. Atmos. Ocean. Tech*.

Mobley, C.D., L.K. Sundman, and E. Boss. 2001. Phase function effects on oceanic light fields. Submitted, *Applied Optics*.

McClain, C.R., J.R. Christian, S.R. Signorini, M.R. Lewis, I. Asanuma, D. Turk and C. Dupouy-Douchement. 2001. Satellite ocean color observations of the tropical Pacific Ocean. *Deep Sea Res. in press*.

McNeil, C.L., D.M. Farmer, B.D. Johnson and J. Lazier. 2001. The annual cycle of dissolved air in the central Labrador Sea; submitted to *J. Geophysical Res*. August 2001

Murtugudde, R., J. Beauchamp, C.R. McClain, M.R. Lewis and A. Busalacchi. 2001. Effects of penetrative radiation on the upper tropical ocean circulation. *J. Climate, in press.*

Sildam, J. and M.R. Lewis 2001. Detection, classification and identification of seagoing vessels and surface oil based on Support Vector Machine (SVM) analysis of hyperspectral reflectance signatures. Requested, *Can. J. Remote Sensing.*

Turk, D., M.J. McPhaden, A.J. Busalacchi and M.R. Lewis. 2001a. Remotely-sensed biological production in the tropical Pacific during 1992-1999 El Nino and La Nina. *Science,* 293: 471-474.

Turk, D., M.J. McPhaden, I. Asanuma, and M.R. Lewis. 2001b. Heat, nitrate and carbon balances in the western Pacific Warm Pool under weak La Nina, and strong El Nino conditions. *J. Geophys. Res., ad judicum*.

Turk, D., M.R. Lewis, G.W. Harrison, T. Kawano, and I. Asanuma. 2001c. Geographical distribution of new production in the western/central Equatorial Pacific during El Nino and non-El Nino conditions. *J. Geophys. Res.* 106: 4501-4515

Zhang, X.., M.R. Lewis and B.Johnson. 1998. The role of bubbles in the scattering of light in the ocean. *Applied Optics,* 37: 6525-6536

Zhang, X., M.R. Lewis, M. Li, B. Johnson, and G. Korotaev. 2001a. The volume scattering function of natural bubble populations. *Limnol. Oceanogr., ad judicum.*

Zhang, X., M.R. Lewis, B. Johnson and Alex Hay. 2001b.. Optical influence of ship wakes. *Journal of Applied Optics, ad judicum*.

PUBLICATIONS (LAST 3 YEARS)

Turk, D., M.J. McPhaden, A.J. Busalacchi and M.R. Lewis. 2001. Remotely-sensed biological production in the tropical Pacific during 1992-1999 El Nino and La Nina. *Science* 293: 471-474.

Murtugudde, R., J. Beauchamp, C.R. McClain, M.R. Lewis and A. Busalacchi. 2001. Effects of penetrative radiation on the upper tropical ocean circulation. *J. Climate, in press.*

Ciotti, A.M., J.J. Cullen and M.R. Lewis. 2001. Assessment of the relationships between dominant cell size in natural phytoplankton communities and the spectral shape of the absorption coefficient. *Limnol. Oceanogr., in press*.

Boudreau, B.P., B.S. Gardiner and B.D. Johnson. 2001. Rate of growth of isolated bubbles in sediments with a distributed source of methane. *Limnol. Oceanogr*. 46: 616-622.

Boudreau, B.P., B.S. Gardiner and B.D. Johnson. 2001. Erratum: Rate of growth of isolated bubbles in sediments with a distributed source of methane; *Limnol. Oceanogr,. in press*.

McClain, C.R., J.R. Christian, S.R. Signorini, M.R. Lewis, I. Asanuma, D. Turk and C. Dupouy-Douchement. 2001. Satellite ocean color observations of the tropical Pacific Ocean. *Deep Sea Res. in press*.

Lewis, M.R. 2001. Variability of plankton and plankton processes on the mesoscale. *In*, Phytoplankton Productivity: Carbon Assimilation in Marine and Freshwater Ecosystems. (P. J. le B. Williams, D. N. Thomas and C. S. Reynolds (eds.) Blackwell, London, *in press*.

Turk, D., M.R. Lewis, G.W. Harrison, T. Kawano, and I. Asanuma. 2001. Geographical distribution of new production in the western/central Equatorial Pacific during El Nino and non-El Nino conditions. *J. Geophys. Res.* 106: 4501-4515.

Zedel, L., and A.E. Hay, 2001. A three component bistatic coherent Doppler velocity profiler: Causes of error and accuracy limitations, *IEEE J. Oceanic Eng, in press.*.

Crawford, A.M., and A.E. Hay. 2001. Linear transition ripple migration and wave orbital velocity skewness: Observations. *J. Geophys. Res*. 106 (C7): 14,113-14,128.

Lewis, M.R., and S.D. McLean. 1999. Optical observations for operational oceanography. *Backscatter* 10: 22-25.

Ciotti, A., J.J. Cullen, and M.R. Lewis. 1999. A semi-analytical model of the influence of phytoplankton community structure on the relationship between light attenuation and ocean color. *J. Geophys. Res.*. 104: 1559-1578.

Irish, J.D., J.F. Lynch, P.A. Traykovski, A.E. Newhall, K. Prada, and A.E. Hay. 1999. A self contained sector scanning sonar for bottom roughness observations as part of suspended sediment studies. *J. Atm Oceanic Tech*. 16: 1830-1841.

Zedel, L., and A. E. Hay. 1999. A Coherent Doppler Profiler for High Resolution Particle Velocimetry in the Ocean: Laboratory Measurements of Turbulence and Particle Flux. *J. Atmos and Ocean. Tech.*, 16: 1102-1117.

Traykovski, P., A.E. Hay, J.D. Irish, and J. F. Lynch. 1999. Geometry, migration, and evolution of wave orbital ripples at LEO-15. *J. Geophys. Res*. 104: 1505-1524.

Zhang, X.., M.R. Lewis and B.Johnson. 1998. The role of bubbles in the scattering of light in the ocean. *Applied Optics* 37: 6525-6536.

Crawford, A. M., and A. E. Hay. 1998. A Simple System for Laser-Illuminated Video Imaging of Sediment Suspension and Bed Topography. *IEEE J. Oceanic. Eng.* 23(1): 12-19.

Zhang, Xiaodong, M.R. Lewis, B. Johnson and A.Hay. 2001. Optical influence of ship wakes. Submitted to *Journal of Applied Optics*.

Zhang, X., M.R. Lewis, M. Li, B. Johnson, and G. Korotaev. 2001. The volume scattering function of natural bubble populations. *Limnol. Oceanogr, in revision.*

McNeil, C.L., D.M. Farmer, B.D. Johnson and J. Lazier. 2001. The annual cycle of dissolved air in the central Labrador Sea; submitted to *J. Geophysical Res*. August 2001

Turk, D., M.J. McPhaden, I. Asanuma, and M.R. Lewis. 2001. Heat, nitrate and carbon balances in the western Pacific Warm Pool under weak La Nina, and strong El Nino conditions. *J. Geophys. Res*., *ad judicum*.

Emerson, Steve, Charles Stump, Bruce Johnson and Dave Karl. 2001. In situ determination of oxygen and nitrogen concentrations in the upper ocean; submitted to *Deep Sea Research*; May 2001.

Gardiner, B.S., B.P. Boudreau and B.D. Johnson. 2001. Growth of disk shaped bubbles in sediments by fracture; submitted to *Geochim. Cosmochim. Acta*. August 2001.

Gardiner, B.S., B.P. Boudreau and B.D. Johnson. 2001. Diffusion-limited growth of a disc-shaped bubble; submitted to the *International Journal of Heat and Mass Transfer*. August 2001

Johnson, B.D., B.P. Boudreau, B.S. Gardiner and R. Maass. 2002. Mechanical Response of Sediments to Bubble Growth; submitted *to J. Mar. Geol*. Jan. 2001.

Smyth, C, and A.E. Hay, 2001. Near-bed turbulence and bottom friction during SandyDuck97. *J. Geophys. Res*., submitted.

Smyth, C., A.E. Hay, and L. Zedel. 2001. Cohenent Doppler Profiler Measurements of Near-bed Suspended Sediment Fluxes and the Influence of Bedforms. *J. Geophys. Res., in revision.*

Zou, Q., and A.E. Hay. 2001. The vertical structure of the wave bottom boundary layer over a sloping bed: Theory and field measurements. *J. Phys. Ocean*, submitted.