ticular, remote measurement of color from space or an aircraft involves sensing of the near-surface volume of the ocean; the signal measured by satellite or aircraft color sensors is actually a weighted average over the light attenuation depth (roughly an e-folding length scale), which is dependent on the water's optical properties. Unfortunately, this weighted average does not contain the detailed information concerning the vertical structure of optical properties, information that we would find most useful. HyCODE was conceived to exploit the new capabilities of hyperspectral ocean color sensors, some of which are described in this issue. In particular, HyCODE took advantage of the fact that different wavebands of light penetrate to different depths because, in principle, the absorption and scattering of light within each waveband is dependent upon the optically influential substances within the water. Thus, there is the potential for using hyperspectral data to determine the presence of and to constrain the depths of optical layer in the ocean (e.g., Zaneveld and Pegau, 1998).

HyCODE was also poised to capitalize on advances in coupled atmosphere-ocean models and improved understanding of optically important ecosystem members. Specifically, HyCODE investigators are developing fully three-dimensional models that incorporate physical-biological-optical components and interactions. Data collected during the intensive HyCODE field campaigns are being used for testing these models. The model results (e.g., water-leaving radiance) will be compared with both aircraft and *in situ* observations obtained during HyCODE and these models will be used for future hyperspectral ocean-color satellite missions. The modeling approach should be useful in extracting vertical structure information pertinent to optical properties in the coastal ocean. Of course, these modeling efforts are highly dependent upon hyperspectral optical and physical data sets including the unique HyCODE field results presented in this issue.

Because of the fast-moving nature of bio-optical oceanography, the papers appearing in this issue can be considered as progress

TINY BUBBLES: AN OVERLOOKED OPTICAL CONSTITUENT

BY ERIC TERRILL AND MARLON LEWIS

While it can be imagined that one of the earliest descriptions of the ocean's surface viewed by man when he put forth to the ocean on rudimentary vessels might be the intensity of whitecapping, the science of understanding the influence of bubbles on marine light fields is an active area of research. Breaking waves at the ocean's surface inject bubbles and turbulence into the water column. During periods of rough weather, the scales of wave breaking tend to increase with increasing sea states, resulting in mixing of the surface waters and the turbulent transport of bubbles to depth. The bubbles injected by breaking will span several orders of magnitude in size from perhaps less than microns in diameter to O(1) cm. To complicate matters, the size distribution of bubble populations will evolve in time due to a complex interplay between the bubble rise speed, gas dissolution, surface tension, and turbulence, which are size-dependent, physical influences. In addition to breaking waves, bubble formation and stabilization result from biological processes such as photosynthesis in the surface layer, microbial decomposition in the sediments, the passage of low-pressure fronts that can bring gas out of solution, and cavitation due to ships and other moving objects. The ubiquitous dissolved organic matter present in all oceans adheres onto bubbles almost immediately on formation, which significantly alters their physical dynamics, their optical characteristics, and potentially their gas dissolution rates.

Bubbles predominantly influence the optical properties of the upper ocean by scattering light. Their index of refraction, which is less than seawater, renders them very efficient at scattering; this is particularly true for the proportion of the total scattering in the backwards direction (see Boss et al., this issue). Despite the fundamental importance of particulate scattering for radiative transfer in the upper ocean, their central role in fixing the amplitude of light scattered out of the ocean, and their impacts on laser propagation, it is perhaps surprising that we cannot explain much more than 5 to10 percent of the particulate backscattering in the ocean based on known constituents. Furthermore, we have been aware of this backscattering conundrum for a long time, almost as long as we have known its significance. One candidate to account for the "missing backscattering" is bubbles perhaps very small, stabilized bubbles, in the upper ocean.

The temporal and spatial variability of the bubble field has required the development of unique measurement approaches that include the use of underwater sound and optical imaging combined with the more traditional tools that optical oceanographers rely upon. For example, field efforts during the HyCODE program demonstrated with acoustic and optical techniques that the average optical scattering due to bubbles could range from 10^{-3} m^{-1} at a depth of 4 m to 10^{1} m^{-1} near the ocean surface during winds of 9 m/s off the coast of New Jersey; significant increases were observed in the bubble component of the backscattering coefficient with the onset of high winds. Without accounting for bubbles, potentially large errors result in a wide variety of optical remote-sensing efforts including the remote-sensing retrieval of in-water constituents such as chlorophyll and laser imaging of the seafloor.

Eric Terrill *is Assistant Research Scientist, Marine Physics Laboratory, Scripps Institution of Oceanography.* **Marlon Lewis** *is Professor, Department of Oceanography, Dalhousie University.*