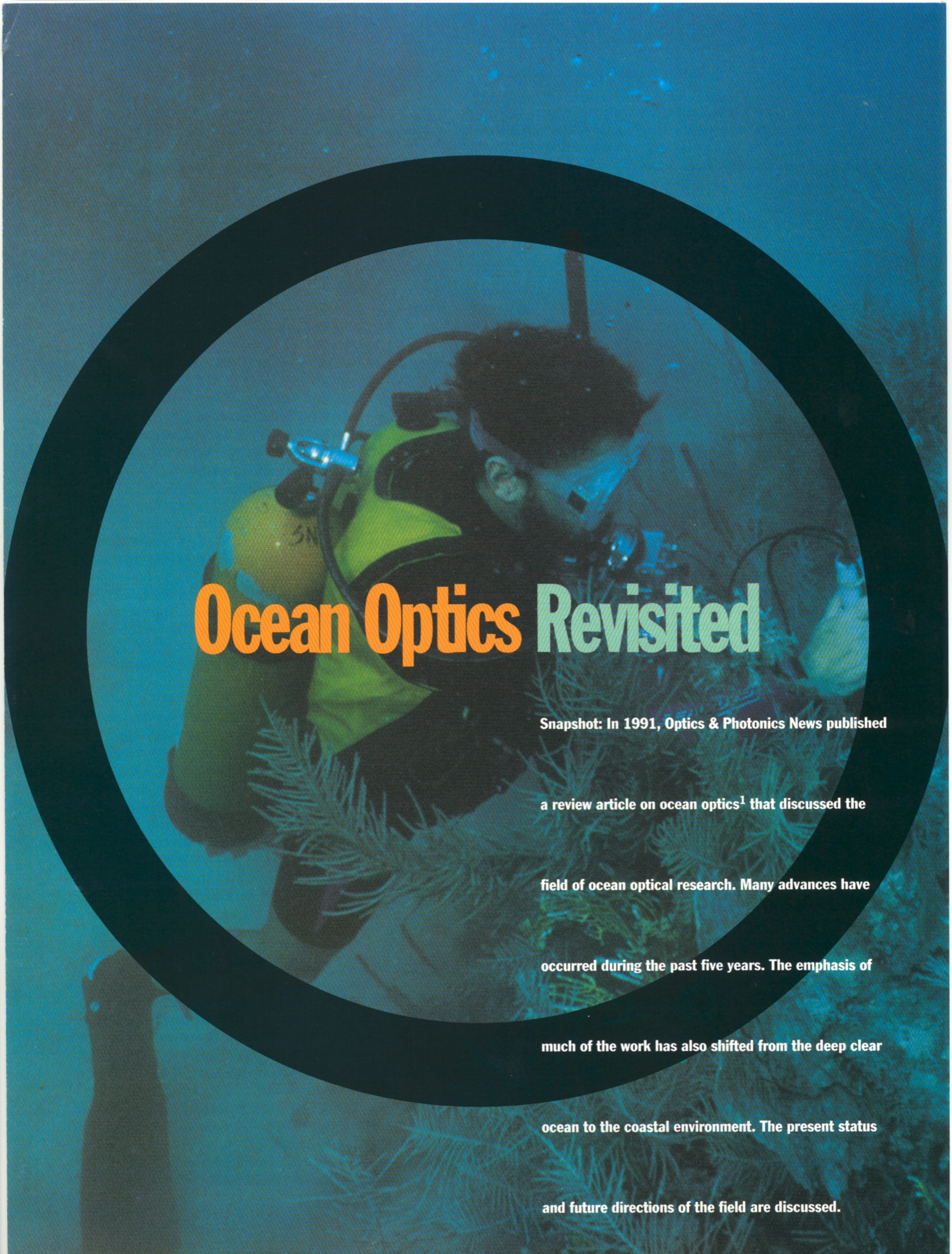


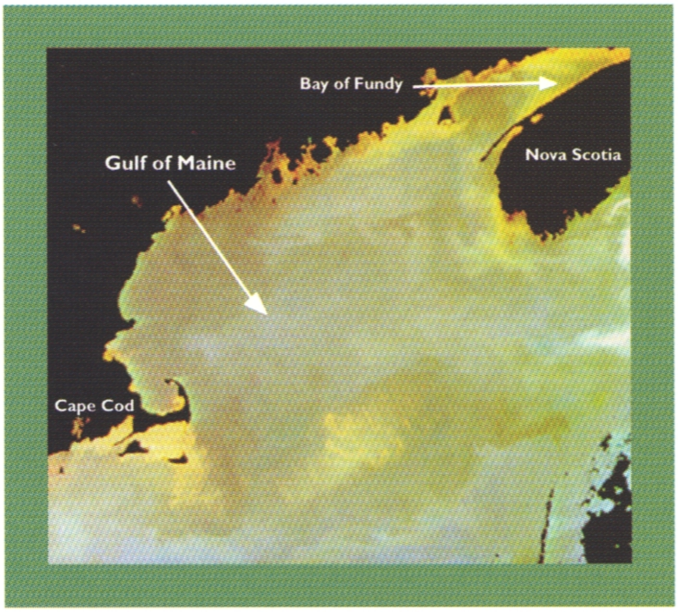
Ocean Optics Revisited

Snapshot: In 1991, Optics & Photonics News published a review article on ocean optics[1] that discussed the field of ocean optical research. Many advances have occurred during the past five years. The emphasis of much of the work has also shifted from the deep clear ocean to the coastal environment. The present status and future directions of the field are discussed.

Previous page. To investigate the optical properties of the shallow ocean floor, it is necessary to address the high spatial variability in the benthic biological community. To measure this spatial variability, a new generation of optical devices, self-contained and operated by divers, is being developed. In this photograph, Charles Mazel (MIT) uses a prototype device to measure the reflectance and fluorescence properties of coral.

By Kenneth J. Voss
and Steven G. Ackleson

In 1991, *Optics & Photonics News* published a review article on ocean optics[1] in which the reader was introduced to the field of ocean optical research. Work during the past five years has resulted in tremendous advancements in man's ability to model radiative transfer within the ocean and to measure the appropriate boundary and initial conditions required to apply radiative transfer theory to a variety of real-world conditions. The purpose of this article is to bring the reader up to date with the new directions of ocean optics since the 1991 *OPN* article.



Courtesy of Janet Campbell, University of New Hampshire.

Figure 1. Coastal zone color scanner (CZCS) false color composite of the Gulf of Maine, acquired June 14, 1979. The image was constructed by combining the satellite-received radiances in three spectral bands of the CZCS: 433–453 nm, 510–530 nm, and 540–560 nm. Black areas along the left and top margin are land masses while the black area in the lower right corner is clouds. At least five distinct water masses can be seen based on color. Blue represents clear ocean water, green represents waters dominated by high concentrations of marine algae (phytoplankton), yellow areas over Georges Bank (lower central portion of the photograph) are waters having both high concentrations of phytoplankton and other suspended particles that scatter light, and dark brownish colors along the coast represent waters having high concentrations of dissolved organic matter. The fifth water mass can be seen along the coast of Nova Scotia and appears as a bright white color. These waters are believed to have high concentrations of coccolithophores, a phytoplankton species that produces high concentrations of highly-reflective calcite particles.

Why study ocean optics?

Ocean optics, or more generally hydrologic optics, is the study of how light interacts with natural water bodies. The emphasis has always been, and will likely continue to be, on the ocean for a number of economic and military reasons. For example, the ocean produces most of the fish that man consumes and that production is ultimately controlled by how microscopic marine algae absorb and use light. To ensure national security, man has always sought to control access and use of the ocean. Such activity often requires peering into the ocean with visible light to detect and identify submerged threats or to characterize areas of the ocean of tactical or strategic value. However, let us keep in mind that the concepts derived from ocean experiments are directly applicable to other natural water bodies such as lakes, streams, and rivers.

In terms of oceanic processes, the most compelling reasons for studying light in the ocean are related to how the oceans affect global climate. Most of the light absorbed by the ocean will cause a warming of the water as a function of depth (greater warming near the ocean surface) and latitude (greater warming near the equator). The resulting temperature gradients help drive ocean currents that, in turn, redistribute heat from the tropics to high latitudes. Another issue related to global climate is how the oceans affect atmospheric carbon dioxide (CO_2), a greenhouse gas. The concentration of atmospheric CO_2 is related to the partial pressure of CO_2 in the ocean. Since oceanic CO_2 is used in the photosynthetic process and the associated carbon is converted to biomass, knowledge of how light affects marine primary production is key to understanding and modeling global transport rates of CO_2 between the atmosphere and the ocean.

Optical variability in the ocean is determined by the concentration of optically active matter, the particulate and dissolved components of ocean water. The concentration and distribution of optically active matter is governed by biological, chemical, and physical processes; thus the field has developed into a multi-disciplinary effort with oceanographers from many areas of research collaborating to develop a better understanding of this complicated natural environment. Major contributions have come from computer modeling of radiative transfer, field campaigns using research vessels, instrumented moorings, remote sensing platforms, and controlled experiments in the laboratory.

To understand how light interacts with, and propagates through, the ocean, it is necessary to know how light is affected by ocean boundaries (the sea surface and the ocean floor) and the water column (pure water and associated suspended and dissolved optically active matter). At the ocean surface, sky and sunlight are reflected from or refracted into the water. The light that propagates into the water column can be affected by several processes. It may be scattered into other directions or absorbed and converted to heat, used in chemical reactions (as in the photosynthetic process), or re-emitted at longer wavelengths (fluoresced). In the shallow ocean, light penetrating to the ocean floor is either reflected back into the water column or absorbed by a variety of organic and inorganic compounds comprising the benthic biological community and marine sediments. As in the water column, portions of the absorbed light are converted to heat, biomass, or fluoresced. The rates at which light is absorbed and scattered are considered to be the inherent optical properties of water or ocean bottom. Measuring and modeling these parameters and their variability is central to the study of ocean optics. With these coefficients, radiative transfer theory can be used to describe how the light field is modified as it propagates in the ocean. Much of the theoretical groundwork in radiative transfer theory has existed for some time. Indeed, if it were possible to completely describe the shape of the sea surface and the distribution and inherent optical properties of the suspended and dissolved matter within the water column and that associated with the sea floor, our present knowledge of radiative transfer could be used to completely describe the oceanic light field. In practice, this is not possible because we cannot completely describe the distribution of optically active matter within the ocean and on the ocean floor and, more importantly, our knowledge of these properties is woefully incomplete.

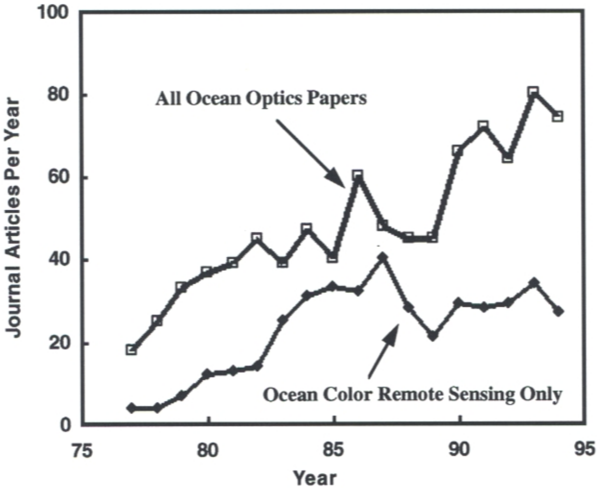


Figure 2. Interest in ocean optics has increased dramatically during the past 20 years, as illustrated by the red (upper) curve representing the number of annual peer-reviewed journal articles on ocean optics as a function of year from 1977–1994. CZCS observations of global ocean color had a significant impact on interest in ocean optics; the number of ocean color and CZCS papers published per year is shown with a green (lower) curve. While the number of ocean color papers leveled off after the completion of the CZCS mission in 1986, the total number of ocean optics papers published per year continued to increase.

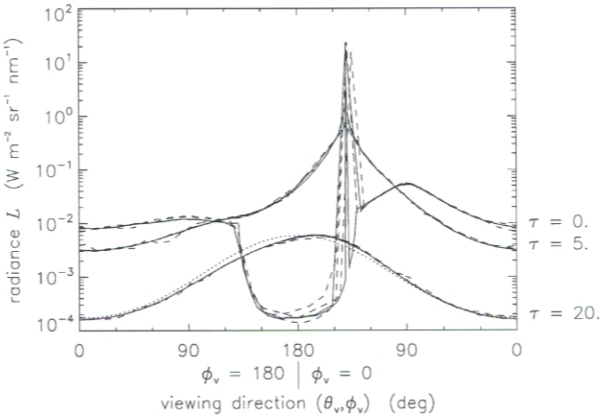
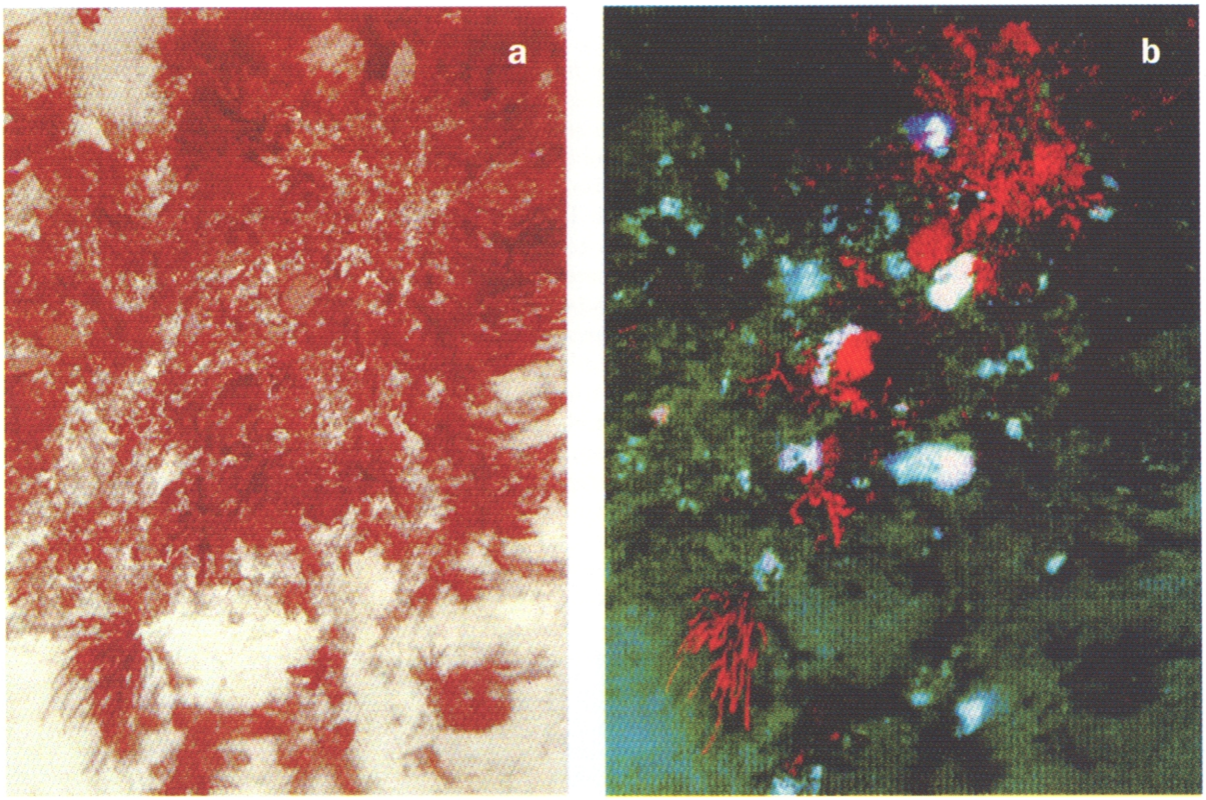


Figure 3. Fast, accurate, radiance-based radiative transfer models are now within the grasp of anyone having a workstation-size computer, while just five years ago such modeling efforts required the use of super computers. One such workstation-based model, HYDROLIGHT, yields results very close to more computer intensive Monte Carlo models. In this figure, five radiative transfer models, including HYDROLIGHT and several Monte Carlo models, are compared in simulations of the distribution of downward propagating radiance at three different optical depths.[7]

Knowledge of the global abundance of microscopic marine algae is key to understanding global marine primary production, the global carbon budget, and climate variability. For this reason, NASA launched the Coastal Zone Color Scanner (CZCS) in 1979 with the mission of mapping global ocean color.[2] It was believed that the concentration of photosynthetic pigments contained in the oceanic phytoplankton could be derived accurately by measuring the amount of light reflected from the ocean in the blue portion of the spectrum relative to that in



Courtesy of Bryan Coles, Raytheon Inc., and Michael Strand, Naval Undersea Warfare Center.

Figure 4. The ocean floor in the area of the Dry Tortugas imaged using a laser line scan system capable of measuring benthic fluorescence. The area is located in 10 m of water and is inhabited largely by coral. (a) Light reflected from the ocean floor at 488 nm. Dark areas are various species of coral and light areas are uncolonized calcarious sediments. (b) The same area imaged simultaneously in three fluorescence bands typical of hard and soft corals: 520 nm (appears blue in the image), 570 nm (appears green), and 685 nm (appears red). Coral species appearing red contain mostly chlorophyll and indicate mostly soft corals and algae. Features that appear white fluoresce brightly in all three of the spectral bands and indicate the presence of specific species of hard coral.

the green portion of the spectrum. The CZCS mission was tremendously successful and provided large-scale, synoptic images of ocean color and near-surface chlorophyll concentration at 1 km resolution for many areas of the global ocean from 1979 to 1986 (See Fig. 1). The data from this sensor is still being analyzed today with great interest.[3] In addition to providing high-quality ocean color imagery, the CZCS mission had a profound effect on the level of research interest in ocean optics around the world (See Fig. 2) for two reasons. First, the imagery was visually intriguing leading to speculation as to how important oceanic biological, physical, and chemical processes may be gleaned from the associated optical properties. Second, algorithms were needed to relate the optical properties to known biological and chemical processes to make maximum use of the CZCS data.

Sources and scales of oceanic optical variability

The clear, blue ocean represents the least complicated ocean optical problem because the primary cause of variability results almost entirely from pigments associated with phytoplankton and, to a much less extent, the associated degradation products. Effects of the ocean floor are neglected because the water depth is very large compared to the attenuation length of light. In addition to limited sources of optical variability, the dominant time-scales of variability in the open ocean are generally long (days to months) and the spatial scales tend to be large (1–100 km). Superimposed on the temporal and spatial scales of optical variability are much more subtle changes in the absorption and scattering properties of ocean waters throughout the course of each day. In general, both absorption and light scatter will increase during the day as the number of phytoplankton cells increases due to production. These optical properties tend to decrease during the night as primary production falls to zero and phytoplankton cells are consumed by zooplankton grazing.[4] Adding to this effect is evidence that the optical properties of the individual algal cells change with illumination intensity.[5] The effect of the environment on the optical properties of marine plants is a relatively new area of research and issues such as the relative role of production/grazing and phytoplankton optical properties in diel variability in the open ocean are not completely understood.

Optical variability in coastal waters is much more complicated because of the additional influence of optically active matter of terrestrial origin and, in some cases, the ocean floor. In many coastal areas, components such as inorganic suspended sediment, dissolved organic material from decaying terrestrial plants, and pollution can have a significant impact on the optical properties of water. Therefore, it is important that all of the potential sources of optical variability be taken into consideration when trying to interpret an optical signal, such as ocean color. In contrast to the open ocean, the optical properties of coastal water can vary significantly on small length scales in every direction (<< 1 km) and short time scales (minutes to hours). In the open ocean it is common to assume a horizontally homogeneous water column, with a vertically homogeneous surface mixed layer, from the surface to a depth of 20-100 m. Much of the theoretical and modeling work describing radiative transfer in the water column has incorporated this assumption, often with demonstrated success. However, recent coastal work has suggested that thin (cm) sheets of intense biological activity can develop and persist over tidal time scales (See Fig. 3).[6] This kind of situation requires a careful experimental design and treatment of radiative transfer theory to unravel the optical effects.

Finally, the ocean floor can play an important role in modifying the distribution of light within the shallow coastal ocean. Our knowledge of factors that affect the optical properties of the ocean floor is very limited because few measurements of spectral reflectance and absorption of the ocean floor and its constituents exist. In addition, we have almost no knowledge of their fluorescent properties. Compared to situations in which suspended particles in the water column may be treated as having simple shapes (to efficiently calculate light scatter) with random orientation, the ocean floor's directional reflectance and fluorescence can be relatively complicated.

Advances in radiative transfer modeling

Progress in personal computing has placed accurate radiative transfer models at our fingertips (See Fig. 3). Five years ago, the most accurate means of modeling the complete in-water radiance field required a large computer, often a supercomputer, and millions of executions of a radiative transfer model using a statistical technique called Monte Carlo. In this technique, the radiative transfer equation is solved by assigning probabilities to absorption and scattering events and following the life-histories of a very large number of individual photons. Analytical irradiance-based models, such as the well-known two-flow approach, have existed for nearly a century. However, these models are not capable of accurately simulating the details of the radiance distribution. Recently radiance-based analytical models have been developed that are as accurate as the Monte Carlo models[7] and yet require only a workstation-level computer to run efficiently. In the near future, one model, HYDROLIGHT, will be configured to run on modern personal computers.

Advances in instrumentation

Much of the recent advances in understanding how light interacts with the ocean has been realized through advances in the instruments that measure water optical properties. While optical field equipment designed years ago was primarily for open ocean research applications, it is not appropriate for coastal research due to the greater range in concentrations of optically active matter, the temporal and spatial scales of optical variability, and the additional complication of a shallow ocean floor. For example, because light in coastal waters is absorbed much faster than in the clear ocean, especially in the blue portion of the spectrum, by high concentrations of dissolved organic matter, radiometers must be smaller to avoid the corrupting effects of the instrument's shadow.[8] Also, because chlorophyll is only one of potentially many materials suspended and dissolved within the water column, measurements made with more spectral bands are required to completely characterize the spectral shape of the inherent optical properties. While instruments lowered from a ship are adequate for open ocean applications, remotely operated vehicles fitted with optical instrumentation are commonly used in coastal research to avoid the effects of the ship's shadow. Perhaps the most radical change in measurement techniques as been at the shallow ocean floor. Here, spatial variability is often at centimeter scales requiring precise positioning of small fiber optic probes. In many situations, this can only be accomplished with instruments operated by SCUBA divers.

Glossary

Benthos: Living biological material on the ocean floor.

Biomass: The mass of biological material present.

Ocean color remote sensing: Measuring the spectral color of the ocean using sensors on aircraft and satellites.

Ocean optics: Also called optical oceanography. The study of how light interacts with the ocean.

Radiative transfer: The study of how electromagnetic energy propagates through a medium, such as the ocean.

Water column: The volume of the ocean between the water surface and the ocean floor.

In ocean color remote sensing, new spaceborne instruments will soon be available to investigate both open ocean and coastal waters. The multispectral scanners aboard these satellites will image the oceans with a relatively small number of spectral bands designed to detect marine photosynthetic pigments and colored dissolved organic matter. The first of these satellites will likely be launched this year; the U.S. plans to launch SeaWiFS (Sea-viewing, Wide-Field-of-View Sensor) and Japan plans to launch the Ocean Color and Temperature Sensor (OCTS). In addition, several other space-based, multi-spectral, ocean color sensors are scheduled for launch before the turn of the century. The U.S. will sponsor the moderate-resolution imaging spectrometer (MODIS) and multi-angle imaging spectroradiometer (MISR). France will sponsor polarization and directionality of the Earth's reflectance (POLDER). While the primary mission of these sensors, particularly SeaWiFS and OCTS, is to extend the global ocean pigment distribution time series, started with the CZCS mission, they are also faced with the challenge of deriving accurate pigment concentrations in coastal waters where photosynthetic pigments comprise only a portion of the ocean color signal. The CZCS bands were optimized for open ocean applications and the resulting pigment algorithms were capable of deriving pigment concentrations to within 40%. In coastal waters, the errors are much higher due to the confounding effects of high concentrations of dissolved organic matter of terrigenous origin. While both SeaWiFS and OCTS will have additional bands designed to discriminate between dissolved organic matter and photosynthetic pigments, much field work will be required after these satellites are launched to develop and test algorithms that may be robustly applied to any ocean area, regardless of water type.

In addition to multispectral ocean color, on April 24, 1996, the U.S. launched the first and, by far, the most sophisticated, orbiting hyperspectral (*i.e.,* having hundreds of spectral bands) scanner system: midcourse space experiment (MSX). The primary mission of the MSX is to test ideas about using the complete UV, visible, near-infrared, and thermal-infrared spectrum to detect and track intercontinental ballistic missiles and warheads. While the mission was conceived during the height of the Cold War, with the decrease in tensions between the U.S. and Russia, the once secret MSX mission is now declassified and may be used for Earth observations. One possible use of the MSX will be to test hyperspectral ocean color remote sensing concepts. The challenging issues involve how to move beyond the simple two- or three-wavelength band ratio techniques applied to CZCS data, and planned for SeaWiFS and OCTS data, to a full-spectrum analysis with the hundreds of bands possible with the MSX. The research community has only just started to think about how to analyze a continuous spectrum of ocean color because until recently neither the sensors nor the computing power was readily available.

Another area of ocean color remote sensing that is being implemented involves well-calibrated sensors aboard aircraft. While hyperspectral sensors have been applied to coastal ocean problems in the past, they have only recently developed to the point where their calibration and signal-to-noise ratios approach or exceed that necessary for quantitative ocean color measurements. The most noteworthy airborne hyperspectral systems appropriate for ocean applications are airborne visible-infrared imaging spectrometer (AVIRIS), developed at the Jet Propulsion Laboratory, and the PHYLLS (portable hyperspectral imager for low light spectroscopy), recently developed at the Naval Research Laboratory. Airborne remote sensing has associated problems that are not encountered with space-based systems—most notably, the effects of clouds on the measured water-leaving radiance. In satellite imagery, cloud covered regions are simply omitted from the analysis. However, since aircraft can fly below clouds, they have the capability to measure the water-leaving radiance resulting from illumination that is much different than a clear, cloudless sky. Research on how illumination effects water-leaving radiance has yet to be conducted. Aircraft remote sensing may not have the spatial coverage of a satellite system, however this is compensated by a much higher spatial resolution that will find applications in the rapidly changing coastal environment.

At still higher spatial scales, underwater systems are being developed that are capable of imaging the color and fluorescence characteristics of the ocean floor (See Fig. 4). One promising approach to imaging benthic fluoresence is laser line scan in which the ocean floor is illuminated by a rapidly-scanning, narrow laser beam. The detection system is configured with a narrow field of view and is synchronously scanned with the laser beam. The geometries of the laser beam and detection system intersect at a predetermined distance below the scanner. Anything within the intersection volume, such as benthic features, are imaged while light scatter and fluorescence from the intervening water volume and not included within the intersection volume is eliminated from the image. As a result, the system can image benthic fluorescence clearly through five or more attenuation lengths of water. Other approaches to underwater imaging, such as cameras with flood lights, are generally limited to less than three attenuation lengths. As in the case of airborne ocean color measurements, algorithm development applied to underwater imagery for measuring the optical properties and composition of the ocean floor has lagged far behind that applied to satellite ocean color imagery and it is expected that this will be a major area of research investment during the next 5 to 10 years.

Conclusions

Interest in how light interacts with the world's oceans has increased steadily in the past 20 years because of concern for national security and the global climate. The past five years have seen significant advancements in our ability to measure *in situ* the optical properties of open ocean and coastal waters. At the same time, accurate ocean imaging spectrometers on aircraft and satellite platforms and multispectral underwater imaging systems capable of measuring the fluorescence properties of the ocean floor have been developed and the next generation of satellite, global ocean color, multispectral scanners will soon be launched. With these tools, the next five years will likely see an emphasis on developing robust image analysis algorithms designed to remotely sense the optical properties and concentrations of optically active matter within open ocean and coastal ocean waters and on the shallow ocean floor.

References

1. C. Mobley, "Oceanic optics," Opt. & Phot. News **2** (7), 14–19 (1991).
2. W. A. Hovis *et al.*, "Nimbus-7 coastal zone colour scanner: System description and initial imagery", Science **210**, 60–63 (1980).
3. B. G. Mitchell, "Coastal zone color scanner retrospective," J. Geophys. Res. **99** (C4), 7291–7292 (1994).
4. D. A. Siegel *et al.*, "Optical determination of particulate abundance and production variations in the oligotrophic ocean," Deep-Sea Res. **36** (2), 211–222 (1989).
5. S. G. Ackleson *et al.*, "Irradiance-induced variability in light scatter from marine phytoplankton in culture," J. Plank. Res. **15** (7), 737–759 (1993).
6. P. L. Donaghay *et al.*, "Optical layers in an isotropic coastal ocean: an ephemeral phenomena or an inappropriate physical model?," in *1996 Amer. Geophys. Union Ocean Science Meeting Abstracts,* San Diego, Calif., (American Geophysical Union, 1996) p.48.
7. C. D. Mobley *et al.*, "Comparison of numerical models for computing underwater light fields," Appl. Opt. **32** (36), 7484–7504 (1993).
8. H. R. Gordon and K. Ding, "Self-shading of in-water optical instruments," Limnol. Oceanogr. **37** (3), 491–500 (1992).

Kenneth J. Voss is associate professor in the Physics Dept., University of Miami, Coral Gables, Fla., and Steven G. Ackleson is scientific officer in the Office of Naval Research, Arlington, Va.