Ocean Optics Research at the Start of the 21st Century

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Advances in ocean optical modeling and sensor design, coupled with the development of autonomous sampling platforms, have provided the oceanographic community with unprecedented opportunities to measure, monitor and investigate the processes that control the interaction of light with the ocean and its boundaries. Increases in measurement accuracy, optimizations in sensor specifications (power, size, weight, cost, and maintenance), the expanded range in temporal and spatial scales over which such measurements can be made, and the speed at which solutions to radiance-based optical models can be obtained, coupled with a national commitment to monitoring the coastal ocean and international interest in measuring the state of the global ocean have ushered in what could arguably be called the golden age of ocean optics research and application.

For most of the 20th century the ocean optics community was primarily concerned with developing the tools required to investigate the details of radiative transfer within the ocean, starting in the first decade with simplistic models of light propagation within scattering and absorbing media (Schuster, 1905) and early attempts to measure the subsurface light field (Hojerslev [1989] and references therein) and culminating at the close of the century with the capability to monitor and interpret the color of the global ocean from space (see Mitchell [1994] and companion articles) and measure extreme events within the ocean using autonomous sensors (e.g. Dickey et al., 1998) and highly accurate numerical simulations (Mobley et al., 1993). Today, at the start of the 21st century, we find ourselves at the beginning of the most interesting part of any scientific endeavor—the application of our assembled tools to learn more about the nature of light in the world's oceans.

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Cumulatively these accomplishments have resulted in several important trends during the 20th century that have shaped the way that light in the sea is investigated. As we continue to turn our attention to ever more complicated, interdisciplinary problems requiring observations over wider ranges in temporal and spatial scale, we expect that these trends will continue well into the 21st century.

Irradiance-Based → Radiance-Based Models

The first models of light propagation within scattering and absorbing media, developed early in the 20th century, treated the light field as two streams of irradiance propagating in opposite directions—the so-called two flow approach (Schuster, 1905; Hulbert, 1943). The values of this and other similar approaches (e.g. Zaneveld and Spinrad, 1980; Gordon et al., 1988) are computational simplicity and physically meaningful analytical solutions. The shortcomings of such irradiance-based models are that they require *a priori* knowledge of the subsurface radiance distribution and are based upon the assumption of a plane-parallel ocean. So, the user had to know something about the light field to be simulated and the models could not be applied to three-dimensional problems. As computer technology advanced in the latter half of the century, statistical approaches to solving the radiative transfer problem for radiance distribution, e.g. Monte Carlo models, were developed that trace the life histories of many individual photons (e.g. Kattawar and Plass, 1972; Gordon and Brown, 1973). Three-dimensional radiance distribution as a function of depth could then be defined as the integrated effects of individual photon experiences. While these radiance-based models led the way to more accurate simulations of the subsurface light field and played a supporting role in the development of submersible radiometers and ocean color remote sensors and algorithms, they were not widely embraced by the oceanographic community because they required what was at the time considered to be immense computational resources that were not readily available. Even with modern computational tools, Monte Carlo radiative transfer models are too slow to be used in dynamic ocean simulations. For this reason alone, irradiance-based models with simple analytical solutions continue to be used for their computational efficiency as well as the insight that can be gained from analytical solutions. However, within the past decade, increases in computer speed and innovative numerical approaches to solving the radiative transfer equation have circumvented the computational problems attributed to Monte Carlo models and placed the capability to accurately model the details of sub-surface radiance distribution within the hands of any interested researcher with little effort and expense. Whereas only a decade ago, simulations of subsurface radiance distribution required hours of processing time on a supercomputer, today, it is possible to complete the same simulations with equally high accuracy in a few minutes using a standard laptop computer running an invariant imbedding model (Mobley, 1994). Depending on the degree of detail required, versions of such models are currently being employed in ocean physical, chemical, and biological process models (see article, this issue, by Bissett et al.).

Apparent → Inherent Optical Properties

Regardless of how the sub-surface light field is to be simulated or characterized, the starting point is information pertaining to the rates of absorption and scatter. This requires putting instruments into the water that either measure these properties directly or through a surrogate measure that represents the combined effects of absorption and scatter. The first class of ocean optical instruments to be developed were broadband radiometers that measured characteristics of irradiance as a function of depth (see article, this issue, by Maffione). The observed decrease in light intensity with depth could then be described as an exponential decay rate, the diffuse attenuation coefficient or K (Jerlov, 1976). From a modeling perspective, sub-surface light intensities could then be characterized reasonably well by using K to constrain an exponential decay function. With the development of satellite-based ocean color sensors, starting with the launch of the Coastal Zone Color Scanner in 1978, color ratio techniques were developed to estimate K at 490 nm globally for open ocean waters where optical variability is dominated by local marine biological processes (Austin and Petzold, 1981). Such waters represent greater than 90% of the global ocean and perhaps it is for this reason that they are referred to as Case I ocean waters (Jerlov, 1976).

The limitation of K is that it is a convolution of absorption and scatter as well as radiance distribution from which these properties cannot be easily retrieved. This limits the utility of K; for example, K cannot be used solely to address the ocean color problem because it cannot be used to specify the rate of light scatter in the backward direction. Therefore, without the capability to measure the inherent optical properties of the ocean, initial applications of more complicated solutions to the radiative transfer equation, such as Monte Carlo and invariant imbedding, were limited to modeling exercises based on the scant amount of information that could be gleaned from laboratory analysis of water samples. Validation of radiance-based models was, therefore, put on hold until *in situ* sensors capable of directly measuring the total absorption and scattering properties of ocean water were developed.

Throughout the second half of the century, submersible radiometers were refined to measure a number of narrower bands across the visible light spectrum and constructed (Smith et al., 1984), with the aid of accurate radiative transfer simulations, so as to reduce the effects of instrument self-shading (Gordon and Ding, 1992; Leathers et al., 2001), and data reduction procedures were established to account for ship shadow. However, it is interesting to note that little headway was made towards directly measuring the details of radiance distribution as a function of depth and precious few data sets exist today (Tyler, 1960; Voss, 1989). This remains a gap in our experience base as well as a limitation to validating radiance-based models.

The decade of the 1990s was a period of intensive development of *in situ* optical sensors capable of accurately and rapidly measuring inherent optical properties of ocean water (see article, this issue, by Maffione). Initially, emphasis was placed on quantifying the spectral absorption of the various components of ocean water, e.g. phytoplankton, detritus, and dissolved matter. Most recently, attention has shifted towards characterizations of light scatter with the ultimate goal of providing routine measurements of the complete volume scattering function. While this goal has yet to be achieved, prototype volume scattering instruments are currently under development and expected to yield much-needed data sets representing a wide range of ocean environments in the coming years.

Laboratory/Ship-Based Observations → Autonomous Sampling

Ocean optical observations that a decade ago required time-consuming analyses of water samples conducted within land-based or ship-based laboratories can now be made rapidly using *in situ* sensors. Spectral absorption, scattering, and beam attenuation sensors that, not too long ago, were no more than wishful thinking, are now considered standard equipment on hydrographic profiling packages. Where a short time ago researchers based their ideas about ocean processes on discrete water samples collected at a small number of discrete times and locations, nearly continuous profiles and high-frequency time series are revealing ocean processes that few have even imagined. In 1998, an array of oceanographic sensors, including irradiance and absorption sensors, were moored in the mid-Atlantic Bight and documented the change in water column optical properties with the passage of two hurricanes—Edouard and Hortense (see article, this issue by Dickey and Chang and references therein). Where the pre *in situ* sensor oceanographic community could only consider long temporal and large spatial scales of optical variability, small-scale features and processes can now be investigated. For example, optical sensors positioned on slow-drop instrument platforms resulted in the discovery of thin, sub-tidal layers of concentrated biological activity within many coastal environments that may, at times, account for a large percentage of the water column integrated biomass and primary production (Cowles et al., 1998; Jaffe et al., 1998). These features were completely missed or overlooked with traditional hydrocast sampling techniques.

Throughout the 20th century, the majority of oceanographic observations were conducted from floating platforms—ships and crew dedicated to the task of getting man and equipment to sea. Today, while ships continue to serve as the backbone for oceanographic observations, recent advances in mooring, buoy, and underwater autonomous vehicle and remote sensing technology have enabled the researcher to monitor the ocean autonomously at a variety of temporal and spatial scales for extended periods of time.

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21st Century Challenges

What are some of the outstanding challenges awaiting us in the 21st century? There is no definitive answer to this question since it depends on one's point of view—the more you know the more you realize that you don't know, as well as your reference point in time. The pace of discovery is difficult to predict and one's expressed grand challenge today can be reduced to triviality tomorrow. However, in the spirit of musing about the future, allow me to point out a few ocean optics problems that will not likely be solved soon, or perhaps not at all, in the century before us.

Optical measurements with accuracy approaching that of temperature and salinity. In comparing different systems for measuring the inherent optical properties of ocean water, such as absorption, under optimal environmental conditions, measurement error on the order of 20% is proclaimed a success (Pegau et al., 1995). Yet, such an error would be unacceptable when comparing temperature or conductivity probes. Our challenge for the coming decades is to reduce these errors across the entire visible spectrum to the point where they are compatible with other standard physical measurements. Until we can do this, our ability to validate models that predict optics-based, nonlinear, ocean systems should not be expected to advance much beyond our present capability.

Process-based ocean color algorithms. Ocean color algorithms have historically assumed vertical homogeneity within 1 - 2 attenuation lengths of the ocean surface. While this may be a robust assumption for Case I waters, it is frequently erroneous within coastal environments. This is both a problem for current algorithms and a hope for greater things to come. The water-leaving radiance, being a vertically-integrated quantity, contains information regarding the vertical distribution of optically-important water constituents. Likewise, near-surface processes within the coastal ocean are never totally isolated from mid-water column and even near-bottom processes. One possible approach to linking the vertically-integrated property of color to vertical water column structure may be to use the remotely-sensed water-leaving radiance to constrain process models that account for the details of radiative transfer. In this scenario, distributions of water constituents would not come directly from simplified ocean color algorithms but from properly constrained ocean process models that can potentially yield accurate assessments of optical properties far removed from the ocean surface. Under such a scenario, the remotely sensed ocean color data would likely comprise only a portion of the data necessary to properly constrain an appropriate process model. Other data sources would likely be sensors positioned within an adaptive sampling network, perhaps deployed on autonomous vehicles, and other remotely sensed properties, such as sea surface temperature and surface winds. Specifying the amount and type of data necessary to adequately constrain ocean process models as a function of environmental condition is a related issue that the oceanographic community has only started to address.

Beyond the plane-parallel assumption. A standard assumption in modeling radiative transfer within the ocean is that the water column is composed of horizontal layers that, optically-speaking, extend to infinity in all directions—the plane-parallel assumption. And yet, variability in the subsurface light field is inherently a three dimensional problem, even under the most quiescent conditions. In fact, the temporal and spatial distribution of sub-surface light contains a wealth of information regarding the distribution of optically-important constituents within the water column, the distribution of features at the ocean boundaries (the sea surface and the shallow ocean floor), and even about processes and features associated with the local marine atmosphere. The challenge is to develop techniques for sampling radiance distribution at the appropriate time and space scales and analyzing the resulting data so as to unravel the highly convoluted environmental information. For example, some recent work has used time series of sub-surface light field fluctuations to constrain a surface wave model and reconstruct the above-water scene (Potter, 1996). Likewise, the near-bottom light field within shallow marine environments is also an inherently 3-dimensional problem that cannot be addressed with the standard assumption of a plane-parallel ocean (see article, this issue, by Mazel).

Generic submersible radiometer. Present day radiometers come in a variety of styles and sizes, driven by the sort of data required; e.g. photosynthetically-active radiation (PAR), multispectral vector or scalar irradiance, and remote sensing radiance. When deployed from a floating platform, we apply empirical relationships to correct for ship and instrument shadow. The challenge is to develop an affordable generic radiometer that is applicable to all radiance- and irradiance-based requirements and that automatically corrects for ship and instrument shadow effects. This can be accomplished with rapid measurements of the complete radiance distribution and on-board data storage and processing. The objective is not necessarily to deliver all of this massive quantity of data, e.g. representing a deep profile or long time series, but to store, process, and transmit only what is requested, such as PAR or remote sensing reflectance. Having measured the complete radiance distribution, non-traditional quantities could also be observed routinely such as the average cosine, a quantity required for irradiance-based radiative transfer models, and Q, a factor used in ocean color models to relate remote sensing radiance to upwelling irradiance. One could also contemplate methods of parameterizing the radiance distribution and transmitting only a few controlling factors required for reconstruction. Indeed, this is the sort of instrument that is required to conduct comprehensive optical closure experiments, validate radiance-based models, and to start addressing the issue of 3-dimensional variability in the sub-surface light field.

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