Global Surveys of Bio-Optical Ocean Properties

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The Joint Global Ocean Flux Study is organized into five components: process studies, time series observations, modeling, data management, and global surveys [JGOFS, 1991]. The last of these will consist of large-scale surveys of ocean processes and properties important to the global carbon cycle. The planners of the study decided that, for the immediate future, it would be best to carry out the surveys in cooperation with another global study, the World Ocean Circulation Experiment (WOCE) in the WOCE Hydrographic Program (WHP). This article aims to promote interest in the global survey, and to provide guidelines for those proposing research along these lines. The WHP aims to promote interest in the global circulation Experiment (WOCE) in the WOCE another global study, the World Ocean Circulation Experiment (WOCE) in the WOCE hydrographic program (WHP). This article aims to promote interest in the global survey, and to provide guidelines for those proposing research along these lines. The WHP is truly comprehensive and will require many investigators over the next several years to complete the survey. Here, we describe the need for a global survey of optical and biophysical properties in the ocean, and identify how these measurements are to be implemented in JGOFS.

Optics Data on the World Ocean

Large-scale ocean surveys, such as Geosecs, Transient Tracers in the Ocean, and the international Indian Ocean Expedition, as well as compilations of data into atlases (for example, Wyrtki [1971]; Levitus [1982]) have been extraordinarily significant to the development of the science of oceanography. Without these influential contributions, our understanding of ocean processes would be primitive indeed. No comparable surveys exist of biological parameters or optical properties. It could be argued that ocean satellite imagery suffices for global coverage of these; however, sea-truth is required to interpret the satellite signals. As stated by Gordon and Morel [1983], such interpretation rests entirely on the "data bank generated by ship-bound oceanographers." Now it is possible to add moored and drifting bio-optical instruments to our sampling repertoire, which can address scales of variability not accessible from ships (see, for example, Dickey [1991]; McClean and Lewis [1991]).

In addition, improvements in algorithms for the estimation of chlorophyll from satellite data do not depend on a satellite overhead. Jerlov, in 1951, was the first to compile optical data for the world ocean (see Jerlov [1976]). He used his own data from the North Sea, North Atlantic, and Mediterranean (later adding Chinese and Japanese data from the areas of the Pacific) to arrive at an optical classification of ocean waters. This semi-quantitative way to categorize waters according to their color and attenuation has proven useful over the years to many investigators (see, for example, Simon and others, 1988). The other data-set on optical properties in the ocean is for the Secchi depth. This has recently been compiled by the U.S. NODC (see Lewis et al. [1988]). While useful, the Secchi depth does have shortcomings. As discussed by Preisendorfer [1986], interpretation of Secchi disk data requires corrections for the physiological state of the observer and corrections between observers. Furthermore, the Secchi depth is inversely proportional to a compound optical property, the sum of beam attenuation (an inherent optical property) and the diffuse attenuation coefficient (an apparent property). It is not necessarily true that these will co-vary, and the only way to learn about the behavior of either is to use an irradiance meter of different wavelength. As pointed out by Preisendorfer [1986], the use of such a meter then obviates the need for the Secchi depth. There are other data sources for optical properties (Austin and Petzold, 1984; Morel, 1988); however, the database is still unacceptably small.

Large-Scale Surveys of Phytoplankton Pigments

One conclusion we can make regarding these data is that in the open ocean, optical properties are closely tied to the pigment and biogenic particles suspended in the water. Relationships between spectral irradiance and pigment, although inexact, have proven useful to remote sensing of chlorophyll [Gordon and Morel, 1983]. We now need to be able to understand: the relationship between chlorophyll a and optical properties in the water column to improve algorithms for the interpretation of satellite color images; the vertical distribution of chlorophyll in the water column, to evaluate what the satellite sensors, and the distribution of plant pigment and particles as causes for the variation in optical properties, as well as their interrelationship with primary production (see, for example, Morel [1981]).

Protocols for the Global Survey

The authors of this article have respectively chaired three different meetings this year to discuss issues related to the role of optics in global programs and to define measurements and protocols for the various components of these programs. Reports being prepared on these meetings will provide guidance to those proposing research with JGOFS objectives.

The first meeting, chaired by J. Marra and sponsored by the Scientific Committee on Ocean Research, was that of the JGOFS Optics Task Team (March 21-22, 1991, Palisades, N.Y.). The Task Team consists of representatives from countries on the JGOFS Committee and advises international JGOFS on ocean optics issues. The team consists of J. Aiken, Plymouth Marine Laboratory, U.K.; H. Gordon, University of Miami, U.S.A.; M. Lewis, Dalhousie University, Canada; J. Marra, Lamont-Doherty Geological Observatory, U.S.A.; A. Morel, Laboratoire Physique et Chimie Marine, France; J. Mueller, San Diego State University, U.S.A.; R. Reuter, University of Oldenburg, Germany; and M. Wernand, Netherlands Institute for Sea Research, The Netherlands.

The second meeting, chaired by J. L. Mueller and sponsored by NASA, was the SeaWiFS Project Workshop, which addressed issues related to the validation of satellite images using in situ optical data (April 4-5, 1991, Monterey, Calif.). The third meeting, organized and chaired by T. D. Dickey (and sponsored by U.S. JGOFS), considered the overall role of optics and bio-optics in fulfilling the objectives of JGOFS, from the perspective of the U.S. JGOFS program (June 17-18, 1991, Boulder, Colo.). During these meetings, protocols were defined for the JGOFS-WOCE collaboration for the global survey of bio-optics.

Sampling on WHP Cruises: Since time on the WOCE transects will be at a premium, the bio-optics casts must be done separately from the WOCE profiler (CTD) so that the optical sensors do not interfere with the profiler's operation—its descent through the water, electronic power supply, and other aspects. The casts must also be of short duration—less than 30 minutes. The U.S. WOCE program has allocated one berth for the JGOFS global survey optics program, and the International Program has agreed in principle to provide a berth on cruises on a space-available basis.

These sampling considerations mean that measurements in the JGOFS bio-optics program will largely require sensors rather than water-bottle sampling; a ship-launched bio-optical system; and one cast per day, with a two-wire operation. The bio-optical system must also be relatively lightweight, operable by a non-person, and flexible enough to work on a variety of ships.

Ship-launched sensors: An ideal set of sensors would directly measure spectral ab-
or early 1990s, but none, not even the U.S. National Oceanic and Atmospheric Administration were at the time willing to risk the potential loss of the WHP transect that the new production of the open ocean, as defined by satellite ocean color, would cause. The effort would be made at a planned rate of $55 million per year, with the aim of having the full suite of bio-optical properties, as well as those dependent upon the Sun, to be collected day or night. Measurements are not dependent upon the Sun and near the stern of the ship. The only real solution is to configure sensing packages to operate independently of the ship. Although a few systems have been configured this way, they are not able to measure the full suite of bio-optical properties, nor have they become easy enough to use under the limitations of sampling on WHP transects already noted. **Sampling Resolution:** With one optical cast per day, the optical data on these cruises will exist at a station spacing of about 100 km. A shipboard flow-through system for surface seawater to measure such variables as temperature, salinity, and nutrients and dissolved oxygen could help determine spatial variability at the surface and help to interpret the station data. Temporal variability is in the form of seasonality (whether tropical or temperate) and shorter period phenomena. Seasonal coverage for the global ocean is a desirable goal, but one that will take many years to accomplish. Optical properties, influenced by biology, are akin to similar data sets such as those on nutrients and CO2 obtained over the years, which have proven particularly valuable in recent years for modeling (see, for example, Glover and Brewer [1988]; Wroblewski et al. [1989]) and in studies of the global carbon cycle (see Kao and Sarmiento [1985]). Even if the optical measurements for the global survey are not made at the appropriate spatial scale, the collection of data will further the study of the relationship between optical properties and the factors that cause their variability (Morel, 1988). The JGOFS Optics Task Team identified the optics measurements necessary to meet the objectives of the three observational components of JGOFS: the time series, process studies, and global survey. Table 1 summarizes recommendations for the optical measurements over the depth range 0-200 m for the global survey, with the overriding factor being that this component of JGOFS will be important for remote sensing applications. Most underwater optical sensors are sensitive to a range of light wavelengths. The table gives the minimum set of wavelengths, which correspond to the wavelengths of radiance that SeaWIFS will measure. For measurements above water, a range of wavelengths is also desirable; however, a minimum requirement is to record data at 550 nm, coupled with a total (broad-band) sky irradiance (E(total)). Another useful variable is the upwelled radiance (Lw) at 683 nm, which can be related to the pigment chlorophyll a and photosynthetic activity of the phytoplankton [Chamberlin et al., 1990]. Beam attenuation, c, at 660 nm is a good indicator of the amount of particulate matter in the ocean. In addition to these, water sampling is required to identify phytoplankton pigment types and quantities via chromatographic and fluorescence methods. To help characterize the spatial variability of the subsurface optical properties, optical sensors (fluorescence) should be mounted in the shipboard flow-through system for surface seawater. J. Aiken of Plymouth Marine Laboratory uses an optical sensor suite (Eg, Eθ, at several wavelengths) called “Lightfish” that can be towed behind a ship at a fixed depth to record the variability in optical data. **Current Planning** The National Science Foundation, the National Aeronautics and Space Administration, and the National Oceanographic and Atmospheric Administration have all entertained proposals to conduct these measurements as part of their respective global change programs (see Committee on Earth and Environmental Sciences [1989]). An announcements of opportunity for these programs are circulated periodically, while proposals to NSF can be submitted at scheduled target dates as well. NSF has provided initial