SATELLITE OCEAN COLOR—STATUS REPORT

Considerable progress has been made.

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Satellite ocean color measurement is 10 years old this year. The Coastal Zone Color Scanner (CZCS) was launched on the Nimbus-7 satellite in October, 1978, as a 1-year proof-of-concept mission. CZCS measured reflected sunlight at 443, 520, 550, 670 and 750 nm and infrared emissions at 11.5 um, across a swath 2200 km wide and with a spatial resolution (pixel size) at nadir of 0.8 km^2. CZCS produced data until summer, 1986, when technical problems with the instrument forced an end to the mission. During the past 10 years, engineers, physicists, optical oceanographers, phytoplankton ecologists and physiologists, numerical modelers and others worked together to develop the methods and procedures for incorporating CZCS imagery into mainstream oceanography. Progress has not been easy and technical problems still remain. However, many oceanographers now feel that satellite ocean color measurements are an essential, if not indispensable, component of oceanographic field experiments. This is especially true of the U.S. Global Ocean Flux Study (GOFS) and other initiatives that are developing under the multi-agency U.S. Global Ocean Science Program (U.S. GOSP Interagency Working Group, 1987) and its international analogues.

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The purpose of this report is to briefly summarize where ocean color research stands today, as well as to outline the plans for the next 10 years. Much of the satellite ocean color research effort in the past 10 years was focused on understanding what CZCS was actually measuring, as well as learning the limitations of the measurements and how to improve the accuracy and increase the applicability of the technique. Considerable progress has been made, and we are now at the point where scientific applications, rather than development, will be the future research emphasis.

The Ocean Color Technique

As for all photosynthetic plants, phytoplankton contain chlorophyll-a and other pigments which absorb sunlight to provide energy for photosynthesis. Phytoplankton absorb primarily blue and red light and reflect green. Thus, as phytoplankton pigment increases, ocean color changes from blue to green. For most ocean waters, equations developed by optical oceanographers accurately predict chlorophyll-a (including chlorophyll degradation products) from measurements of backscattered light at only 3 wavelengths (443, 520 and 550 nm). These equations predict the mean chlorophyll-a concentration within the upper photic depth (inverse of the attenuation coefficient for sunlight irradiance, 400-700 nm). Pigments other than chlorophyll-a contribute to ocean color and photosynthesis, but chlorophyll-a alone is useful as a measure of total phytoplankton biomass (abundance).

Sediment, detritus, and humic substances also affect the spectrum of backscattered light. Algorithms used to calculate chlorophyll from CZCS measurements work poorly for waters where reflectance of these substances contribute a relatively high proportion of total backscattered light. Thus, CZCS does not yield reliable estimates of chlorophyll concentration for many nearshore areas around the world. Research is underway to develop algorithms to separate detrital, sediment and phytoplankton signatures from coastal waters. These algorithms require measurements at more channels than available on CZCS. One approach is to take advantage of the strong blue and near-ultraviolet (ca. 400 nm) absorbance of detrital substances to separate them from living phytoplankton which do not absorb strongly at wavelengths shorter than ca. 420 nm. Another approach is to use sunlight-stimulated chlorophyll-a fluorescence at 685 nm to estimate phytoplankton concentration and possibly the rate of phytoplankton photosynthesis. Although the latter approach seems promising, the requisite satellite sensors for space applications will not be available for at least 7 years.

High concentrations of coccoliths (calcium carbonate plates attached to the cell walls of species classified within the phytoplankton taxon, Coccolithophorid) are strongly reflecting and have a unique signature in CZCS imagery. European investigators (Holligan *et al.* 1983) first noticed patches of high reflectance in CZCS imagery of open ocean waters and were later able to prove that the patches consisted of detached coccoliths and coccolithophorids. The CZCS chlorophyll-algorithm does not work for waters high in coccoliths. On the other hand, the unique reflectance signature of high coccolith concentrations can be used to locate coccolithophorid blooms in CZCS imagery and to study bloom dynamics. Coccolithophorids are particularly significant to GOFS, since sinking coccoliths are an important mechanism for transporting carbon from surface waters to the seafloor. In addition, coccolithophorids produce the chemical compound, dimethyl sulfide (DMS), as a by-product of photosynthesis. DMS seeds cloud formation over ocean waters. Researchers have proposed that long-term changes in the mean abundance of coccolithophorids may have had a significant impact on the Earth's radiation budget, thereby contributing to changes in mean temperature (Rampino and Volk, 1988).

The most difficult problem to overcome to successfully apply the ocean color technique from space was to correct sensor measurements for atmospheric reflectance. Sunlight backscattered by the atmosphere contributes about 80-90% of the energy measured by CZCS at the key ocean color wavelengths of 443, 520 and 550 nm. Before CZCS measurements could be used to study the ocean, researchers had to develop atmospheric correction procedures which in effect threw out the baby to study the bath water. Atmospheric correction is possible because blue ocean water reflects negligible light at 670 and 750 nm. Energy measured by CZCS at these wavelengths is due only to the scattering characteristics of the atmosphere, particularly those of dust particles (aerosols) suspended in the air. Measurements at 670 and 750 nm, when used with an appropriate model of atmospheric optical properties, are then used to correct the signal measured at 443, 520 and 550 nm for the aerosol contribution to atmospheric scattering. The contribution of molecular (Rayleigh) scattering is calculated separately with a mathematical model.

The first atmospheric correction algorithms could not correct CZCS measurements at low sun angles. A new multiple scattering algorithm was recently introduced which extended the lower limit of the range of sun angles for which accurate estimates of chlorophyll-a could be obtained (Gordon *et al.* 1988). The new algorithm more than doubles the spatial/temporal range for CZCS chlorophyll estimates. Annual CZCS-chlorophyll time series are now possible for latitudes which fall between 60N and 60S. Good results from polar regions are obtained for more than half the year.

Use of CZCS Imagery

To date, the principal use of CZCS imagery has been to study mesoscale or regional scale oceanographic processes. The imagery provides a synoptic map of near-surface chlorophyll concentration that is impractical to obtain using other methods. Single images are useful for locating and providing X,Y scale information for fronts, eddies, coastal currents and other mesoscale features. Image sequences are used to study the dynamics of these features. Applications include studies of the spring bloom in continental shelf and slope waters off the U.S. northeast coast (Brown *et al.*, 1985), dynamics of Gulf Stream rings (Evans *et al.*, 1985; Smith *et al.*, 1987), upwelling features off the U.S. west coast (Abbott and Zion 1985, 1987), Gulf Stream and coastal dynamics off the U.S. southeast coast (McClain *et al.*, 1984; Yoder *et al.*, 1987), phytoplankton blooms in the Arabian Sea (Banse and McClain, 1986) and the effect of El Nino in the eastern equatorial Pacific (Feldman *et al..*, 1984).

A second research use of CZCS imagery is to estimate primary production for relatively large areas of the ocean (10^3 - 10^4 km^2). With this approach, CZCS images are used as input to mathematical relations incorporating terms for chlorophyll, temperature, irradiance and other variables (Eppley *et al.* 1985; Perry 1986; Collins *et al.* 1986). Work in progress shows good agreement between *in situ* measurements and satellite estimates for at least some regions. However, major issues remain unresolved. For example, CZCS images provide chlorophyll estimates for only the first photic depth (see above), whereas primary production extends at least 3 times deeper into the water column. How can primary production models based on CZCS imagery account for vertical chlorophyll structure and its effect on depth-integrated primary production? Secondly, how can one estimate the effects of nutrient limitation on primary production from satellite sensors? These and other issues need to be resolved before biological oceanographers will accept primary production estimates based only on satellite measurements and mathematical models.

Future emphasis is to use CZCS imagery to study basin- and global-scale processes. By compositing the results from many orbits, CZCS-chlorophyll images of entire ocean basins (e.g. see back cover of this issue) and of the global ocean are possible (Esaias *et al.* 1986). Weekly and monthly composites yield information on seasonal phytoplankton blooms. Annual composites could yield insights in the study of interannual variability. To date, only a few test images have been produced. Nevertheless, these few images have intrigued biological oceanographers. Based on these images, a common assumption is that the "G" in GOFS will be possible only by using composite imagery from CZCS and future sensors to extrapolate local measurements to larger scales.

However, many issues need resolution before routine analysis of composite images are possible. For example, the number of observations at each pixel within a composite image is not constant. In some parts of the image, a pixel may represent the mean of many observations, because cloud-free conditions were common during the compositing interval. In another part of the same image, a pixel may represent only 1 observation. Clearly, the statistical implications of image composites need to be carefully considered

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by those who plan to use them to study large scale processes.

Future Plans

One of the most criticized aspects of the CZCS mission was the lack of an efficient data distribution program. Until recently, relatively few oceanographers have been able to routinely incorporate CZCS imagery into their research programs. Ironically, the data distribution problem originated because the 1-year proof-of-concept mission for CZCS lasted 8 years. NASA did not anticipate the need for data distribution to a broad constituency, since the mission was planned only to evaluate the potential of satellite ocean color measurements during a 1-year mission. In addition, algorithms to convert raw data to chlorophyll concentrations were initially unavailable, and image processing hardware was very expensive. In recent years, data distribution has received a high priority and the situation is much improved. For example, all of the CZCS data collected for the U.S. west coast at the Scripps Satellite Oceanography Facility has been processed to Level 2-3 products (i.e. gridded, chlorophyll fields) and is available on 9-track tape for a nominal charge. Goddard Space Flight Center is engaged in an ambitious program to process all of the global CZCS data to Level 2-3, including various types of composite imagery. The imagery will be distributed on both 9-track tape and digital optical disk by a new archive. The first complete year (1979) of global CZCS data consisting of approximately 15,000 scenes should be in the archive by summer, 1988. To increase the image processing capability of the oceanographic community, several groups are developing CZCS image analysis software packages for PC-class computers. One of these systems will be available in 1988. Thus, in the near future we can expect much broader access to, and wider use of, CZCS imagery.

The next 10 years should see a large increase in the number of investigators, research programs and publications which take advantage of this important new data source for oceanography.

To replace the CZCS, NASA and the Earth Observation Satellite Company (EOSAT) are planning a new satellite ocean color instrument to be launched on the Landsat-6 satellite in 1991 (Joint EOSAT/NASA Sea-WiFS Working Group Report, 1987). The new sensor, Sea Wide Field Sensor (Sea-WiFS), will have the same 5 visible/near-infrared channels as CZCS, as well as an additional channel centered at 860 nm. Data from the extra channel will be used to increase the accuracy of atmospheric correction in comparison to what is possible with CZCS. Because of the extra channel and other improvements, Sea-WiFS will yield better results than CZCS for both coastal and oceanic waters. Sea-WiFS will also have 3 thermal infrared channels for determining sea surface temperature.

Sea-WiFS will record 40 minutes of data per orbit, which is essentially all of the daytime data. Of the 40 minutes of data per orbit, 10 will be recorded at full resolution (1 km^2) and the remainder will be recorded at reduced resolution (ca. 16 km^2). A fixed location on the sea surface will be covered every 1-2 days. In addition to the tape-recorded data, full resolution data will be continuously broadcast using the HRPT format. The latter data stream is primarily designed for commercial and operational users who must license a de-coder to be able to interpret the HRPT downlink. Research users will have access to the global data (from the tape recorders) through the NASA Sea-WiFS project to be located at Goddard. The project is planning to process and distribute Sea-WiFS data within days-to-weeks from the time the data is collected. An Announcement of Opportunity to fund Sea-WiFS research projects is expected from NASA prior to launch.

Other satellite ocean color instruments are planned for the future. The Japanese are planning the Ocean Color and Temperature Sensor (OCTS) for their Advanced Earth Observing Satellite (ADEOS) to be launched in 1994. The specifications for the OCTS are not final, but will probably include the same visible/near-infrared channels as Sea-WiFS, 2 additional visible band channels and several thermal infrared channels. One of the additional visible band channels may make measurements at 410-415 nm, so that an algorithm separating phytoplankton from detrital absorbance may be possible (see above). NASA is planning Moderate-Resolution Imaging Spectrometer (MODIS) and High-Resolution Imaging Spectrometer (HIRIS) for the Earth Observing System of the middle 1990s. Both are advanced instruments having many spectral channels. Science teams to guide the development of MODIS and HIRIS will be selected based on proposals submitted by 1 July, 1988.

In conclusion, satellite ocean color research during the past 10 years focused on technique development. As a result of these efforts, algorithms, processing capability and the data are now available to many more research users than was possible even just a few years ago. The next 10 years should see a large increase in the number of investigators, research programs and publications which take advantage of this important new data source for oceanography.

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A POST-GRADUATE VIEW [CONTINUED FROM PAGE 13]

Thirdly, graduate schools need to recognize that entering students come from a variety of backgrounds, each with its own inherent strengths and weaknesses. Some allowance must be made for this in the graduate curricula.

One step that has been taken in this direction by the Joint Program is the introduction of a math course in the first summer, designed to help ensure that students do not start their first semester with a disadvantage in this area. Finally, departments offering bachelor's degrees in oceanography should track their graduates and see how they have fared in their further education and careers. This information, along with statistics from graduate departments of oceanography on the rate of acceptance of applicants and the fate of the admittees, classified by undergraduate major, should be useful in future evaluation of undergraduate programs.

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TABLE 1. A PARTIAL LIST OF INSTITUTIONS OFFERING BACHELOR'S DEGREES IN OCEANOGRAPHY OR MARINE SCIENCE.

Florida Institute of Technology, FL
Humboldt State College, CA
Millersville State College, PA
Southampton College, NY
Stockton State College, NJ
Texas A&M University at Galveston, TX
U.S. Naval Academy, MD
University of Miami, FL
University of Michigan, MI
University of South Carolina, SC
University of Washington, WA

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OPTICAL OCEANOGRAPHY [CONTINUED FROM PAGE 23]

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OCEANOGRAPHY SOCIETY [CONTINUED FROM PAGE 21]

strength to a society in their own specialty. A new society would provide a mechanism for evaluating this strength, for focusing it , and maximizing its application. The changes which can be brought about in the world of social organizations by the activities of The Oceanography Society could well be comparable to the changes which were brought on-campus by the establishment of oceanography departments.

As in the universities, where all departments cooperating in the marine sciences saw those programs strengthened by the existence of an oceanography department in their midst, it is likely that the ocean-oriented programs of brother societies would be strengthened by their association with The Oceanography Society. A broader and deeper basis for support of all applications of ocean science, engineering, and technology could be tapped.

The potential of oceanography seems unlimited. The oceans constitute a major part of our planet. Understanding and fully utilizing the oceans will require all the knowledge of the basic sciences and all of the skills of engineering and technology. To obtain appropriate support and to seek this understanding effectively requires the coordination and focusing of the many different participating institutions and societies. A missing element has been a dedicated Oceanography Society.

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