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SeaWiFS Technical Report Series

Stanford B. Hooker and
Elaine R. Firestone, Editors

Volume 17, Ocean Color in the 21st Century: A Strategy for a 20-Year Time Series

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Abstract

Beginning with the upcoming launch of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), there should be almost continuous measurements of ocean color for nearly 20 years if all of the presently planned national and international missions are implemented. This data set will present a unique opportunity to understand the coupling of physical and biological processes in the world ocean. The presence of multiple ocean color sensors will allow the eventual development of an ocean color observing system that is both cost effective and scientifically based. This report discusses the issues involved and makes recommendations intended to ensure the maximum scientific return from this unique set of planned ocean color missions. An Executive Summary is included with this document which briefly discusses the primary issues and suggested actions to be considered.

1. INTRODUCTION

The development of a 20-year time series of ocean color measurements from satellites starting with the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), presents many scientific opportunities to study long-term variability of biological processes in the upper ocean. These studies will range from the response of the upper ocean ecosystem to global climate change to the management of coastal zone resources.

There are several challenges that must be overcome before these studies can be done. These include: cross-calibration and validation of the different sensors which will be launched by the National Aeronautics and Space Administration (NASA), the National Space Development Agency (NASDA) of Japan, and the European Space Agency (ESA); initiation of a program to ensure comprehensive, coordinated observation and modeling plans; and consistency of data processing and data access. The presence of multiple ocean color sensors will allow the eventual development of an ocean color observing system that is both cost-effective and scientifically based.

This report discusses these subjects and makes recommendations to ensure the maximum scientific return from this unique set of planned ocean color missions. The Executive Summary (Section 2), encapsulates the primary points made in this document. The remaining content is an in-depth discussion of these subjects and concerns. Some sections of the Executive Summary recur in the main discussion for emphasis of particular points and narrative clarity.

2. EXECUTIVE SUMMARY

Over the past decade, the following scientific objectives have been developed for using ocean color measurements for ocean research.

1. Improve the quantitative understanding of the ocean's role in the global carbon cycle. Specifically, ocean color imagery, *in situ* bio-optical measurements, numerical models, and measurements from other space sensors (for example, infrared thermometers and scatterometers) will be used to:
    a) improve estimates of the production and fate of particulate and dissolved organic carbon (DOC) in the global ocean;
    b) estimate the effects of phytoplankton blooms on the exchange rates of carbon dioxide (CO_2) between the atmosphere and the upper ocean;
    c) describe the evolution of the coupled biological and physical processes in the upper mixed layer; and
    d) provide the first quantitative estimates of interannual to decadal changes in global ocean primary production.
2. Improve the quantitative understanding of how light absorption by the upper ocean affects the ocean heat budget;
3. Improve the quantitative understanding of how phytoplankton blooms affect the production and air-to-sea exchange of dimethyl sulfide (DMS) and other trace gases that may affect cloud formation and other atmospheric processes; and
4. Understand the relationship between phytoplankton and other components of the marine ecosystem as related to fisheries, environmental stress, and resource management.

The long-term scientific goal is to understand not only how ocean biological processes affect the global carbon cycle, but how they will change in response to changes in physical forcing on local, regional, and global scales. An understanding of the coupled dynamics of ocean biology, ocean physics, and atmospheric forcing on the oceanic upper mixed layer is the ultimate objective.

In addition to these scientific objectives, ocean color measurements will provide valuable information for managing ocean resources. For example, Coastal Zone Color Scanner (CZCS) data were used successfully in several fishery studies for both research and operational applications. Other applications, such as monitoring coastal water movements and detection of eddies and fronts for shipping, will also be conducted using ocean color observations.

To meet these goals, the following observational requirements must be met:

a. Two-day global coverage at 1 km resolution with a sensor that meets the technical specifications at least at the level of those of SeaWiFS (continuous record) and direct read-out of Local Area Coverage (LAC) data using off-the-shelf equipment;

b. In-water measurements to validate water-leaving radiances and to evaluate regional chlorophyll *a* algorithms and other bio-optical variables;

c. Develop coupled biological and physical numerical models which incorporate ocean productivity and its effects on air and sea CO_2 and trace gas exchanges, fates of organic carbon, and ocean heat budgets using the following inputs: satellite ocean color imagery, *in situ* data, and derived products from other satellite sensors such as wind stress, sea surface temperature (SST), and solar insolation;

d. Acquire measurements centered near 412 nm for estimates of detrital carbon and improved estimates of chlorophyll *a* in oceanic and coastal waters, and at the sunlight induced fluorescence band (around 685 nm) for improved estimates of coastal chlorophyll *a* concentrations and for determining the physiological state of phytoplankton (to improve estimates of primary production); and

e. Space based observations with full spectral coverage from 400 nm through the near infrared (IR), 800 nm, to resolve accessory pigments and for refined estimates of chlorophyll *a*, detrital carbon, and other in-water constituents.

As ocean color observations will be made from a wide range of sensors with different capabilities and from satellites with different orbits, considerable effort will be required to merge these data sets into a consistent, quantitative view of upper ocean biology. Ocean color measurements will require a high level of stability and accuracy. The desired signal is very small (usually less than 10% of the total, satellite-sensed signal because of atmospheric effects) as are interannual changes in biomass and productivity.

To meet the science objectives, the following capabilities must be developed in addition to making ocean color measurements:

1. The development of fully coupled ocean and atmosphere models that include both biological and physical processes will require a full suite of physical measurements concurrent with measurements of ocean biology.
2. An active program of cross-calibration between the sensors is essential to develop a statistically homogeneous, long-term (greater than 20 years) data record which can be used to study low-frequency events such as the El Niño Southern Oscillation (ENSO). This program must include some overlap period between the sensors and an active *in situ* calibration and validation program.
3. Access to the data and the analogous algorithms must be ensured.

The net result of this research will be an improved understanding of the processes that control carbon cycling and storage in the ocean. The availability of a multidecade, consistent time series on ocean pigment and primary productivity will allow the scientific community to study the role of low frequency variability in ocean biology. For example, ENSO events occur roughly every 3–4 years so that a 20-year time series should contain about five such events. The impact of ENSO events should be characterizable with a high degree of statistical robustness. More importantly, this long time series, if properly calibrated, will allow scientists to determine the ocean's response to long-term climate change.

By using numerical models that assimilate observations from satellites and *in situ* sensors, predictions could be made about the interactions between atmospheric forcing and primary productivity. However, data assimilation requires that the variance (error) structure is known of both the data sets being assimilated and the model relationships. For example, the temporal and spatial variance spectrum of light utilization parameters would be a key component of a productivity model that relies on assimilation techniques. At present, the understanding of the time and space variability of most biological properties is quite crude. However, such measurements are not beyond the scope of many planned and operational global oceanography programs. If the ultimate goal is the prediction of ocean carbon cycling in response to changes in atmospheric forcing, then collection of such data must begin, as well as the development of assimilation models.

Although the focus of this discussion is on global-scale processes, small-scale studies will also benefit from access to ocean color observations. For example, studies of coastal dynamics, river plumes, and fisheries have made extensive use of 1 km resolution CZCS data (Abbott and Chelton 1991). International efforts such as the Land Ocean Interaction in the Coastal Zone (LOICZ) program and the Global Ocean Ecosystems dynamics (GLOBEC) program will require high spatial resolution ocean color observations. In particular, high spectral resolution observations will be necessary in order to distinguish the various dissolved and particulate components of the upper ocean in both turbid and productive coastal waters.

2.1 Recommendations

2.1.1 Management Issues

The goal of a 20-year time series of global ocean color observations requires an unprecedented level of coordination between US federal agencies and their international partners. Sensor design and calibration should be well-documented such that data processing can take sensor performance into account. Data systems must be designed so that the processing history can be preserved and data and algorithms can be easily shared. Such coordination, however, must take place in an era of constrained financial resources. New methods for management must be explored.

1. An interagency working group on satellite ocean color research and applications should be formed by the Committee on Environment and Natural Resources (CENR) with representation from all interested US agencies. A charter for this working group should include both US and foreign missions. It should serve as the focal point for foreign collaboration. This group must also consider the necessary modeling activities and physical observations needed to analyze and interpret ocean color data.
2. The National Aeronautics and Space Administration (NASA) should convene a meeting of the appropriate project and program personnel (including contract management) along with representatives of the ocean color research community as soon as possible to develop an overall ocean color program. This program should consist of plans for research, software development, data processing and delivery, funding, and management.
3. SeaWiFS and the Earth Observing System (EOS)-Color efforts should be considered by the EOS Data Information System (EOSDIS) as the prelaunch system capability tests which will facilitate the transition from 4 km SeaWiFS data to 1 km Moderate Resolution Imaging Spectrometer (MODIS) data.
4. The MODIS Oceans Team should be designated the EOS-Color Science Team, which would be expanded upon the results of an EOS-Color NASA Research Announcement (NRA). NASA should negotiate clear agreements with the MODIS Oceans Team regarding deliverables and funding. These agreements must be coordinated across the full set of ocean color activities so an efficient, realistic plan is developed.
5. NASA should plan an EOS-Color NRA for the 1996–97 time frame.
6. NASA should encourage investigator relationships between US and foreign scientists. This may require agreements on data delivery and policies, in which case NASA, the European Space Agency (ESA), and the National Space Development Agency (NASDA) of Japan should establish appropriate understandings as soon as possible.

2.1.2 Calibration and Validation Issues

Each ocean color sensor must be calibrated and an initial *in situ* validation cruise will be required shortly after each launch. The vicarious method developed by Gordon and co-workers (Evans and Gordon 1994) provides a powerful technique to calibrate the entire ocean color system. An extensive calibration program is planned for the EOS sensors; these efforts must be coordinated with the methods described in this document. The issue of international coordination also arises in this context; extensive *in situ* observations are costly, and cooperation between the various international partners could reduce the costs for each country.

Given that there will be periods when more than one sensor is in orbit at any one time, maximum priority should be given towards conducting calibration and validation cruises to compare the sensors during these overlap periods. Collecting extensive calibration and validation measurements should help develop a consistent time series of ocean color measurements from this diverse set of sensors. This would also ensure radiometric continuity between the missions which, to the extent that the system algorithms (atmospheric and bio-optical) provide accurate products, would facilitate continuing studies of interannual variability. Clearly, this intercalibration effort will require cooperation on an international level. Recommendations to achieve these goals follow.

a. Calibration and validation cruises must take place as soon after launch as possible in regions with appropriate bio-optical properties.

b. Feasibility studies should be conducted on the use of high-altitude, oligotrophic lakes as calibration and validation sites.

c. Calibration and validation cruises must be located in both northern and southern waters to investigate thermal effects on sensor performance.

d. Calibration and validation cruises should be planned for other bio-optical water types, but these need not be completed during the initial period of sensor operation.

e. NASA should encourage investigators to collaborate with their international colleagues to develop a global network of bio-optical moorings.

2.1.3 Data System Issues

The primary goal of a 20-year time series requires that the data processing and distribution system be designed to safeguard the raw data and the calibration and validation information, to enable reprocessing, and to ensure efficient transfer of data and algorithms to US and international researchers. The data system cannot view itself in isolation from contemporaneous data centers or systems that may precede or follow it. High priority must be given towards ensuring compatibility of these basic services. While a data system may focus on a specific mission, e.g., SeaWiFS, its role in the larger constellation of ocean color missions must be retained. It must be carefully integrated into a data systems strategy that ensures ease of use of other Earth data sets. Particular attention should be paid to retention of the sensor design, calibration, and validation information. This will allow future researchers to reprocess the data in a consistent manner.

- NASA must work to eliminate all restrictions on access to ocean color observations, consistent with the EOS data policy. This policy must apply to both US and foreign researchers.
- Consistency should be maintained between the various sensor data sets as they move from one data processing and delivery system to another.
- SeaWiFS and the Ocean Color Temperature Sensor (OCTS) from Japan, should serve as a testbed for such exchanges between international partners. Although the primary focus may be at the investigator level, NASA may need to support efforts on data policies, data exchange, and satellite downlinks.

2.1.4 Convergence

As more nations begin ambitious programs for space based research on the Earth system, there appears to be considerable overlap between observing capabilities. The distinctions between the different sensors are sometimes subtle. With increasing budget pressures, there is substantial pressure to merge these various observing capabilities. While the scientific rationale for long-term, continuous observations of ocean processes is well in hand, the appropriate sampling strategies are not in place, in part because of the lack of understanding of the critical processes and their associated temporal and spatial scales. The next decade should focus on the necessary studies to develop such an operational observing system that can adequately resolve these processes in order to develop sound predictions of the coupled ocean and atmosphere system and how it will respond to climate change. In essence, convergence should be viewed as an opportunity to move *from* purely science-driven observations *towards* observations for monitoring and predicting, which must remain firmly based on scientific understanding of ocean processes. Although national interests are often involved in the launching of satellite remote sensors, the opportunity presented by the multiple ocean color missions must be used to design an effective international program. The following are recommendations for achieving this effectiveness.

a. NASA should coordinate research activities with the other sponsoring agencies to develop the observing and sampling requirements for an ocean color system which will make the essential measurements for ocean monitoring and prediction.
b. An interagency effort needs to be implemented to define new products for the coastal zone and to collect, process, and distribute the LAC data.
c. NASA must support efforts to link ocean models with both physical and biological data and ensure that lessons learned from both modeling and data analysis are used in the design of ocean color observing systems.

3. OCEAN COLOR RESEARCH

3.1 Research Priorities

An ad hoc committee was formed in 1991 to report on ocean color research in the pre-EOS and EOS eras. The committee recommended the following scientific objectives:

1. Improve the quantitative understanding of the ocean's role in the global carbon cycle. Specifically, ocean color imagery, *in situ* bio-optical measurements, numerical models, and measurements from other space sensors (for example, infrared thermometers and scatterometers) will be used to:
    a) improve estimates of the production and fate of particulate and dissolved organic carbon (DOC) in the global ocean;
    b) estimate the effects of phytoplankton blooms on the exchange rates of carbon dioxide (CO_2) between the atmosphere and the upper ocean;
    c) describe the evolution of the coupled biological and physical processes in the upper mixed layer; and
    d) provide the first quantitative estimates of interannual to decadal changes in global ocean primary production.
2. Improve the quantitative understanding of how light absorption by the upper ocean affects the ocean heat budget;
3. Improve the quantitative understanding of how phytoplankton blooms affect the production and air-to-sea exchange of dimethyl sulfide (DMS) and other trace gases that may affect cloud formation and other atmospheric processes; and
4. Understand the relationship between phytoplankton and other components of the marine ecosystem as related to fisheries, environmental stress, and resource management.

The long-term scientific goal is to understand not only how ocean biological processes affect the global carbon cycle, but how they will change in response to changes in physical forcing on local, regional, and global scales. An understanding of the coupled dynamics of ocean biology, ocean physics, and atmospheric forcing on the oceanic upper mixed layer is the ultimate objective.

In addition to these scientific objectives, ocean color measurements will provide valuable information for managing ocean resources. For example, CZCS data were used successfully in several fisheries studies for both operational and research, e.g., Fiedler et al. 1984. Other applications, such as the monitoring of coastal water movements and detection of eddies and fronts for shipping, will also be conducted using ocean color observations.

3.2 Observation Plan

Beginning in 1994, there should be nearly continuous ocean color measurements for the next 20 years. SeaWiFS will provide the first data set, beginning in 1994 with a planned 5-year mission. It will be followed by OCTS on the first Advanced Earth Observation Satellite (ADEOS-1) launched by NASDA in 1996, and by MODIS on the first EOS morning (AM-1) platform scheduled for 1998. A follow-on SeaWiFS-class sensor will also be launched in 1998 (EOS-Color) as will the Medium Resolution Imaging Spectromenter (MERIS) on the Environmental Satellite (ENVISAT) to be launched by the European Space Agency (ESA). A second MODIS will be launched on the second EOS (PM-1) platform in 2000. The Global Imager (GLI) will also be launched by NASDA in 2000. After this point, there will be two copies of MODIS in orbit at any one time for the 15-year EOS mission.

3.2.1 Implementation Priorities

The ad hoc committee proposed several implementation priorities to accomplish the science objectives, using the satellite missions as the basic observational framework. These priorities are:

a) two-day global coverage at 1 km resolution with the sensor meeting the technical specifications at least at the level of SeaWiFS (continuous record) and direct read-out of LAC data using off-the-shelf equipment;

b) in-water measurements to validate water-leaving radiances and to evaluate regional chlorophyll *a* algorithms and other bio-optical variables;

c) develop coupled biological and physical numerical models that incorporate ocean productivity and its effects on air and sea CO_2 and trace gas exchanges, fates of organic carbon, and ocean heat budgets using as inputs: satellite ocean color imagery, *in situ* data, and derived products from other satellite sensors such as wind stress, SST, and solar insolation;

d) acquire measurements centered near 412 nm for estimates of detrital carbon and improved estimates of chlorophyll *a* in oceanic and coastal waters, and at the sunlight-induced fluorescence band (around 685 nm) for improved estimates of coastal chlorophyll *a* concentrations and for determining the physiological state of phytoplankton (to improve estimates of primary production); and

e) space based observations with full-spectral coverage from 400 nm through the near-IR (800 nm) to resolve accessory pigments and for refined estimates of chlorophyll *a*, detrital carbon, and other in-water constituents.

These priorities serve well as an initial start for a research plan. However, some important issues for future missions should be addressed. First, multiple global observations at 1 km spatial resolution on a daily basis will greatly improve scientific understanding of the role of mesoscale processes in the upper ocean. Given that eddy sizes in many parts of the ocean are of the order of 10 km, the initial Global Area Coverage (GAC) SeaWiFS spatial resolution of 4 km will not be adequate to resolve such features. Coupled with cloud patterns, more frequent sampling will also be necessary to resolve the temporal variability of these features. Recent field and model studies have shown that variability on these space and time scales plays a critical role in the coupling of the atmosphere and the upper ocean and in the control of biological productivity. Second, improved sensor performance beyond SeaWiFS is essential to detect chlorophyll *a* fluorescence and to characterize completely the optical properties of the upper ocean, but no planned sensor will have the necessary high spectral resolution across the visible wavelengths. The original MODIS-T (which was *tilted* to minimize sun glint) sensor met these specifications.

3.2.2 Requirements for Observations

Given nearly-continuous ocean color measurements and the long-range goal of understanding the coupled physical and biological system, there are several requirements for observations. First, the development of fully coupled ocean and atmosphere models that include both biological and physical processes will require a full suite of physical measurements concurrent with measurements of ocean biology. Second, an active program of cross-calibration between the sensors is essential to develop a statistically homogeneous, long-term (greater than 20 years) data record which can be used to study low-frequency events such as the ENSO. This program must include some overlap period between the sensors and an active *in situ* calibration and validation program. Third, the data should be processed and archived by several groups so that access to the data and the corresponding algorithms is ensured. These requirements will be challenging, given that the time series will be comprised of measurements from several sensors from various countries.

Although these challenges are not insurmountable, planning must begin immediately to achieve the fundamental goal of a consistent, long-term record. Numerous examples exist, such as the Advanced Very High Resolution Radiometer (AVHRR) and the Active Cavity Radiometer Irradiance Monitor (ACRIM), where such a consistent record could not be assembled even when similar sensors from an individual nation were used to collect the record.

3.2.3 Field Measurements

In the context of a satellite ocean color program, field measurements should be focused on calibration and validation of the sensors, as well as algorithm development and validation of products. The SeaWiFS Project has defined a suite of measurements and protocols that should serve as a baseline for future field programs (Mueller and Austin 1992). Sampling strategies should consist of both intensive, focused cruises, and extensive, less intense measurements from moorings and drifters.

Algorithm and numerical model development will take place as part of investigator-driven field programs, rather than as part of specific flight projects. The exception would be new algorithms designed to take advantage of new sensor capabilities, such as the 412 nm band for dissolved organic matter (DOM). In terms of numerical model development, specific activities need to be directed towards characterizing the spatial and temporal variability of the critical variables of the models as well as the relationships between processes. This characterization is essential if construction of models that can assimilate satellite data is to be realized. Although this activity is beyond the scope of an instrument flight project, it must be conducted in a systematic manner, and not be restricted to a few locales. Critical information must be delivered back to the flight project to ensure instrument performance and data product definition.

The field component of satellite missions must work in close cooperation with existing and planned field programs, especially those with a global focus such as the Joint Global Ocean Flux Study (JGOFS). NASA must work cooperatively with agencies that control ship funding and schedules to ensure that these vital field measurements are supported. In the past, coordination between agencies responsible for satellite observations and agencies responsible for ship observations has been difficult to achieve.

3.3 Convergence of Ocean Color Missions

As more nations begin ambitious programs for space based research on the Earth system, there appears to be considerable overlap between observing capabilities. The distinctions between MODIS, MERIS, and GLI are sometimes subtle. With increasing budget pressures, there is substantial pressure to merge these various observing capabilities. While the scientific rationale for long-term, continuous observations of ocean processes is well in hand, the appropriate sampling strategies are not in place, in part because of the lack of understanding of the critical processes and their associated temporal and spatial scales. The next decade should focus on the necessary studies to develop such an operational observing system which can adequately resolve these processes in order to develop good predictions of the ocean and atmosphere system and how it will respond to climate change. In essence, convergence should be viewed as an opportunity to move from purely science-driven observations towards observations for monitoring and predicting, which must remain firmly based on the scientific understanding of ocean processes. Although national interests are often involved in the launching of satellite remote sensors, the opportunity presented by the multiple ocean color missions must be used to design an effective international program.

Along with the joint scientific and calibration studies described earlier, examination must begin of the optimal sampling strategies for the various ocean color missions. Although crossing times and orbital altitudes have been established for all of the planned missions, slight changes in these parameters can greatly affect the type of sampling patterns that will be obtained by the full suite of ocean color missions. These issues include:

- Does diel variability in phytoplankton fluorescence need to be resolved, and what is the optimal set of measurements that will resolve these time scales?
- How do morning and afternoon overpasses interact with the variations in the cloud fields?
- What are the impacts of not flying a near-noon orbit on data quality?
- How does clear-weather sampling change with location and season?

In essence, a complete analysis of all error sources in the observing system (including both sensor and sampling errors) is needed in the context of the underlying biological variability. This analysis must consider the impact of these errors on scientific return. Close coordination between the various agencies responsible for ocean color observations will be required to develop an effective strategy that is based on scientific requirements.

In addition to sampling, studies should be conducted on the instrument characteristics required to make the necessary observations. For example, which wavelengths need to be measured? What signal-to-noise ratio (SNR) is required? Although the fundamental phytoplankton pigment observing requirements are understood, other variables such as pigment groups and chlorophyll *a* fluorescence are only in the experimental stage. Thus, this opportunity should be used to develop the observation requirements as well.

3.4 Advances in Scientific Understanding

With the CZCS, it was only possible to estimate total pigment concentrations as there was insufficient spectral resolution to separate chlorophyll *a* from its associated degradation products. Although this approach worked reasonably well, several studies have shown that the bio-optical algorithms fail in the presence of DOM, such as humic acids, which occur in coastal waters, in river plumes, and in the open ocean. SeaWiFS and follow-on sensors will have channels near 412 nm to correct pigment estimates and to estimate the concentration of colored dissolved organic matter (CDOM). Although there remain challenges for atmospheric correction at these short wavelengths, the availability of these measurements may extend the range of water types, which can be observed quantitatively from space.

Additional wavelengths and increased sensitivity will also permit chlorophyll *a* to be measured separately from other pigments. Certainly MODIS will be able to make this measurement and perhaps SeaWiFS. Other accessory pigments, such as phycoerythrin, will require at least the increased spectral resolution of MODIS and probably additional bands between 580 nm and 610 nm. Extensive airborne active and passive data have provided strong evidence that the phycoerythrin influence is contained within the ocean color spectrum (Hoge and Swift 1990), but appropriate wavelength bands must be provided to extract the actual pigment concentration.

3.4.1 Identifying Pigment Groups

One of the challenges remaining in bio-optical research is the use of full spectral measurements to separate all of the materials suspended and dissolved in the upper ocean and to correct for bottom reflectance in coastal waters, e.g., Lee et al. (1992) and Carder et al. (1993a). For example, can increased spectral resolution measurements be used to identify pigment groups within the phytoplankton, thus obtaining information on species composition? Can specific degradation products be identified? What minimal wavelength set and what concentration levels are required to derive this information? There is evidence from laboratory studies and limited *in situ* research that this approach can be used to characterize the bio-optical properties of the ocean. By using inversion techniques, it is possible to derive many of the bio-optical properties based on measurements of the complete spectrum of water-leaving radiance (Carder et al. 1993a and 1993b). The challenge for the next 10 years is to collect the necessary field data that will improve bio-optical models and strengthen the scientific underpinnings of this approach.

Such information on pigment groups is particularly important in studies of ocean carbon cycling. The patterns of cycling and vertical fluxes depend on the species structure of the phytoplankton community. Long-term changes in species composition, in response to changes in atmospheric forcing, is an important feedback in global climate change. Subtle shifts from one phytoplankton community to another can have dramatic impacts, yet little is known about large spatial scale changes in community structure. For example, the reduction of the ozone layer in the Southern Hemisphere results in increased ultraviolet (UV) radiation reaching the surface of the ocean. Preliminary studies indicate that the response to this increased UV radiation is species-dependent; changes in species composition will likely ripple throughout the entire ecosystem (Smith and Baker 1989).

Estimates of CDOM are also important in understanding carbon cycling. The amount of carbon in all DOM is thought to be as much as the entire terrestrial biomass. Processes that affect the partitioning of carbon between DOM and particulate forms will also impact carbon cycling. Partitioning, however, has been accomplished near the shore using hyperspectral data from aircraft (Carder et al. 1993a). Limitations due to the spatial and spectral resolution of planned ocean color sensors (approximately 1 km with one band every 10–20 nm) will reduce their utility in coastal regions.

Rivers are major sources of fresh water, sediments, nutrients and DOM to the coastal zone, in addition to pollutants that may be transported in soluble and particulate forms. Since CDOM from rivers is rather conservative with respect to salinity, it can be viewed from aircraft or space and used to trace terrigenous effluents and to quantify coastal salinity (Carder et al. 1993b). As riverine nutrients are incorporated into biomass by phytoplankton, the balance between absorption by CDOM and phytoplankton shifts, and a partition between mixing effects (CDOM) and growth and loss effects on phytoplankton biomass (chlorophyll *a*) may be achieved. Furthermore, knowledge of the river flux, plume area, and salinity provides valuable information necessary for estimating plume thickness from space; these data are important to calculating the light field in and beneath the plume (Müller-Karger et al. 1989).

Near the major rivers of the world, this approach can be attempted using ocean color sensors with 1 km resolution. For smaller rivers and estuaries, higher resolution is required to resolve smaller patch sizes and to correct for interference from bottom reflection which can perturb low-resolution coastal imagery. Hyperspectral imagery with spatial resolutions of about 100 m appears appropriate to help in assessing the flux of materials across the land-sea boundary as well as their influence on primary production, sediment dynamics, and pollution.

3.4.2 Interpreting Ocean Color

Any rise in sea level or coastal subsidence (for example, the Mississippi delta), may greatly affect nutrient fluxes, land usage, and nursery grounds for important fisheries. To interpret ocean color in the coastal zone where perhaps the strongest influence of humankind on the ocean is likely to occur, a significant improvement in the performance of the LANDSAT class of sensors is required, with a movement away from hyperspatial sampling and toward hyperspectral sampling. Improved SNR can be achieved by using larger pixels, e.g., 60–90 m and increased dwell or integration time in order to cope with a need for 10–15 nm sampling with contiguous bands, e.g., Carder et al. (1993a).

Although improved estimates of phytoplankton biomass and perhaps the separation of biomass into contributions by major phytoplankton groups will be of great value, scientists must look beyond these static variables to measurements of dynamics, specifically primary productivity and cycling of DOC. Although several approaches to estimating primary productivity using remotely sensed data have been described over the last 10 years, at present, scientific understanding and data sets are still inadequate. Most models rely on the basic biomass estimates collected from ocean color sensors to infer production rates. Various empirical methods are used to derive light adaptation and other physiological parameters to improve these rate estimates. Existing models explain less than 50% of the variance, and the model predictions are only within about an order of magnitude of the actual values (Balch et al. 1992, Platt and Sathyendranath 1993, and Balch 1993). However, there has been much recent progress, and it is expected that improved models will appear in the next year.

3.4.3 Discrepancies in Productivity

The challenge for remote sensing and biological oceanography is to understand the reasons for these discrepancies between *actual* and *predicted* productivity and to determine the appropriate time and space scales that can be modeled. No doubt some of the discrepancies result from the differing sampling characteristics of the satellite-based approach and the *in situ* measurements; that is, the satellite averages over depth and over area, whereas ships sample discrete points. The use of aircraft sensors to extend the ship measurements over wide areas of the satellite image should improve the estimates. However, this cannot explain all of the variability. When physiological information is added into the productivity models, the quality of the predictions increases substantially. Clearly, models based only on biomass are missing critical information. This is not a surprising result—the same results have been noted with terrestrial ecosystems. Although biomass is related to productivity, it is not the only determinant.

Much of the variability in the standing stock productivity relationship is a result of physiological processes, either due to adaptation or changes in species composition (Platt and Sathyendranath 1993). At present, species changes and the use of other variables to parameterize adaptation are generally ignored. For example, temperature may be used to infer nutrient availability (through mixing) as well as respiration. Presumably, similar relationships could be used involving SST, wind stress, and latent and sensible heat fluxes to derive vertical mixing rates which could then be used to infer light and nutrient supply rates. Although such an approach explicitly includes processes that are only parameterized in simpler models, they are burdened with many other parameters that must be defined, such as adaptation rates.

3.4.4 Promising Lines of Research

In terms of ocean color studies, there are at least two promising lines of research. First, existing research indicates that information on the photoadaptive state will significantly improve productivity estimates. Although the relationship of sun-stimulated fluorescence to photoadaptive parameters is not completely understood (especially for surface, light-inhibited populations), fluorescence bands will be included on MODIS, GLI, and MERIS. This information will provide direct estimates of the physiological state of the phytoplankton and, coupled with biomass estimates using measurements from other wavelengths, will improve productivity models (Chamberlin et al. 1989 and Kiefer and Reynolds 1992). The availability of morning and afternoon MODIS sensors early in the next century will allow the study of some aspects of diel variability, at least in regions of the world ocean that are not obscured by glint during one of the passes. Measurement of diel variations in sun-stimulated fluorescence might further improve models of phytoplankton growth rates. However, considerable field work remains before sun-stimulated fluorescence can become a standard tool for estimating productivity.

The second line of research is to expand the productivity models to incorporate more biological and physical processes explicitly. Clearly such an approach must reflect the increased understanding of the processes that regulate growth rates. A balance must be maintained between increasing the *realism* of the productivity models and adding unnecessary detail. As noted earlier, realistic models increase the number of free parameters that must be estimated.

The net result of this research will be an improved understanding of the processes that control carbon cycling and storage in the ocean. The availability of a multidecade, consistent time series on ocean pigment and primary productivity will allow the scientific community to study the role of low frequency variability in ocean biology. For example, ENSO events occur roughly every 3–4 years so that a 20-year time series should contain about five such events. The impact of ENSO events should be characterizable with a high degree of statistical robustness. More importantly, this long time series, if properly calibrated, will allow scientists to determine the ocean's response to long-term climate change.

By using numerical models that assimilate observations from satellites and *in situ* sensors, predictions could be made about the interactions between atmospheric forcing and primary productivity. However, data assimilation requires that the variance (error) structure is known of both the data sets being assimilated and the model relationships. For example, the temporal and spatial variance spectrum of light utilization parameters would be a key component of a productivity model that relies on assimilation techniques. At present, the understanding of the time and space variability of most biological properties is quite crude. However, such measurements are not beyond the scope of many planned and operational global oceanography programs. If the ultimate goal is the prediction of ocean carbon cycling in response to changes in atmospheric forcing, then collection of such data must begin, as well as the development of assimilation models.

Although the focus of this discussion is on global-scale processes, small-scale studies will also benefit from access to ocean color observations. For example, studies of coastal dynamics, river plumes, and fisheries have made extensive use of 1 km resolution CZCS data (Abbott and Chelton 1991). International efforts such as the Land Ocean Interaction in the Coastal Zone (LOICZ) program and the Global Ocean Ecosystems dynamics (GLOBEC) program will require high spatial resolution ocean color observations. In particular, high spectral resolution observations will be necessary in order to distinguish the various dissolved and particulate components of the upper ocean in both turbid and productive coastal waters.

4. Concerns

There are numerous concerns associated with ocean color research, running the gamut from management issues, to those regarding the sensors themselves. In this section, some of these issues are discussed.

4.1 Management Oversight

The goal of a 20-year time series of global ocean color observations requires an unprecedented level of coordination between US federal agencies and their international partners. Sensor design and calibration should be well-documented such that data processing can take sensor performance into account. Data systems must be designed so that the processing history can be preserved and data and algorithms can be easily shared. Such coordination, however, must take place in an era of constrained financial resources. New methods for management must be explored.

The programmatic direction for current and planned work in ocean color remote sensing during the next decade is not very well focused. Several federal agencies, e.g., the US Navy, the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and NASA have interests in ocean color research and applications in the US. Similarly, there is strong international interest in Japan and Europe. NASA and NSF have taken the lead in national and international coordination through sponsorship of meetings, but there is currently no specific US federal focal point for such activities nor any ad hoc or standing group which coordinates US federal policy. Historically, NASA has taken the lead in this area, however there is no longer a civil service associated with this portfolio.

A loose triumvirate of program managers is acting as an advisory group for the oceans with the biogeochemistry program manager taking the lead on ocean color matters. A diffuse federal focus coupled with a diffuse programmatic base in NASA has forced the development of a variety of ad hoc efforts to deal with issues such as SeaWiFS calibration and validation, ship time, etc., and has left the community with an unclear idea of which agency is responsible for which activities. The challenge is even greater in regards to foreign missions. In a cost-constrained environment, all of the available resources must be leveraged where possible. For example, shared cruises could help reduce ship time costs. Although SeaWiFS has extensive international involvement, there must be similar efforts focusing on the whole spectrum of ocean color missions.

4.2 Pre-EOS Missions

With the launch of SeaWiFS in 1994, the oceans community will again have access to high quality ocean color data after an eight-year gap. SeaWiFS has an established science team who will ensure that the data are processed and calibrated to the highest standards. It should be recalled that SeaWiFS has had a science oversight committee throughout its definition, design, and construction phase.

4.2.1 EOS-Color Background

The EOS-Color mission arose from the EOS program as a substitute for MODIS-T, which was deselected from the EOS payload. With the launch of the nadir-viewing MODIS (formerly MODIS-N) on the first EOS morning (AM-1) platform, it was realized that the coverage of the ocean would be greatly reduced, given the contamination by sunglint. EOS-Color is designed to provide measurements to complement the single MODIS sensor until the first EOS afternoon (PM-1) platform is launched in 2000. Two MODIS sensors will provide complete global coverage in the same amount of time as a tilting sensor. EOS-Color was conceived as a sensor with identical specifications as SeaWiFS, using the *data buy* model.

There are a number of advantages to the data buy model. SeaWiFS is the first ocean satellite mission which may take less than four years from inception to launch. Historically such missions have taken 5–10 years to complete. Ideally, a similar program should be established for EOS-Color. However, only recently has there been an organization established within the EOS Project to ensure that the EOS-Color mission is designed and implemented. With the establishment of a group designated with the responsibility for EOS-Color, the risks of it becoming an orphan in an era of constrained resources have diminished. However, note that EOS-Color is often forgotten in various reports, such as those from the EOSDIS Core System.

It is not known which of several mechanisms may be chosen to implement EOS-Color. Time is growing short for formalization of the EOS-Color mission so that a platform and sensor will be available in 1997–98 as a SeaWiFS follow-on, even if a mechanism similar to SeaWiFS is utilized. If the EOS-Color sensor is not similar in design to SeaWiFS, then it will be more difficult to cross-reference sensor calibrations, and particularly data algorithms, in order to achieve the goal of a consistent time series. These issues should be resolved as soon as possible.

4.2.2 EOS-Color Science Issues

The global biogeochemistry community has made it clear that the most important attribute of satellite ocean color missions during the 1990s should be continuity so that a decadal time series can be constructed. Events such as the Mt. Pinatubo eruption which resulted in global cooling, are also thought to have impacted the carbon cycle in both oceanic and terrestrial ecosystems to an extent that the rate of atmospheric CO_2 increase slowed significantly for the last three years. The absence of an ocean color sensor during this period has hampered critical studies of the Earth's carbon cycle. Improvement in sensor spectral coverage is a secondary requirement.

The EOS-Color sensor specifications should provide continuity with the SeaWiFS spectral and SNR performance. That is, EOS-Color can have additional bands with higher digitization rates and SNR goals, but at a minimum it should provide continuity to the SeaWiFS mission. Initial discussions with the Hughes Santa Barbara Research Center (SBRC) indicates that additional channels beyond the SeaWiFS baseline entails trade-offs which must be considered. However, there will be improvements in sensor technology over the next few years which may allow these additional bands. Such studies should begin as soon as possible to determine their scientific and financial impact on the mission.

Implicit in the planning for the EOS-Color baseline element is the need for temporal coverage with similar illumination conditions to SeaWiFS; this element will affect orbital parameters such as crossing time. The most noticeable changes to EOS-Color would be an upgrade to the onboard recorder capabilities so that 1 km data can be collected globally, along with 12-bit digitization of the data to improve SNR and to accommodate high quality measurements over land. These improvements will greatly simplify the integration of global high resolution data that is, at present, problematic for SeaWiFS and will improve sensor sensitivity in low chlorophyll *a* regions of the world ocean. The continuity requirement also implies that ancillary support fields such as ozone, surface wind and pressure, and *in situ* calibration and validation observations must be consistently available.

4.2.3 OCTS

The other pre-EOS mission is OCTS which is planned for ADEOS. ADEOS is scheduled to e launched in 1996 and will carry a suite of sensors, including the NASA scatterometer (NSCAT). OCTS will have performance characteristics that are better than CZCS but not of SeaWiFS quality. However, the availability of simultaneous vector winds (from NSCAT) and SST (from the IR bands on OCTS) will allow sophisticated studies of upper ocean dynamics. For example, it may be possible to estimate CO_2 gas flux across the air-sea interface. It must be remembered, however, that OCTS was conceived primarily as an engineering experiment in sensor design, and it is not driven by science requirements such as those used to design SeaWiFS, EOS-Color, and MODIS.

Currently, NASA and NASDA have ongoing discussions concerning a Memorandum of Understanding (MOU) for ocean color and *in situ* data exchange between their two scientific and technical communities. Representatives from each of the respective scientific communities serve on the other science team. NSF and NASDA have sponsored several workshops to coordinate ocean color science. These workshops have also facilitated coordination of instrument and data processing design. However, reciprocal access to SeaWiFS and OCTS data has not been completely defined, nor have procedures been established to ensure data compatibility.

4.3 Calibration and Validation

Through experience gained using the CZCS, the ocean color community learned the painful process of retrieving useful data from a sensor with slowly degrading performance and at times, strangely perturbed data (Gordon et al. 1983). It is very difficult to determine a sensor's calibration once it has been launched (Viollier 1982, Gordon et al. 1983, Hovis et al. 1985, Mueller 1985, and Gordon 1987). Operating on a spacecraft shared by many sensors, the CZCS time-shared many of the resources of the platform such as power, recording, and communications, and operated at a maximum of 10 minutes per orbit. Such cycling likely contributed to sensor instability through changes in the thermal and power environments of the instrument.

The CZCS performed under such conditions, with decreasing efficiency and stability with time, for nearly eight years. Because of the relatively large atmospheric contribution to the total observed radiances (Gordon 1981) and the great sensitivity of the bio-optical algorithms to the estimated water-leaving radiances (Clark 1981), small errors in the calibration can induce sizable errors in the derived geophysical products, rendering them useless for many applications. On must remember that *typical* values of remote-sensing reflectance ($R_{rs} = L_W/E_d$ where R_{rs} is the reflectance, L_W is the water-leaving radiance, and E_d is the downward irradiance) for open ocean waters are less than 0.008, so the relative stability of the instrument performance is extremely important.

4.3.1 The CZCS Method

The method used to achieve vicarious calibration for CZCS is described in detail in Gordon (1987) and more recently by Evans and Gordon (1994). By observing the apparent changes in water-leaving radiance values for clear-water regions (e.g., the Sargasso Sea) where stable values of normalized water-leaving radiance are the norm, the clear, normalized water-leaving radiances, $L_{WN}(443)$, $L_{WN}(520)$, $L_{WN}(550)$, were assumed to be 1.40, 0.48, and

$0.30\,\mu\mathrm{W\,cm^{-2}\,nm^{-1}\,sr^{-1}}$, respectively. The Angstrom exponents were assumed to be zero, corresponding to standard marine aerosols. The calibration was *initialized* after launch by forcing agreement between the sensor determined radiance and the *expected* radiance based upon radiometric measurements made at the surface under very clear atmospheric conditions. Since the calibration changed with time, most applications occurred under more turbid atmospheric conditions and different illumination geometries than for the initial data sets. Calibration coefficients, derived for other scenes, were adjusted by water-leaving radiance measurements.

Finally, a compromise calibration curve, as a function of time, was derived based upon the *best* agreement between sensor-retrieved pigments and measured pigments, since high-quality water-leaving radiance measurements were available for only a few of the campaigns made during the operation of the CZCS. Thus, the CZCS calibration was not strictly radiometric, but was a calibration of the entire system including the sensor and algorithms. The vicarious calibration of the 443 nm band is tenuous because of the great variability in $L_{WN}(443)$ even in *clear-water*. Clearly, this approach ignores real variability that may be present in the ocean, such as in the central gyres, so other methods must be developed for long-term studies.

4.3.2 The SeaWiFS Method

The calibration of SeaWiFS will include both onboard and vicarious approaches. SeaWiFS will have a deployable diffuser plate and will be capable of periodically imaging the moon by maneuvering the spacecraft. The diffuser provides the means of making reflectance measurements from the spacecraft, and the moon observation can correct for long-term changes in the albedo of the diffuser plate. Optical moorings will be maintained at *clear-water* sites to continuously measure $L_{WN}(\lambda)$, and research campaigns to and around the moorings will provide additional data for vicarious calibration activities.

It is necessary to vicariously calibrate each ocean color sensor since it is likely that the calibration will change significantly during launch. The vicarious calibration requires extensive measurements of the optical properties of the atmosphere and ocean nearly simultaneously with a satellite overpass. The required data cannot be obtained by simply comparing the output of two different satellites, e.g., MODIS and EOS-Color, when contemporaneously viewing the same oceanic area. This is due to the highly variable aerosol component of the signal, to variations in reflectance with time of day, and to differences in the sensors themselves. Thus, a dedicated initialization cruise is a minimum requirement for each ocean color sensor. After initialization, one can monitor the calibration of the two sensors by comparing water-leaving radiances over regions with homogeneous optical properties, e.g., the Sargasso Sea. Consistency between derived radiances would suggest that the calibration has remained stable since the last comparison.

Clear-water calibration sites in the Northern and Southern Hemispheres are needed to evaluate any effects of thermal cycling on sensor performance. It is preferable to have multiple sites viewable on a single orbit, with northern and southern sites in the Atlantic and Pacific oceans and a site in the Indian Ocean. It is hoped that by controlling orbital temperature fluctuations on the sensor to less than 2° C, a high degree of performance stability can be achieved on the sub-orbital time scale where diffuser-plate calibration data for drift correction are unavailable.

4.3.3 Other Concerns

The ocean color sensor to follow SeaWiFS may be unable to view the moon by spacecraft maneuvering if flown on a multi-sensor bus unless a special mirror or tilt mechanism is built into the design, e.g., MODIS and the High Resolution Imaging Spectrometer (HIRIS) types of designs. Moon-view capability should be a requirement for all post-SeaWiFS ocean color sensors. However, if lunar viewing is possible only through the use of special optics as opposed to direct viewing, then particular attention must be paid towards minimizing polarization of these systems.

It is unlikely that SeaWiFS or the EOS-Color sensor can survive the vibrational and thermal environments of launch without changing its calibration. Calibration errors relative to the solar *constant* of the order of 5% are likely after launch. This level of radiance error is of the order of $L_W(\lambda)$, a totally unacceptable level of error even under the best of prelaunch calibration scenarios.

Presumably the diffuser plate albedo will suffer little degradation during launch. However, when deployed for calibrating SeaWiFS or EOS-Color in the reflectance mode, condensates and other particles will adhere to the surface of the diffuser, and high-energy photons may degrade it. Even if the prelaunch reflectance values for the diffuser surface were as accurate as 2% and no degradation occurred after launch, that still would result in about a 40% error in derived values of reflectance for the ocean.

For SeaWiFS and EOS-Color, a more vigorous radiometric approach will be taken. More high quality water-leaving radiance measurements from field studies are anticipated, especially in the vicinity of the calibration mooring sites. Furthermore, rather than simply making comparisons of satellite *derived* versus *measured* pigments, comparisons of the satellite *derived* versus *measured* absorption coefficients and diffuse-attenuation coefficients can be made, eliminating the errors induced by uncertainties in the pigment-package effect and by variations in absorption due to CDOM, e.g., Carder et al. 1991 and Gordon 1991.

Although the above discussion was framed in terms of SeaWiFS and EOS-Color, the same issues apply to OCTS, MERIS, GLI, and the MODIS sensors. Simply stated, each sensor must be calibrated and an initial *in situ* validation cruise will be required shortly after each launch. The vicarious method developed by Gordon and co-workers (Evans and Gordon 1994) provides a powerful technique to calibrate the entire ocean color system.

An extensive calibration program is planned for the EOS sensors; these efforts must be coordinated with the methods described here. The issue of international coordination also arises in this context; extensive *in situ* observations are costly, and cooperation between the various international partners could reduce the costs for each country.

4.3.4 Mission Overlap

The final point in the issue of calibration is the overlap between the various missions. Given that there will be periods when more than one sensor is in orbit at any one time, maximum priority should be given towards conducting calibration and validation cruises to compare the sensors during these overlap periods. For example, in 1998, SeaWiFS, OCTS, EOS-Color, MERIS, and MODIS should all be in orbit. GLI will follow in 2000. Collecting extensive calibration and validation measurements should help develop a consistent time series of ocean color measurements from this diverse set of sensors.

A six-month overlap between ocean color sensors, e.g., between SeaWiFS and EOS-Color, would enable recalibrating the likely degraded SeaWiFS with the new EOS-Color. This would also ensure radiometric continuity between the two missions which, to the extent that the system algorithms (atmospheric and bio-optical) provide accurate products, would facilitate continuing studies of interannual variability. Clearly, this intercalibration effort will require cooperation on an international level.

4.4 Data System Issues

The primary goal of a 20-year time series requires that the data processing and distribution system be designed to safeguard the raw data and the calibration and validation information, to enable reprocessing, and to ensure efficient transfer of data and algorithms to US and international researchers. The data system cannot view itself in isolation from contemporaneous data centers or systems that may precede or follow it. High priority must be given towards ensuring the compatibility of these basic services. While a data system may focus on a specific mission, e.g., SeaWiFS, its role in the larger constellation of ocean color missions must be retained. It must be carefully integrated into a data systems strategy that ensures ease of use of other Earth data sets.

Particular attention should be paid to retention of the sensor design, calibration, and validation information. This will allow future researchers to reprocess the data in a consistent manner. Rather than becoming a standard product assembly line, the SeaWiFS data system should be able to locate and retrieve the raw satellite data and apply any algorithm. Interfaces should be clearly defined so that future advances in computer technology can be inserted. This requires a level of flexibility in the basic system design that is not usually found in most data systems.

4.4.1 SeaWiFS

Distribution of SeaWiFS GAC derived products will be provided by the GSFC Version 0 (V0) Distributed Active Archive Center (DAAC). Data will be available via standard media or network access and will be governed by the EOSDIS data charging policy. The SeaWiFS Science Team should work with the SeaWiFS Project and V0 DAAC to ensure that access to SeaWiFS data products satisfies the needs of the SeaWiFS investigators. Additionally, the methods for delivery of near-real time products for support of cruise activities need to be identified.

Standard level-1, -2, and -3 products will be produced by the SeaWiFS Project, which include reduced resolution browse images and several time scales for temporal composites. In addition to the data services, standard SeaWiFS processing software will be available through the DAAC. The browse capability will be available to registered SeaWiFS investigators through network accessible X Window software. Data will be available following the embargo period specified in the Orbital Sciences Corporation (the manufacturer of the SeaWiFS instrument) SeaWiFS data purchase agreement with NASA.

4.4.2 The DAAC

The DAAC will distribute standard products as received from the SeaWiFS Project and provide for the generation of special products whose preparation costs would be borne by the requesting investigator. Special products could include subsetting by selected area. A series of sectors is being used by the Physical Oceanography DAAC at the Jet Propulsion Laboratory (JPL) to distribute SST and CZCS data that cover portions of the ocean basins. Availability of these sectors for the new sensors would permit simpler data set manipulation by a wider user group. Mechanisms should be identified and implemented, however, to enable dynamic subsetting of the archived data.

Also, it is noted that the DAAC has not been designed to accommodate either raw or processed LAC (full spatial resolution) data. Users may access catalogs that contain the holdings of the various receiving sites that have agreed to provide such services. However, there are no plans at present to produce data sets composed of the full resolution, 1 km data, such as chlorophyll *a* in the US Exclusive Economic Zone (EEZ).

Although there is interest in acquiring some data products directly from investigators, the basic requirement should be flexible processing so that new algorithms can be applied to the entire data set as scientific understanding of ocean color remote sensing evolves. The data system should be viewed as a processing and delivery system, rather than just a storehouse for predefined standard products.

4.4.2 EOSDIS

Eventually, the needs for ocean color research will transcend those of a specific flight project (SeaWiFS). The need to negotiate agreements with foreign data centers, as well as the need to maintain continuity over the full suite of ocean color missions, will require a data system with a much larger mandate. It is clear that EOSDIS must assume responsibilities for SeaWiFS (and its successors) in the near future. Transition of processing or services from the SeaWiFS Project to EOSDIS should be seamless. New capabilities can be added, but transition to the new environment should not introduce changes (or degradation) in definition or access to products, quality, or timeliness in delivery.

4.4.3 Data Access

Global change research is based on the premise that access to consistent, high quality data sets will be maintained through successive generations of sensors. For ocean color research, this implies a need to retain timely access to data sets such as CZCS. The DAAC must provide fast access and distribution of CZCS data as a requirement equal in importance to the support of future data sets, e.g., SeaWiFS, MODIS, etc.

The present SeaWiFS data policy will require the EOS data policy to be modified to include additional access and use constraints for proprietary data sets. This policy does not address the point at which the data provider is no longer able to restrict distribution of multiple generation data products. For example, do the restrictions that pertain to the original proprietary data set automatically extend to include a heat flux map that was computed in part by incorporating a diffuse attenuation field derived by using the satellite observed radiances?

The implications of incorporating proprietary data sets in the broader EOS data product inventory need to be articulated. The present SeaWiFS data policy, if interpreted in the most restrictive manner, will not permit the dissemination of digital global change results to a wide range of Earth science applications and users.

4.4.4 OCTS, MERIS, and GLI

NASA and NASDA are negotiating an MOU which lays the framework for exchange of SeaWiFS and OCTS level 1, 2, and 3 data sets. Given the existence of access restrictions for at least one of the data sets, what is the appropriate route for US investigators to apply for access to OCTS data and what limitations exist for use and release of data or publication of results? Again, the need to collaborate with the entire ocean color research community on both science and calibration and validation issues, requires that close ties be established between US and international scientists and agencies in conjunction with their respective projects. Delivery and timeliness should be complementary for the two data sets. Special arrangements should be made to support calibration and comparison of the two data sets. It is expected that this proposed relationship will be continued with GLI.

At present, there are no formal arrangements between ESA and NASA on the incorporation of MERIS into the time series of ocean color observations. In part, this is because the MERIS development activities are somewhat behind those of MODIS. Like OCTS, MERIS is viewed as an experimental sensor with programmable bands which will be used to explore new algorithms for land, atmosphere, and ocean processes. MERIS is not an operational ocean color sensor in the sense of SeaWiFS. It is unlikely that it will be used to collect global ocean color measurements on a consistent, daily basis; there are, however, obvious possibilities for cooperation.

A critical issue facing the scientific use of data from non-US sensors is the lack of support for calibration and validation or analysis activities by US agencies. Presently, there is no mechanism for a US investigator to obtain funding to analyze data from OCTS or MERIS. More importantly, there are no funds to support cross-calibration studies. As Earth science becomes increasingly dependent on international partnerships to obtain critical Earth science data, US agencies must be willing to support science and calibration and validation activities that rely on non-US sensors.

4.4.5 EOS-Color and MODIS

It is anticipated that the EOS-Color instrument will be very similar to SeaWiFS, but perhaps with a radiometric sensitivity that approaches MODIS. This being the case, only a slight modification of the SeaWiFS and MODIS algorithms will be required. For example, the look-up tables for the contribution by molecular scattering to the sensor radiance will have to be recomputed for the actual EOS-Color spectral functions. Other lookup tables may have to be recomputed as well (depending on the structure of the SeaWiFS and MODIS algorithms). As it is expected that the SeaWiFS algorithms will be updated continually as improvements are made, little effort should be required to incorporate SeaWiFS and MODIS improvements into EOS-Color.

The data distribution policy for EOS-Color should follow rules applicable to NASA furnished EOS sensors and not be subject to SeaWiFS specific access and distribution restrictions.

The EOS-Color mission is scheduled for a time frame consistent with the launch of MODIS. It is reasonable to assume that the EOSDIS programming and facilities support that are available to MODIS will also be available to EOS-Color. The specific product generation facilities could include dedicated EOS-Color, MODIS Team Leader, or EOSDIS computer and personnel resources. The data delivery policies and mechanisms should parallel those for MODIS consistent with the data downlink capabilities of the spacecraft.

Additional support may be required for sensor initialization cruises depending on the applicability of planned MODIS experiments to support the EOS-Color sensor after launch. Support for radiative transfer modeling or bio-optical algorithms will be required to the extent that channel selection or sensor characteristics depart from SeaWiFS specifications. It is expected that the experience derived from the SeaWiFS mission and from the preparation for MODIS will minimize special activities for EOS-Color. However, additional time will be required to initialize, calibrate, and ensure quality control for the EOS-Color mission; availability of personnel resources will depend on the phasing of the EOS-Color and MODIS missions.

4.5 Convergence

The planned ocean color missions over the next 10 years must not be viewed as interchangeable—each sensor is being designed according to scientific and engineering requirements from each sponsoring agency. Although there is overlap, it is a mistake to assume that one sensor can simply be replaced by another. The goal of the science community is a continuous observing system to monitor and predict changes in the Earth system. Thus, the next decade should focus on understanding the critical Earth system processes and their associated scales of variability. In this regard, scientists must be able to define both the measurement and sampling characteristics of a future ocean color observing system. Such an evaluation must include the instrument characteristics (bands, SNR, etc.) and sampling (orbits, number of sensors, etc.).

An understanding is needed of all of the sources of error in estimating critical variables such as phytoplankton biomass and primary productivity. The past focus with CZCS has been on algorithm and calibration errors; future work must also consider sampling errors (Chelton and Schlax 1991). The impacts of these errors must then be assessed on the potential scientific return from the observing system. For example, is the cost of a higher SNR justified in terms of improved scientific understanding and prediction, or is the improvement only marginal? How much investment must be made in long-term moorings for calibration given the total system (sensor plus sampling) error?

Numerical models of the physical and biological processes in the upper ocean will play an important role in these studies. Models will provide the underpinning for any ocean prediction system. However, it is apparent that the models are too primitive at present, even in the area of physical oceanography. The ties must be strengthened between modeling and observing systems so that the two approaches can complement each other. Because such models must rely on both physical and biological data sets, the development of an ocean color observing system must also specify the necessary data sets on physical processes.

At present, there is very little interagency coordination at this level. The responsible agencies are just beginning to explore fundamental issues such as calibration and data systems, but the missions are still viewed as essentially separate. The science community must use this opportunity of multiple sensors to conduct the necessary studies and evaluations. This must be an international effort from the outset with an eye towards developing a cost effective system for making ocean color observations over the long term in the context of climate change. Tradeoffs between sensor capabilities and cost must be made in light of the overall science return of the mission.

5. An Implementation Plan

This section discusses issues that need to be addressed in order to implement the plan.

5.1 Science Oversight

The development of a 20-year time series of ocean color observations from a disparate set of sensors will require an enormous effort and cooperation between many agencies and several countries. At present, there is no formal group at the government level in the US that has responsibilities for these activities.

> 1 *Recommendation:* CENR should form an interagency working group on satellite ocean color research and applications with representation from all interested US agencies. A charter for this working group should include both US and foreign missions. It should serve as the focal point for foreign collaboration. This group must also consider the necessary modeling activities and physical observations that will be required to analyze and interpret ocean color data.

Presently, NASA has three ocean color missions in various stages of planning and implementation, each with its own management structure. Given the interlocking web of funding, algorithm development, and management, a coherent, coordinated plan must be developed as soon as possible. Not only will this result in a more effective use of investigators' time, it will also provide a roadmap so that the research community and NASA can identify how resources are being allocated.

> 2 *Recommendation:* NASA should convene a meeting of the appropriate project and program personnel, including contract management, along with representatives of the ocean color research community as soon as possible to develop an overall ocean color program. This program should consist of plans for research, software development, data processing and delivery, funding, and management.

5.1.1 EOS-Color

Although the initial plan is for EOS-Color specifications to be identical to those of SeaWiFS, there are some potential improvements that must be investigated from a scientific, technical, and financial point of view. These include lossless data compression, or additional recorder capacity, so that 1 km resolution data can be collected globally; improved digitization (12 bits versus 10 bits for SeaWiFS); increased SNR; and the possibility of additional bands. With a launch date of 1998, these studies should begin as soon as possible. The impacts of EOS-Color on EOSDIS and other aspects of the EOS Project also need to be evaluated.

$\boxed{3}$ *Recommendation:* An EOS-Color Mission Working Group should be designated during calendar year 1994. This should include both science and project representation. This group should consist of members of the MODIS Oceans Team and the SeaWiFS Team. It should be tasked with providing the science oversight for the EOS-Color mission.

5.1.2 EOS-Color and SeaWiFS Interfaces

The community has expressed a clear desire that an effort be initiated to produce a consistent, decadal scale, global time series of satellite ocean color observations. This suggests that science, mission management, and data management will have to be coordinated between SeaWiFS, EOS-Color and MODIS so that products, data sets, calibration, validation, etc., are consistent across these efforts. To address these issues, there must be a consistent view from the scientific community, from NASA, and other federal agencies. Community consensus should be fostered by formation of interlocking science teams for the missions, while a single program manager should be designated to coordinate these missions in NASA. Federal interagency issues should be addressed by the aforementioned interagency group.

Coupled with interlocking science teams and interagency management must be a coordinated approach to data management. Scientific need and available resources necessitate a single, workable interface to ocean color data fields, not several. Given the current EOSDIS architecture it seems that the most effective mechanism would be to generalize the current MODIS arrangement with EOSDIS to include EOS-Color as an early EOSDIS, prelaunch (pre-MODIS) data stream. This would build upon the SeaWiFS and EOS DAAC structure currently being implemented to provide SeaWiFS data fields to the community. However, it is also clear that the present DAAC plans for SeaWiFS will not accommodate LAC (1 km resolution) data. Clearly, there will need to be a transition from SeaWiFS to MODIS which has 1 km resolution. The data system for SeaWiFS and EOS-Color could help in this transition.

$\boxed{4}$ *Recommendation:* EOSDIS should consider SeaWiFS and EOS-Color as a prelaunch system capability test.

5.1.3 The Science Teams

The MODIS Oceans Team was chosen to provide guidance for the MODIS-T and MODIS-N instruments with respect to ocean color and SST parameters. Thus, the MODIS Oceans Team is the natural unit to provide guidance for the development of the EOS-Color instrument. Augmentation of team responsibilities would be an efficient, timely mechanism to expedite EOS-Color instrument scientific design and mission planning. The recent inclusion of the MODIS Oceans Team in the SeaWiFS Science Team has established a workable venue for coordination between EOS-Color, MODIS, and SeaWiFS. This same venue would be equally usable for EOS-Color.

$\boxed{5}$ *Recommendation:* The MODIS Oceans Team should be designated the EOS-Color Science Team, which would be expanded upon the results of an EOS-Color NRA. NASA should negotiate precise agreements with the MODIS Oceans Team regarding deliverables and funding. These agreements must be coordinated across the full set of ocean color activities so that an efficient, realistic plan is developed.

The SeaWiFS NRA makes it clear that the NRA process is a very good mechanism for encouraging international collaboration, as well as an excellent way to broaden the US satellite ocean color community. Rather than a second announcement for SeaWiFS efforts in the mid-90s, it may be more appropriate for NASA to issue an EOS-Color NRA two years prior to launch. This NRA could then capitalize on SeaWiFS and OCTS observations with a view toward a decadal time series and the use of ocean color heavily focused on primary productivity, integrated ocean models, etc.

$\boxed{6}$ *Recommendation:* NASA should plan for an EOS-Color NRA for the 1996–97 time frame.

5.1.4 OCTS, MERIS, and GLI

As with SeaWiFS, international participation on science teams has been extremely valuable. Similar cross-appointments should be established for OCTS, MERIS, and GLI. Such relationships strengthen scientific ties and help leverage resources of all participating countries.

$\boxed{7}$ *Recommendation:* NASA should encourage investigator relationships between US researchers and their foreign colleagues. This may require agreements on data delivery and policies, in which case NASA, ESA, and NASDA should establish appropriate understandings as soon as possible.

5.2 Calibration and Validation

Initial calibration and validation cruises for each mission must be performed in waters with no significant horizontal gradients in the water-leaving radiances and with vertically isotropic fields of inherent optical properties. For initial calibration and validation research campaigns, this dictates that waters be used with low pigment concentrations which have little sub-pixel scale or mesoscale patchiness.

Effects of spacecraft navigational errors and sub-pixel patchiness must not be allowed to contribute to radiance variations in excess of the noise inherent in the instrument. In the subtropical gyres, these conditions can usually be met if cold-core eddies are absent. Such eddies are usually detectable from both AVHRR and ocean color imagery.

Phytoplankton chlorophyll *a* and phycoerythrin pigment can be easily mapped using aircraft laser systems. Also, concurrent SST and airborne expendable bathythermograph (AXBT) data can be used to define the complete volumetric temperature field. Finally, the airborne passive sensors can supply downwelling irradiance and upwelling radiance within the calibration and validation region. Coupled with ship transects (Smith and Baker 1985) and buoys, the complete multi-platform sensor suite (Smith et al. 1987) can be brought to bear on the characterization of the in-water optical properties.

$\boxed{8}$ *Recommendation:* As soon after launch as possible, calibration and validation cruises must take place in regions with appropriate bio-optical properties.

To reduce atmospheric effects and to extend clear-water calibration and validation studies to higher latitudes, consideration should be given to using and instrumenting large, oligotrophic mountain lakes such as Lake Tahoe, Lake Titicaca, and Lake Baikal for calibration and validation activities for EOS-Color. Logistical costs would be greatly reduced for lake moorings and cruises, and aerosol optical thicknesses would be relatively *thin* and more easily monitored from a stable, shore-based facility. These measurements may help to more effectively separate sensor calibration issues from atmospheric correction errors and difficulties with pigment algorithms.

$\boxed{9}$ *Recommendation:* Feasibility studies should be conducted on the use of high-altitude, oligotrophic lakes as calibration and validation sites.

5.2.1 Required Cruises

Shortly after launch, at least two vessels should be positioned in the Pacific, one each in southern and northern clear waters, most likely near 30° N and 30° S latitudes. They should be positioned so that both would be near the center of the swath on a given orbit and should be well away from eastern boundaries. Two additional vessels could be used in the Atlantic in similar positions if the orbit is ascending. This deployment should permit detection of any significant thermal effects on the sensor performance over the 60° latitude separation between ships, and will provide several summer-winter pairs and spring-fall pairs of observations during the first 90 days after sensor turn-on. It ensures that solar zenith angles as low as 7° and greater than 50° will be encountered by at least one ship in clear water for calibration initialization activities. At least one time during this initialization period, the ship tracks should converge for intercalibration purposes. Clear lake measurements can extend the range of sun angles and latitudes encountered to provide further checks on the thermal stability of the sensor.

$\boxed{10}$ *Recommendation:* In order to investigate thermal effects on sensor performance, calibration and validation cruises must be located in both northern and southern waters.

Additional cruises will be required to evaluate instrument and algorithm performances for eastern-boundary and high-latitude settings, regions subjected to infusions of desert aerosols, and for various major river plumes and coastal environments. These waters are expected to affect algorithms in the following ways:

1. High-latitude, spring bloom regions and eastern-boundary upwelling produce phytoplankton which are large with significant nonlinear light absorption effects due to pigment packaging. Degradation products from senescent blooms, e.g., CDOM and detritus, provide excess absorption relative to Case 1 waters (Carder et al. 1991).
2. High-latitude stations will test the robustness of the method as they have low sensor signals, large solar slant paths through the atmosphere, and high wind stress, e.g., large foam areas, marine aerosol concentrations, and wave slopes.
3. The eastern tropical Atlantic and the northwest Pacific are subject to large inputs of mineral aerosols from the Sahara and the Gobi deserts, respectively. There is evidence that, unlike typical marine aerosols, such dust absorbs strongly in the blue region of the spectrum. It is essential to verify that the atmospheric correction algorithms perform properly in such regions to enable the derivation of accurate bio-optical parameters and to assess the influence of such materials on productivity.
4. River plumes will provide site-specific particle albedos and terrigenous CDOM in addition to large-celled, diatom-rich phytoplankton assemblages near-shore and smaller cells offshore. Much of the color in the plumes may be due to CDOM.
5. Coastal environments are expected to be site specific due to unique colors of suspended sediments and terrestrial-marine mixes of CDOM, as well as optically complicated due to the shorter time and space scales of variation.

These cruises are deemed to be of secondary importance during the initial 90 days of sensor operation since sensor calibration cannot be easily accomplished in such waters. Resources can be diverted to these other areas after sensor initialization is complete. The measurements and protocols required for the calibration and validation cruises are detailed in Mueller and Austin (1991).

Note that the Commonwealth Scientific and Industrial Research Organization (CSIRO) of Australia, is developing calibration sites for both land and ocean observations. Given that there is the possibility that SeaWiFS may return useful data from land surfaces, it is recommended that NASA coordinate with Australian researchers on the use of these sites for both SeaWiFS calibration and intercalibration with other sensors.

11 *Recommendation:* Although not needed during the initial period of sensor operation, calibration and validation cruises should be planned for other bio-optical water types.

5.2.2 Expansion of Moorings

International partners, such as Japan, have plans for bio-optical moorings to support their ocean color missions. By providing data from NASA supported moorings to these partners in exchange for access to data from their mooring, this critical sensor calibration activity can be effectively expanded at minimal cost. Not only should data be exchanged, but information on calibration techniques and protocols should be transferred so that these data can be used effectively.

12 *Recommendation:* NASA should encourage investigators to collaborate with their foreign colleagues to develop a global network of bio-optical moorings.

5.3 Access to Data

The restrictions imposed by data purchase agreements, such as SeaWiFS, are counter to the open access policy established by EOS. Derived products, such as heat flux, that may be based in part on SeaWiFS data may be subject to commercial restrictions. NASA must work to eliminate these restrictions whenever possible. Although EOS-Color may be a data purchase agreement, NASA must ensure that there is no embargo period for data access nor any restrictions on the distribution of data or derived products.

13 *Recommendation:* NASA must work to eliminate all restrictions on access to ocean color observations, consistent with the EOS data policy. This policy must apply to both US and foreign researchers.

The transition between processing systems for a given sensor should not result in a change of the product. To the extent that the sensor specifications permit, with the introduction of a new sensor type, products associated with the previous sensors should be continued. The SeaWiFS system, product format, or data delivery mechanisms may need to evolve to become and remain compliant with EOS standards as these become better defined with the implementation of EOSDIS.

14 *Recommendation:* Consistency should be sustained between the various sensor data sets as they move from one data processing and delivery system to another.

In the next few years, ocean color data from foreign partners will become increasingly important. However, the mechanism for data transfer, criteria for timeliness and formats, and other requirements, have not been defined. With the need to integrate both sensor and *in situ* data sets, NASA must develop effective working relationships with its international partners to obtain maximum scientific return at minimum cost. These relationships should be established at the investigator level with the support of NASA.

15 *Recommendation:* SeaWiFS and OCTS should act as a testbed for such exchanges between international partners. Although the primary focus may be at the investigator level, NASA may need to support efforts on data policies, data exchange, and satellite downlinks.

5.4 Convergence

Each of the planned ocean color missions, while similar in their basic observing capabilities, is being designed with unique engineering and scientific requirements as well as limitations. While calibration information and data access will help develop a consistent, ocean color time series, the international science community must use this opportunity to design a comprehensive ocean color observing system. Such a system must measure the critical processes at the appropriate scales. At present, the basic phytoplankton pigment measurement is understood, but not all of the critical processes, or their scales of variability, are known in order to design an effective measurement system.

16 *Recommendation:* NASA should coordinate research activities with the other sponsoring agencies to develop the observing and sampling requirements for an ocean color system that will make the essential measurements for ocean monitoring and prediction.

While a baseline set of SeaWiFS products will be available from EOSDIS, there is currently no defined set of LAC (1 km) products. An effort needs to be coordinated to define such high spatial resolution products and formats which are required by coastal resource managers and other operational users. These plans must be implemented to make full use of SeaWiFS for coastal management.

17 *Recommendation:* An interagency effort needs to be implemented to define new products for the coastal zone and to collect, process, and distribute the LAC data.

Coupled physical and biological models must be developed in concert with the observing systems. Too often, data sets and models are produced in isolation without regard to the needs and limitations of the other. The strengths and weaknesses of both models and data must be evaluated so that scientists can develop useful predictive models of the ocean system. These studies must not focus solely on ocean color data, but on the full suite of physical and biological measurements that can be made from space.

$\boxed{18}$ *Recommendation:* NASA must support efforts to link ocean models with both physical and biological data and ensure that lessons learned from both modeling and data analysis are used in the design of ocean color observing systems.

GLOSSARY

ACRIM	Active Cavity Radiometer Irradiance Monitor
ADEOS	Advanced Earth Observing Satellite
AM-1	Not an acronym, used to designate the morning platform of EOS
AVHRR	Advanced Very High Resolution Radiometer
AXBT	Airborne Expendable Bathythermograph
CDOM	Colored Dissolved Organic Matter
CENR	Committee on Environment and Natural Resources
CSIRO	Commonwealth Scientific and Industrial Research Organization (of Australia)
CZCS	Coastal Zone Color Scanner
DAAC	Distributed Active Archive Center
DMS	dimethyl sulfide
DOC	dissolved organic carbon
DOM	dissolved organic matter
EEZ	Exclusive Economic Zone
ENSO	El Niño Southern Oscillation
ENVISAT	Environmental Satellite
EOS	Earth Observing System
EOSDIS	EOS Data and Information System
ESA	European Space Agency
GAC	Global Area Coverage
GLI	Global Imager
GLOBEC	Global Ocean Ecosystems dynamics
GSFC	Goddard Space Flight Sensor
HIRIS	High Resolution Imaging Spectrometer
IR	Infrared
JGOFS	Joint Global Ocean Flux Study
JPL	Jet Propulsion Laboratory
LAC	Local Area Coverage
LANDSAT	Land Resources Satellite
LOICZ	Land Ocean Interaction in the Coastal Zone
MERIS	Medium Resolution Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectrometer
MODIS-N	Nadir-viewing MODIS instrument
MODIS-T	Tilted MODIS instrument to minimize sun glint
MOU	Memorandum of Understanding
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NOAA	National Oceanic and Atmospheric Administration
NRA	NASA Research Announcement
NSCAT	NASA Scatterometer
NSF	National Science Foundation
OCTS	Ocean Color Temperature Sensor
OSC	Orbital Sciences Corporation
PM-1	Not an acronym, used to designate the afternoon platform of EOS
POC	Particulate Organic Carbon
SBRC	Santa Barbara Research Center
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SNR	Signal-to-Noise Ratio
SST	Sea Surface Temperature
UV	Ultraviolet
V0	Version 0

SYMBOLS

E_d	Reflectance.
L_W	Water-leaving radiance.
$L_{WN}(\lambda)$	Normalized water-leaving radiance.
R_{rs}	Reflectance
λ	Wavelength

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13. ABSTRACT *(Maximum 200 words)*

Beginning with the upcoming launch of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), there should be almost continuous measurements of ocean color for nearly 20 years if all of the presently planned national and international missions are implemented. This data set will present a unique opportunity to understand the coupling of physical and biological processes in the world ocean. The presence of multiple ocean color sensors will allow the eventual development of an ocean color observing system that is both cost effective and scientifically based. This report discusses the issues involved and makes recommendations intended to ensure the maximum scientific return from this unique set of planned ocean color missions. An Executive Summary is included with this document which briefly discusses the primary issues and suggested actions to be considered.

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