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SIMBIOS Project 1998 Annual Report

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PREFACE

The purpose of this series of technical reports is to provide current documentation of the SIMBIOS Project activities, NASA Research Announcement (NRA) research status, satellite data processing, data product validation and field calibration. This documentation is necessary to ensure that critical information is related to the scientific community and NASA management. This critical information includes the technical difficulties and challenges of combining ocean color data from an array of independent satellite systems to form consistent and accurate global bio-optical time series products. This technical report is not meant to substitute for scientific literature. Instead, it will provide a ready and responsive vehicle for the multitude of technical reports issued by an operational project.

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Chapter 1

SIMBIOS Background

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The Sensor Intercomparison and Merger for Biological and Interdisciplinary Ocean Studies (SIMBIOS) program was conceived in 1994 as a result of a National Aeronautics and Space Administration (NASA) management review of the agency's strategy for monitoring the bio-optical properties of the global ocean through ocean color remote sensing from space. At that time, the NASA ocean color flight manifest included two data buy missions, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Earth Observing System (EOS) Color, and two sensors, Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-angle Imaging Spectro-Radiometer (MISR), scheduled for flight on the EOS-AM (1998) and -PM (2001) satellites.

Considerable effort was spent by Dr. McClain (Project Scientist) and Dr. Kirk (Study Manager) on examining mission scenarios for EOS Color because of the slips being encountered with SeaWiFS. However, with the delay of SeaWiFS and an uncertain launch schedule, it was not clear that EOS Color was needed to fill a potential gap between SeaWiFS and MODIS, especially when five additional ocean color systems with similar global capabilities [Ocean Color and Temperature Sensor (OCTS), Japan; Global Imager (GLI), Japan; Polarization Detecting Environmental Radiometer-1 (POLDER-1) and -2, France; and Medium Resolution Imaging Spectrometer (MERIS), European Space Agency] and several other non-global missions by Argentina, Germany, Taiwan, India, Korea, the U.S. Navy, and the People's Republic of China, were planned for launch during the late 1990s.

The review led to a decision that the international assemblage of ocean color satellite systems provided ample redundancy to assure continuous global coverage, with no need for the EOS Color mission. At the same time, it was noted that non-trivial technical difficulties attended the challenge (and opportunity) of combining ocean color data from this array of independent satellite systems to form consistent and accurate global bio-optical time series products (Figure 1). Thus, it was announced at the October, 1994 EOS Interdisciplinary Working Group meeting that some of the resources budgeted for EOS Color should be redirected into an intercalibration and validation program. NASA Goddard Space Flight Center (GSFC) was directed to develop a plan for submission to NASA Headquarters (HQ) by May 1995. As a result of the directive from NASA/HQ, the ocean color group lead by Dr. McClain at NASA/GSFC organized an international organizational meeting in February 1995 at the University of Miami Rosenstiel School for Marine and Atmospheric Sciences. The objective was develop a conceptual plan for a comparison program. The plan (Ocean Color Multisensor Data Evaluation and Utilization Plan, under SIMBIOS Documents, http://simbios.gsfc.nasa.gov/) which outlined NASA's contribution to the international effort was completed, submitted, externally reviewed, and revised in 1995.

Based on the final approved plan, a NASA Research Announcement (NRA) was released in July 1996, and the SIMBIOS Project Office was established at the NASA (GSFC) in January 1997 (co-located with the SeaWiFS Project). The initial SIMBIOS Program was scoped for five years (1997-2001) and included separate support for a science team (NRA selections) and the Project Office.

Dr. Mueller (San Diego State University) acted as an interim project manager at NASA/GSFC under a one-year assignment to assist in getting the project office organized and the science team contracts executed. His assistance in this capacity was essential as the SIMBIOS Project was beginning just as the SeaWiFS Project was preparing for launch.

In parallel with the NASA SIMBIOS Program planning, the international effort was being organized. The initial meeting was held in Vittoria, British Columbia during September, 1995. As a result of the recommendations from that meeting, the International Ocean Colour-Coordinating Group (IOCCG) was formed (http://www.ioccg.org/). The IOCCG presently operates under the auspices of the Scientific Committee on Oceanic Research (SCOR) and chairmanship of Dr. Platt (Bedford Institute of Oceanography). The IOCCG meets one or two times per year and is generating a series of special reports on topics essential to the coordination of the international ocean color community (e.g., IOCCG, 1998).

During calendar year 1997, Dr. Mueller's tenure as SIMBIOS Project Manager, the primary accomplishments included the following:

- The science team contracts or interagency agreements were negotiated (3-year contracts) and first year funds were distributed. Several additional investigations, primarily for atmospheric correction studies, were solicited and funded.
- The initial Project Office staffing actions were completed.
- The SIMBIOS processing systems were purchased and installed.
- An instrument pool was established. Submersible instruments for field studies were purchased through some of the science team contracts. The Project also purchased 12 MicroTops hand-held sun photometers, 2 PREDE (Japanese built) sun photometers, and a micro-pulse lidar as part of the instrument pool. Twelve CIMEL (French built) sun photometers were also purchased to augment the Aerosol Robotic Network (AERONET) for deployment at coastal sites.
- A satellite overflight prediction service was established to assist in coordinating field studies in synchronizing data collection with satellite passes (http://simbios.gsfc.nasa.gov/, and http: // simbios.gsfc.nasa.gov/~schedule/Predictions/ Current_Cruises.html).
- The first SIMBIOS science team meeting was held in August at Solomons Island, Maryland.

During the second year of the SIMBIOS Project, Dr. McClain assumed project management of both the SeaWiFS and SIMBIOS as both Dr. Cleave and Dr. Mueller stepped down in their roles as project managers of these two projects, respectively. In the second year, many of the original objectives of SIMBIOS began to come to fruition, some of which are discussed in more detail in subsequent chapters. Project accomplishments included:

- The first SIMBIOS intercalibration round-robin experiment (Riley and Bailey, 1998) was completed.
- The CIMEL sun photometers were re-engineered by Meridian Engineering of Hanover, Maryland to improve their survivability in the field. Confirmed (delivered or negotiated) CIMEL sites include Lanai (Hawaii) with a backup in Honolulu, Ascension Island, Bahraine, Turkey (Black Sea), Tahiti, Wallops Island (Virginia), and South Korea. Additional sites being considered are Perth, Australia and Iceland. Delivery of equipment for calibrating polarized bands was received from the University of Lille as part of the collaboration with the AERONET group at NASA/GSFC [Brent Holben, principal investigator (P.I.)]. An automated procedure for extracting data from the AERONET archive for satellite match-up comparisons was completed.
- The micropulse lidar environmental container was re-engineered by Meridian Engineering to improve temperature stability.
- A second copy of the SeaWiFS Transfer Radiometer (SRX), the SXR-2, was built by Reyer Corporation of New Market, Maryland for use in the calibration round-robin.
- A Marine Optical Spectroradiometer (MOS) ground station subsystem was purchased from Antrix Corporation Limited (Bangalore, India) for installation at Wallops Flight Facility.
- Data processing (Level-0 to Level-3) software for OCTS and MOS were completed. This activity included evaluations of the navigation, band coregistration, calibration, destripping, atmospheric correction, and bio-optical algorithms. Match-up comparisons with field data and OCTS were also completed using match-up subscenes provided by National Space Development Agency of Japan (NASDA) Earth Observation Research Center (EORC).
- SeaWiFS Bio-Optical Archive and Storage System (SeaBASS) holdings were greatly expanded as the science team field activities got underway.
- The SIMBIOS website was substantially enhanced including monthly reports posted by the science team investigators.
- Science team contract performance was reviewed and the contracts were revised as necessary and renewed.
- The second science team meeting was held at Scripps Institution of Oceanography (SIO) in September 1998.

In 1999, the SIMBIOS Project will finalize the processing of it holdings of OCTS data, i.e., all the OCTS data collected at Wallops Flight Facility (east coast of North America, Gulf of Mexico, and the Caribbean Sea), which should be completed by early spring. The OCTS processing software will be incorporated into SeaWiFS Data Analysis System (SeaDAS) Version 3.3. The next ocean color instrument data set to be evaluated will be ADEOS-1/POLDER in cooperation with Centre National d'Edudes Spatialle (CNES) and the POLDER science team. The SIMBIOS Project and science team will assist the ROCSAT Ocean Color Imager (OCI) (launched in January) and MODIS (launch scheduled for July) instrument teams in their evaluations, primarily by providing match-up data for calibration and validation analyses. The SIMBIOS Project will also assist NASA/HQ in drafting the second SIMBIOS NRA which is scheduled for release sometime this summer. Finally, the third science team meeting will be held in September in the Washington, D.C. area.

Chapter 2

SIMBIOS Program and Project Goals

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2.1 PROGRAM GOALS

The purpose of the SIMBIOS project is to develop a methodology and operational capability to combine data products from various ocean color missions in a manner that ensures the best possible global coverage and best exploits the complementary missions of the sensors. NRA 96-MTPE-04 specifically defines the scientific goals in support of this undertaking. "Specifically, the objectives are (1) to quantify the relative accuracies of the products from international ocean color missions, (2) to improve the level of confidence and compatibility among the products, and (3) to generate merged, improved level-3 products" (NASA, 1996). A major goal of the Program is to foster collaborations with the various space agencies and science working groups to assist each other in achieving these objectives. Presently, SIMBIOS is collaborating with Japan on OCTS and GLI, with India and Germany on MOS and just started a relationship with France on POLDER.

2.2 PROJECT OBJECTIVES

The SIMBIOS Program consists of the SIMBIOS Science Team and the SIMBIOS Project. The SIMBIOS Science Team, as initially defined by the NRA selections, was expanded to include additional investigations for atmospheric correction algorithm validation. The SIMBIOS Project has been established to provide support and coordination for the SIMBIOS Program such as administration, project documentation, complete data processing of complementary ocean color missions, support for each of the individual elements, and oversight of data processing systems supported by the Project. "Specifically, the SIMBIOS Project is responsible for the following:

- Assistance in the collection, processing, archiving and documentation of the calibration (including instrument round-robins, pre- and post-launch sensor calibration) and bio-optical data sets;
- Maintenance of a data archive and storage system for tracking instrument calibrations and validating bio-optical algorithms or merger methodologies with in situ data;
- Planning and execution of instrument and analysis round-robins which will include coincident intercomparisons of hardware and software performance;
- Oversight of the regular revision of the ocean optics protocols which will establish the methodologies and standards for calibrating instruments, collecting data, and producing final results from approved analysis procedures.
- Assistance in data acquisition during field studies;
- Management of a centralized facility for providing portable field sources which will be used for tracking the calibration of instruments while they are used in the field;
- Assistance in product validation and quality control assessment;
- Technical monitoring of the prototyping, deployment, or production of new technology developments;
- Assistance in the development, evaluation, and implementation of product merger schemes and algorithms; and
- Administer and oversee the regular meeting of working subgroups concerned with specific issues important to the success of the SIMBIOS Project" (NASA, 1996).

The SIMBIOS Program is augmented by the participation of the NASA-supported MODIS Oceans Team and SeaWiFS Calibration and Validation Program. SIMBIOS calibration activities are accomplished using the calibration activities of the various independent participating missions, coordinating activities of the SIMBIOS Project, and complementary activities of individual investigators selected by the NRAs. The SIMBIOS Project goal is to help science users with a long time series of calibrated radiances extending across the boundaries of individual missions. Close cooperation with the SeaWiFS Project is essential to the success of the SIMBIOS Project. The SIMBIOS Project is co-located with the SeaWiFS Project at GSFC, and many of SIMBIOS staff are shared with SeaWiFS to guarantee a close cooperation to quantify the relative accuracy of the data products from different ocean color sensors and the improve level of confidence and compatibility among the products.

Table 1. SIMBIOS Project

SIMBIOS Project Address	
NASA/Goddard Space Flight Center SIMBIOS Project Code 970.2, Building 28 Greenbelt, MD 20771 Telephone: (301) 286-9676 FAX: (301) 286-0268 E-mail: project@simbios.gsfc.nasa.gov	
Personnel of SIMBIOS Project	
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Robert Barnes *	SAIC General Sciences Corporation
Patty Clow *	NASA
Giulietta Fargion	SAIC General Sciences Corporation
Gene Feldman *	NASA
Ian Durham *	SAIC General Sciences Corporation
Bryan Franz *	SAIC General Sciences Corporation
Lynne Hoppel *	NASA
Alice Isaacman	SAIC General Sciences Corporation
Charles McClain *	NASA
Fred Patt *	SAIC General Sciences Corporation
Christophe Pietras	SAIC General Sciences Corporation
Tom Riley	NASA
India Robinson *	NASA
Kellie Ruebens *	SAIC General Sciences Corporation
Brian Schieber *	SAIC General Sciences Corporation
Linwood Smith *	FutureTech Corporation
Paul Smith *	SAIC General Sciences Corporation
Sung Lee *	SAIC General Sciences Corporation
Tamara Tucker *	SAIC General Sciences Corporation
Grey Valenti *	SAIC General Sciences Corporation
Menghua Wang	Univ. of Maryland Baltimore
Bill Woodford *	FutureTech Corporation
Note: total civil servant staff ~ 2.5 man year	

*shared with SeaWiFS Project

2.3 PROJECT ORGANIZATION

The SIMBIOS Project organization structure is scoped to support the primary activities: 1) sensor engineering and calibration, 2) satellite data processing; 3) data product validation, 4) SIMBIOS Science Team, and 5) SIMBIOS Project Office. The SIMBIOS Project organization chart is shown in Figure 1 and illustrates the individual subtasks under each primary activity with staff associations. The SIMBIOS Project key personnel and their areas of responsibility at GSFC are also given in Table 1. The satellite data processing elements requires close coordination between the data product validation and the sensor engineering and calibration. A complete overview of the primary activities 1 to 4 will be described in the following chapter. The Project Office administrative structure is as follows: system support, administrative support, technical support, science team support, procurement support, and resources support. At the present time, only SeaWiFS and SIMBIOS participants and collaborators associated with other relevant programs, and science teams who actively contribute data or algorithms, are given access to SIMBIOS Project resources, such as the SeaWiFS Bio-optical Archive and Storage System (SeaBASS) and Field Instrument Pool. This limitation is to protect the interests of the researchers currently submitting to the SeaBASS archive.

The SIMBIOS Project policy is to have all documents easily available to the SIMBIOS PIs and to the larger ocean color scientific community. Access to the information is gained through the SIMBIOS website. The SIMBIOS website was organized to serve as the main information resource to access the Project activities, Project Office and Science Team. The website is organized under five main topics: News and Information, Support Services and Schedule, Project Status, Instrument Pool and Contacts. Briefly, under Project Status are found monthly progress updates from the Project and the Science Team. The Project update covers processing and calibration accomplishments for the various missions, the instrument pool and real-time cruise support, and other key events or Project issues. The Science Team oversight is divided into two categories: funded PIs and international collaboration. Under Status of Contracted PIs, the abstracts of the funded research, monthly progress reports, documents in process, and other key events can be found.

Under News and Information, is an archive of most of the produced SIMBIOS documentation and calendar of events. In this section, a user can easily find out which conferences or symposia the Project staff is attending, documents on SIMBIOS workshops and team meetings, and special activities, such as the SIMBIOS participation in Indian Ocean Experiment (INDOEX). An online bibliography includes SIMBIOS technical memoranda or papers presented and published, with online abstracts. SeaWiFS scheduling and the SeaBASS database are accessible online. For further information see http://simbios.gsfc.nasa.gov. All sections are updated as needed.

In addition, the SIMBIOS Project has an internal web interface to closely follow the contractual status of the funded PIs. Contractual issues such as data delivery, contract evaluation performance, contract modifications, requested extensions, procurement support performance, and other items are tracked here. In addition, the SIMBIOS Project holds bimonthly staff meetings, weekly review on technical papers or project issues (such as calibration, *in situ* matchups, etc.), and key staff attends the SeaWiFS meetings. Monthly SIMBIOS Project progress reports are generated and posted to the SIMBIOS website. The Project also gives a formal oral presentation to the Earth Science Directorate (Code 900) management.

Chapter 3

SIMBIOS: NRA Contracts

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3.1 PROJECT RESPONSIBILITY

Contract administration involves ensuring compliance with contract terms and conditions during the performance of the contract. The performance of SIMBIOS Project contracts are monitored in several ways by several individuals in the Project office. These individuals include a Contracting Officer specialist, a Resource/Finance person, the Assistant Project Manager with technical background and experience with projects and their costs, and the Program Manager. The SIMBIOS Project contract personnel and their areas of responsibility at GSFC are given in Table 1. The most important step of contract administration is to review the requirements and specific obligations set forth in the contract. This role is performed primarily by the Assistant Project Manager. In matters related to contract laws and interpretation, assistance is given by the Contracting Officer. In matters related to the status of payments or provisions relating to payments, assistance is given by the Resource/Finance person. While SIMBIOS contractors have historically addressed questions about contract administration to the Assistant Project Manager, they are entirely free to address questions directly to the appropriate personnel.

A wide selection of contract types is available for use between the Project office and contractors. This selection provides a wide selection of services and a large degree of flexibility of contract conditions (FAR, 1998). GSFC Procurement Office selected a Research and Development Service, firm-fixed price (FFP) contract-type for the NASA Research Announcement (NRA) selections. The FFP contract provides for a price that is not subject to any adjustment by reason of the cost experience of the contractor in the performance of the contract. Use of the FFP contract imposes a minimum administrative burden on the contracting parties. Contracts are very different from the usual scientific research grants in three main aspects: 1) a work statement concerning the end objectives of the research (i.e., the proposal), 2) the technical data to be delivered under the contract with time delivery specifications, and 3) scientific and technical reports, consistent with the objectives of the effort involved, as a permanent record of the work accomplished under the contract.

3.2 CONTRACTS OVERVIEW

The initial SIMBIOS program was scoped for five years (1997-2001) and includes support for the NRA selections (i.e., science team) and the SIMBIOS Project. The Interim SIMBIOS Office (ISPO) successfully negotiated specific work statements for the 21 NRA selections and issued contracts starting from late summer 1997. SIMBIOS funded contracts, PI names and delivery requirements are summarized in Table 2.

NASA Procurement requires formal evaluations for all contracts at the end of each contract year. These evaluations are to go into a database and will be shared with the PIs' institutions. The performance evaluation has four categories: quality, time, other and price (price is not relevant here because contracts are fixed cost). SIMBIOS Project Office procedure is to coordinate an inside panel to perform an across-the-board evaluation of all funded contracts. Under quality will be considered 1) data quality and completeness, 2) ancillary information provided on the data (metadata), 3) the data's usefulness in relation to SIMBIOS goals, i.e., calibration, validation, and algorithm development, and 4) quality of technical reports. Time is a mixed bag, but will be viewed in respect to data and documentation (monthly, year-end reports, and special topic publications) and delivery times. Under "other" will be considered 1) scientific publications and scientific achievements, 2) science team collaboration and involvement, and 3) other significant events occurring during the contract period evaluate.

Table 1. Contract key personnel

SIMBIOS NRA Organization	
Contracting Officer:	Lynne Hoppel
Resource/Financial Officer:	Patty Clow
Assistant Project Manager:	Giulietta Fargion
Program Manager:	Charles McClain

3.3 SCIENCE TEAM

NASA SIMBIOS Science Team Principal Investigators are composed of those selected under the NRAs, some members of the MODIS Ocean Teams, and certain members the SeaWiFS Project. The Science Team can be grouped under three working areas: 1) Ocean Bio-optical and Sensor Characterization Studies, 2) Data Merger Studies, and 3) Atmospheric Correction Studies. There are many more U.S. and international co-investigators and collaborators actively participating in the NASA component of the international SIMBIOS program.

The funded Principal Investigators and collaborators are shown in Table 3. SIMBIOS Science Team meeting is held each year, information and documentation's produced in the two previous meetings (1997 and 1998) are posted on the SIMBIOS website.

Figure 1 shows the global distribution of the NRA-selected SIMBIOS field studies, and following chapters from 5 to 27 describe the funded research topics, field studies and the first year research results.

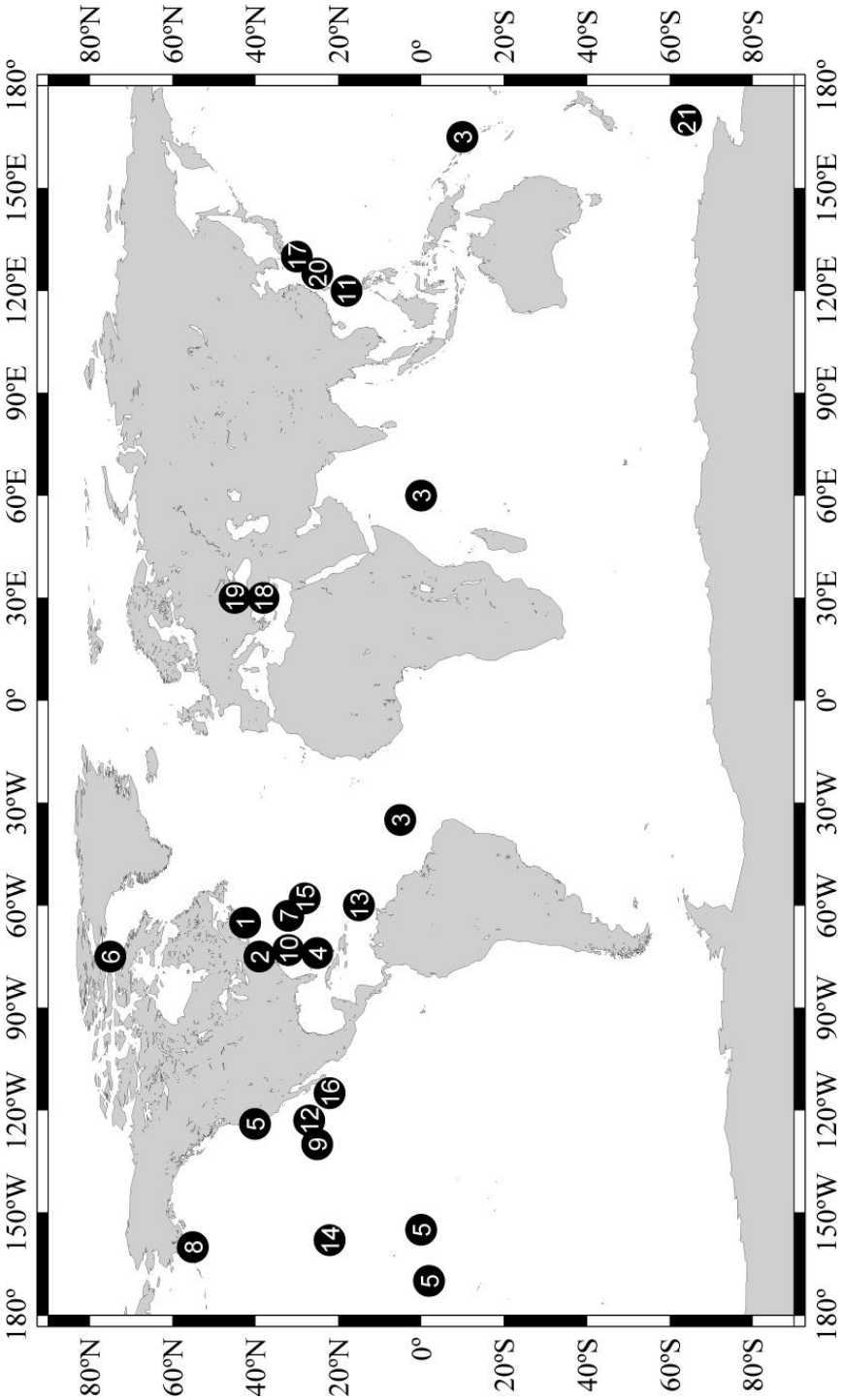
Table 2. SIMBIOS contracts and government interagency agreements *.

Principal Investigator	Contract Number	Begin Date	Monthly Report	End-year TM	Cruise Report Metadata	Special Topic TM	Field Data Within 3 or 6 Months	Algorithm Development	Science Team Meeting
William Balch	97268	9/23/97	√	√	√		√		√
J. Brock / C. Brown	*	7/21/97	√	√	√		√		√
D. Capone / E. Carpenter	97131	9/11/97	√	√	√		√		√
Ken Carder	97137	9/23/97	√	√	√		√		√
Francisco Chavez	97134	9/26/97	√	√	√		√		√
Glenn Cota	97132	9/26/97	√	√	√		√		√
Tom Dickey	97127	7/15/97	√	√	√		√		√
Dave Eslinger	97133	9/17/97	√	√	√		√		√
Robert Frouin	97135	9/22/97	√	√	√		√		√
Robert Green	*	8/6/97	√	√	√		√		√
Watson Gregg	*	2/5/97	√	√	√			√	√
Rick Miller	*	12/16/97	√	√	√		√		√
Greg Mitchell	97130	8/18/97	√	√	√		√	√	√
Jim Mueller	97126	8/18/97	√	√	√		√		√
Frank Müller-Karger	97128	8/18/97	√	√	√		√		√
Dave Siegel	97125	7/11/97	√	√	√	√	√		√
Ron Zaneveld	97129	8/18/97	√	√	√	√	√		√
Piotr Flatau	97139	9/22/97	√	√	√		√	√	√
Mark Miller	*	9/23/97	√	√	√	√	√		√
John Porter	97136	9/29/97	√	√	√		√		√
Knut Stamnes	97138	9/15/97	√	√	√	√	√	√	√

* Interagency agreement

Table 3. Funded Principal Investigators (PI) and collaborators *. Collaborators are funded via EOS (MODIS Ocean Team) and/or SeaWiFS Project.

I.	**Ocean Bio-optical and Sensor Characterization Studies**
	K. Arrigo * (NASA) W. Balch (Bigelow Lab.) J. Brock (NOAA) C. Brown (NOAA) D. Capone (U. of Maryland) E. Carpenter (State U. of New York) K. Carder (U. South Florida) F. Chavez (Monterey Bay Aquarium Res. Inst.) D. Clark * (NOAA) G. Cota (Old Dominion U.) T. Dickey (U. of California/Santa Barbara) M. He (Peoples Republic of China, Ocean U. of Qingdao) W. Esaias * (NASA) D. Eslinger (U. of Alaska) R. Evans *(U. of Miami) R. Frouin (Scripps Inst. Oceanography) R. Green (Jet Propulsion Lab.) F. Hoge *(NASA) S. Hooker *(NASA) O. Kopelevich (Soviet Union, P.P. Shirshov Inst. of Oceanology) G. Korotaev (Ukraine, Marine Hydrophysical Inst.) H. Li (Taiwan, Nat. Taiwan Ocean U.) R. Miller (NASA) G. Mitchell (Scripps Inst. of Oceanography) J. Mueller (San Diego State U.) H. Li (Taiwan, Nat. Taiwan Ocean U.) R. Miller (NASA) G. Mitchell (Scripps Inst. of Oceanography) J. Mueller (San Diego State U.) F. Müller-Karger (U. South Florida) S. Saitoh (Japan, Hokkaido U.) D. Siegel (U. of California/Santa Barbara) R. Zaneveld (Oregon State U.)	
II.	**Data Merger Studies**
	W. Gregg (NASA) D. Siegel (U. of California/Santa Barbara)
III	**Atmospheric Correction Studies**
	P. Flateau (Scripps Inst. of Oceanography) H. Gordon * (U. of Miami) M. Wang (UMD/Baltimore) M. Miller (Brookhaven National Lab.) J. Porter (U. of Hawaii) K. Stamnes (U. of Alaska)



1. Global distribution of the NRA-selected SIMBIOS field studies. United States: (1) Balch; (2) Brown/Brock Carder; (5) Chavez; (6) Cota; (7) Dickey; (8) Eslinger; (9) Frouin; (4/14) Green; Hoge; (11) Miller; (12) Mitchell; (13) Müller-Karger; (14) Porter; (15) Siegel; (16) Zaneveld/Mueller; Kopelevich; (19) Korotaev; (20) Li; and (21) Satoh

Chapter 4

SIMBIOS Project Activities (1997-1998)

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The project accomplishments during this first period (1997-1998) under (a) satellite data processing, (b) data product validation, and (c) sensor engineering and calibration activities are described below.

4.1 SATELLITE DATA PROCESSING

One of the primary goals of the SIMBIOS project is to develop methods for meaningful comparison and possible merging of data products from multiple ocean color missions. Direct comparison of such products is complicated by differences in sensor characteristics and processing algorithms, as well as spatial and temporal coverage.

4.1.1 MOS

The German Modular Optoelectronic Scanner (MOS) (Zimmermann and Neumann, 1997) is an imaging pushbroom Charge-Coupled Device (CCD) spectrometer that was launched in a sun-synchronous polar orbit in the spring of 1996 on the Indian Remote Sensing (IRS-P3) satellite.

MOS is a technology demonstrator instrument with limited geographic coverage capabilities. With the successful launch of NASA's SeaWiFS on August 1 of 1997, there are now two ocean color missions in concurrent operation. Table 1 provides characteristics of MOS compared with SeaWiFS. Therefore, we have an unprecedented opportunity to compare ocean color data from two sensors in simultaneous operation on two different satellite platforms. We have extensively studied the ocean color measurements compared between MOS and SeaWiFS and developed a vicarious calibration approach in which the MOS spectral bands can be recalibrated from the SeaWiFS measurements, which are considered as "truth," thereby allowing remotely retrieved ocean color results from the two sensors to be meaningfully compared (Wang and Franz, 1998 and 1999). The vicarious calibration method has also been successfully applied to Japan's OCTS data, and will also be tested with the French POLDER data. In here, we give some summaries about these studies.

The MOS calibrated and geo-located data (L1B data) are provided by the MOS project at Institute of Space Sensor Technology, Deutshe Forshungsanstalt Luft-und Raumfarhrt (DLR), Berlin, Germany. The MOS L1B data file is prepared as size of 384 x 384. In the following sub-sections, we give brief discuss of our efforts in comparing the MOS results with SeaWiFS.

Atmospheric Correction and Destriping

It is well known that the atmospheric correction, which removes more than 90% of sensor-measured signals contributed from atmosphere in the visible, is the key procedure in ocean color imagery data processing. We have implemented the SeaWiFS atmospheric correction algorithm (Gordon and Wang, 1994b) into the MOS imagery data processing using

the method outlined by Wang (1999). Therefore, a consistent atmospheric correction method can be applied to both SeaWiFS and MOS.

The MOS radiance image has along-track stripes due to variations in the relative response of the individual detectors on the MOS CCD array (total of 384 CCD detectors). Therefore, we have developed a simple destriping algorithm and applied it to the MOS radiance imageries. The MOS destriping procedure can be briefly outlined as follows. First, for each scan (along the detector array) and a given spectral band, fit the radiance to a least-square cubic polynomial along the scan and compute relative gain at each detector. Next, for each detector select the median gain over all scans in the scene to derive the nominal gain factor for that detector. Finally, the MOS radiance image can be recomputed with the destriping correction using the median gain factor.

A complicated stray light and striping correction algorithm is now available from the MOS project. Some study and tests are needed to see the efficacy of this algorithm. We applied the atmospheric correction to both MOS and SeaWiFS for co-located images and compared the retrieved ocean and atmospheric optical properties. Two MOS-SeaWiFS co-located images acquired on January 29, 1998 in the Atlantic ocean (latitude 27° and longitude -32°) and February 28, 1998 in the Mediterranean Sea (latitude 38° and longitude 3°) were first tested. These two scenes, acquired one month apart, differ significantly in their ocean and atmospheric optical properties. In comparing the MOS retrieved ocean and atmospheric optical results with that of SeaWiFS, however, we found that:

- the MOS retrieved aerosol optical thickness at the NIR band was usually a factor of 2-3 times higher than that of SeaWiFS;
- the MOS retrieved ε (7,8) which characterizes the spectral variation of aerosol optical properties is unreasonably low; and
- the MOS retrieved normalized water-leaving reflectances $[r_w(l)]_N$ in the visible are significantly different from those of SeaWiFS.

Since we are applying an identical atmospheric correction process to the two sets of measurements, the large discrepancy in the retrieved results between the two sensors can probably be interpreted as a difference in sensor calibrations. It is therefore necessary to recalibrate one sensor to the other, to allow for meaningful comparisons of the retrieved ocean optical properties.

A Vicarious Intercalibration for MOS

The vicarious intercalibration procedure between MOS and SeaWiFS can be described as follows. We assume that the gain of the MOS 868 nm band is unchanged because of differences in the orbits of MOS and SeaWiFS, thereby using the aerosol concentration from the MOS measurements, and only accept that the aerosol model determined by SeaWiFS is still valid. Next, by using the SeaWiFS retrieved aerosol models we can theoretically predict the atmospheric effects in the MOS imagery. The whitecap radiance contribution can be estimated in the same way as SeaWiFS (Gordon and Wang, 1994a). Finally, using the SeaWiFS retrieved normalize water-leaving reflectance, $[r_w(l)]_N$, the water-leaving and total radiance at the TOA in the MOS imagery can be computed, and the gain coefficients for the MOS bands can be derived. To reduce the variation of the derived gain coefficients with various scans, multiple scans within the MOS scene can be used to obtain coefficient data and derive a best fit for the MOS 384 detectors. Table 2 provides the derived MOS re-calibration gain coefficients fitted with the least-square cubic polynomial. These coefficients were derived from two MOS data set acquired on January 29 and February 28, 1998. We found that the derived gain coefficients for the MOS bands 1-6 have very similar values in the two different cases, indicating that they are nearly independent of temporal and spatial variations. The derived gain coefficients for band 7, however, are different in the two cases. It appears that the MOS 750 nm band performance is related to the atmospheric optical conditions and its gain adjustment is in opposite to other bands (gain coefficient > 1).

Since the derived MOS 750 nm band re-calibration gain coefficients depend on the atmospheric optical properties, we have modified the atmospheric correction algorithm such that the correction can also be operated using the MOS 685 and 868 nm bands. Therefore, a consistent re-calibration gain coefficients for the MOS bands 1-6 and band 8 can be applied.

Results and Discussions

We applied the derived MOS gain coefficients as in Table 2 to the MOS measured-radiance at the TOA, and retrieved ocean and atmospheric optical properties for comparison with results from the SeaWiFS measurements. Figure 1(a) and 1(b) provide examples of the histogram (%) for the retrieved normalize water-leaving reflectances (%) for bands 2 from MOS in comparison with SeaWiFS for the case of January 29 and February 28, 1998. There are four cases in each figure: (i) results from the SeaWiFS measurements with the bands 7 and 8 used in the atmospheric corrections, (ii) results from the MOS re-calibrated radiances with the bands 7 and 8 used in the corrections, (iii) same as in (ii) except that the MOS bands 6 and 8 were used in the corrections, and (iv) results from the MOS original radiance data with the

bands 7 and 8 used in the corrections. Note that for cases in which the MOS bands 7 and 8 were used for the atmospheric corrections, two different calibration gain coefficients were applied for the MOS 750 nm band for cases of January 29 and February 28, 1998. However, when the MOS bands 6 and 8 were used in the corrections, the MOS band 7 reflectance data were simply not used, thereby allowing a consistent set of recalibration gain coefficients for the MOS bands 1-6 and 8 to be applied for both cases. Figures 1(a) and 1(b) show that the vicarious calibration improves the agreement significantly.

To further test the efficacy of the vicarious re-calibration approach, we have applied the MOS re-calibration gain coefficients, which were derived from January 29 and February 28, 1998 data, to a MOS image acquired on September 24, 1997 (4-5 months before) at a location of about latitude 45° and longitude 13° in the Adriatic Sea, and compared the results to those obtained from a co-located SeaWiFS image. Again, MOS results were improved significantly with vicarious re-calibration (Wang and Franz, 1999).

We conclude from these studies that, with the vicarious calibration approach, the retrieved results from different sensors can be meaningfully compared and possibly merged. More importantly, with the same procedure, one can re-calibrate satellite sensors using in situ ocean and atmospheric optical property measurements.

Table 1. Characteristics of MOS with SeaWiFS.

Instrument	MOS	SeaWiFS
Platform	I RS-P3	OrbView-2
Launch date	March 21, 96	August 1, 97
Altitude (km)	817	705
Equatorial crossing time	10:30 AM	12:00 Noon
Resolution at nadir (km)	0.5	1.1
Scan swath (km)	200	2800
Time for one orbit (minutes)	101	99
Spectral range (nm)	408-1010	412-865
Instrument calibration	Lamp	Solar & Lunar

Table 2. The derived MOS gain coefficients as $G(l,i) = \sum_{n=0}^{3} c_n(l)\, i^n$, for i = 1-384

MOS λ (nm)	$c_0(\lambda)$	$c_1(\lambda)$	$c_2(\lambda)$	$c_3(\lambda)$
408	0.9029	3.5×10^{-4}	-9.0×10^{-7}	1.4×10^{-9}
443	0.8453	3.8×10^{-4}	-7.0×10^{-7}	6.5×10^{-10}
485	0.8097	3.8×10^{-4}	-5.3×10^{-7}	2.1×10^{-10}
520	0.8693	1.7×10^{-4}	-4.9×10^{-8}	2.8×10^{-10}
570	0.8701	1.8×10^{-4}	2.2×10^{-7}	-4.6×10^{-10}
685	0.9287	7.6×10^{-4}	-2.6×10^{-6}	3.5×10^{-9}
750†	1.3208	-3.5×10^{-4}	-2.9×10^{-6}	7.4×10^{-9}
750‡	1.2287	5.1×10^{-4}	-5.3×10^{-6}	-3.2×10^{-10}
868	1.0000	0.0	0.0	0.0

† From case of Jan. 29, 1998 ‡ From case of Feb. 28, 1998

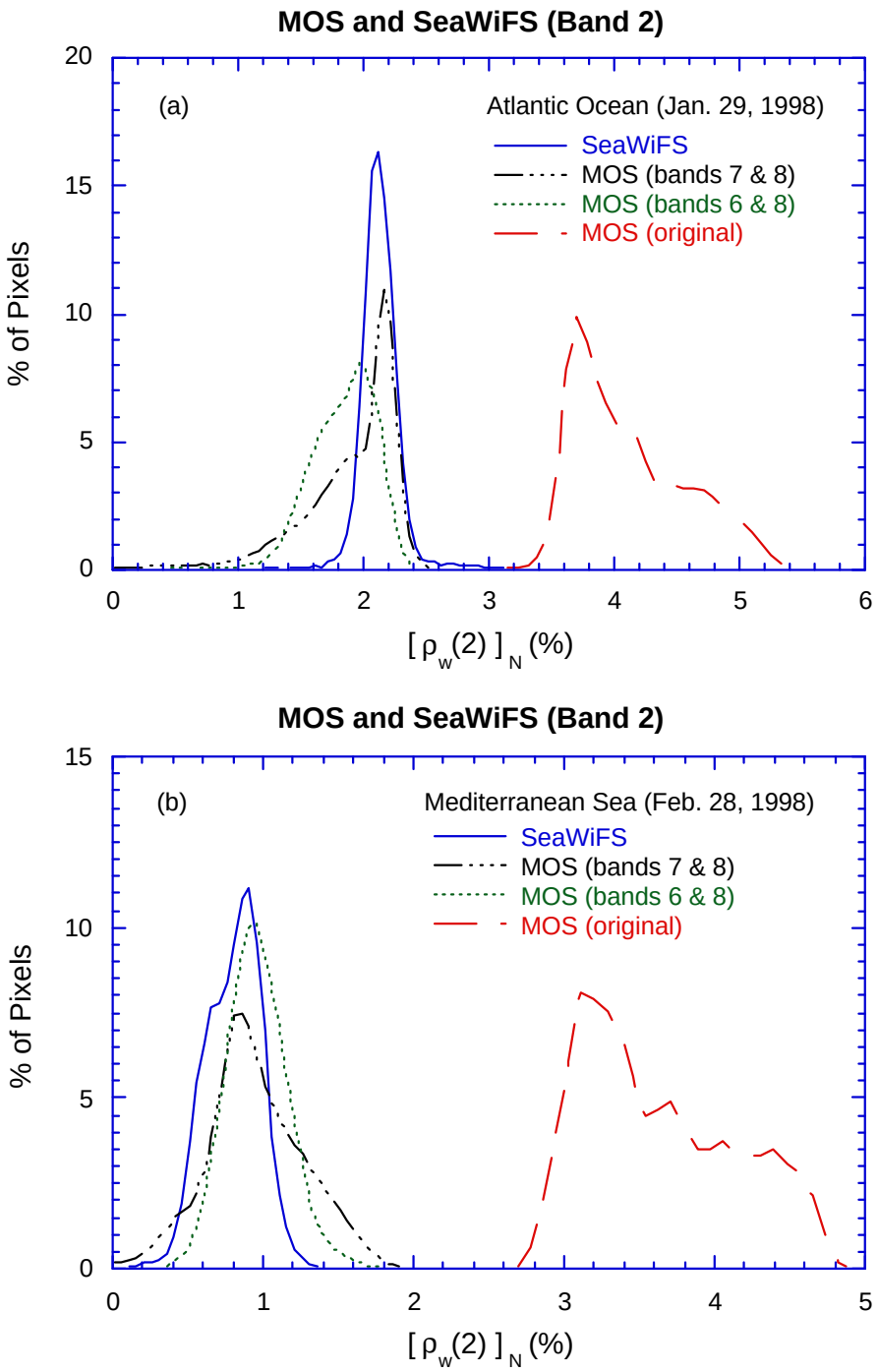


Figure 1. The histogram (%) of the MOS retrieved normalized water-leaving reflectances (%) with and without recalibrations in comparison with the SeaWiFS measurements for 443 nm band for case of (a) January 29, 1998 (Atlantic Ocean) and (b) February 28, 1998 in the Mediterranean Sea.

4.1.2 OCTS

The OCTS is an optical radiometer which flew on the Japanese Advanced Earth Observing Satellite (ADEOS) from August 1996 to June 1997, collecting 10-months of global ocean color data (Kawamura, 1998). During the ADEOS mission lifetime, approximately 450 GB of real-time, 700m-resolution OCTS data was collected by the SeaWiFS project through NOAA ground stations at Wallops, Virginia and Fairbanks, Alaska. The archive consists of 337 scenes of the U. S. East Coast and 1311 scenes over Alaska.

Since no standard software was publicly available, the coastal U.S. data set was originally processed and distributed in near-real time using NASA software developed under rapid prototyping conditions. Over the past year, the SIMBIOS project has been engaged in a comprehensive program to enhance the algorithms and software used to process the OCTS data, with specific attention given to improving the geolocation and image registration, atmospheric correction algorithms, and vicarious calibration. In addition, through its close working relationship with the OCTS team at the Japanese Space Agency (NASDA) Earth Observation Research Center (EORC), the project has collected an archive of OCTS Level-1B and Level-2 NASDA products corresponding to times and locations where *in situ* data is available. This match-up data set has been used to validate the Level-2, Version-3 products from NASDA (Shimada, 1998b), as well as the Level-2 products generated using SIMBIOS project software and algorithms.

Processing to Level-0

The U.S. Coastal data set must first be converted from a raw 10-bit format to a 16-bit Level-0 format. The original processing made use of a NASA-defined Level-0 format, which was inconsistent with the NASDA Level-0 format (NASDA, 1994). To eliminate this inconsistency, the SIMBIOS software was enhanced to generate NASDA format, including headers containing the definitive spacecraft ephemeredes and spacecraft clock timing data. The entire raw-data archive was then reprocessed to NASDA Level-0 format, and the data set was again made available to the public. It can be accessed via the "File Request and Staging" function of the SeaWiFS data processing system at http://falefa.gsfc.nasa.gov /~seawifsd/sdpsdoc/html/main.html.

Processing to Level-1B

In general, the processing of Level-0 data to Level-1B includes conversion of raw sensor counts to physical units and the assignment of geolocation information to each observation (pixel, detector, and band). Several factors in the design of the OCTS instrument complicate this process. Each OCTS band is divided into 10 individual detectors, where each detector is associated with a separate scan line. Each detector has a slightly different and apparently non-linear responsively, which gives rise to horizontal striping in the OCTS imagery. The basis for the SIMBIOS calibration is the NASDA Version 3 preflight calibration and relative detector calibration (Shimada, 1998a). The relative detector calibration substantially reduces the striping effects, but low-level artifacts are still visible and they can become significant following removal of the large, comparatively smooth atmospheric signal.

The design of the OCTS scan mirror and focal plane results in severe misalignment of the line-of-site for different spectral bands viewing at essentially the same time. To perform atmospheric correction or derive chlorophyll concentration at a given location requires that the bands be co-registered to that location.

The SIMBIOS project developed a registration technique in which an idealized focal-plane geometry is defined, and all bands are re-sampled using a nearest neighbor approach to match the idealized ground track. This method is similar in concept to the NASDA approach (NASDA, 1994), but it will result in slightly different re-sampling. Furthermore, while the registration process can correct for differences in geolocation between bands, the re-sampled observations come from different lines-of-sight with unique sensor-to-ground and sun-to-ground geometries.

To ensure accurate atmospheric correction, the true solar and sensor view angles per band are saved in the Level-1B file for use in Level-2 processing. Before the registration process can begin, however, the observations from each band must be accurately navigated. The geolocation algorithm used for SIMBIOS OCTS processing is a modified version of the method used for SeaWiFS navigation (Patt and Gregg, 1994). This technique has the potential to yield an exact solution to the geolocation of each scan line, when the spacecraft position and sensor geometry are accurately known.

Some sources of error include: inexact knowledge of the instrument design and installed, post-launch sensor and mirror alignments (NASDA, 1994), uncertainties in orbit location or spacecraft attitude, and variations in the scan-rate or sensor tilt.

To improve geolocation accuracy, the SIMBIOS project derived time-dependent attitude and tilt adjustments using an automated navigation assessment technique based on island targets (Patt et al., 1997). The final navigation is still being assessed, but preliminary indications show that it is accurate to approximately one kilometer.

Processing to Level-2

Within the SIMBIOS project, Level-1B to Level-2 processing includes application of the vicarious calibration, removal of the atmospheric signal to retrieve the water-leaving radiances, and generation of derived products such as chlorophyll concentration. It is most appropriate to apply the vicarious calibration at this stage, as it must account for deficiencies in the atmospheric correction algorithm, as well as for changes in the preflight calibration. Since this same approach was used by NASDA, the Level-1B products from the Japanese Space Agency and the SIMBIOS project are calibration equivalent, though the atmospheric correction algorithms and file formats differ.

The SIMBIOS OCTS atmospheric correction algorithm is based on the SeaWiFS algorithm of Gordon and Wang (1994a). The SIMBIOS approach has been to identify those few parts of the algorithm which are sensor or band-pass specific, and develop a software package which can process data from multiple ocean color remote sensors. The sensitivity of the algorithm to differences in spectral bands was carefully assessed by Wang (Wang, 1999), wherein he showed by simulation that these differences can be accurately accounted for through exact calculation of the Rayleigh reflectances and minor modifications to the diffuse transmittance calculation. The multi-sensor Level-1B to Level-2 code (MSl12) has been used successfully to process and intercalibrate MOS and SeaWiFS data (Wang and Franz, 1999), and it is now being employed to process the entire SIMBIOS OCTS archive.

When processing OCTS data, the MSl12 software is able to make use of the band-dependent solar and view angles. If these angles are provided in the Level-1B input file, they will be used in the atmospheric correction process when computing the Rayleigh radiances, the air-mass calculations that affect estimates of white-cap radiance and diffuse transmittance, and the normalization of the water-leaving radiances.

The atmospheric correction process includes masking for land, clouds, and saturation and masking for stray-light in the vicinity of those bright sources. To mitigate the effects of residual striping or other forms of systematic or random noise, the MSl12 code includes options for various types of statistical, spatial filtering. For OCTS processing, a 5x5-pixel median filter is applied to the Rayleigh-subtracted radiances in the near-IR bands, based on the assumption that the spatial scale of aerosol variability is expected to be greater than a few kilometers. This smoothing effectively reduces the tendency for the atmospheric correction algorithm to select different aerosol types from pixel-to-pixel. Additional smoothing with a 3x3-pixel median on the Rayleigh-subtracted radiances is applied to the visible bands, reducing the effect of residual striping at the cost of degraded resolution of the in-water spatial structure.

For purposes of vicarious calibration, the SIMBIOS project is fortunate to have time and space-coincident in situ water-leaving radiance spectra from the Marine Optical Buoy (MOBY) buoy (Clark et al., 1997) to match a series of OCTS over-flights. This same buoy is the basis for the SeaWiFS calibration, providing a convenient bridge to connect the two mission life-spans. Unfortunately, there were some problems with the early deployment of MOBY, limiting the number of usable calibration samples to seven measurements spanning the period November 1996 to February 1997. In addition, MOBY measurements are not sufficient to calibrate the near-IR bands at 765 nm and 865 nm, where water-leaving radiances are very close to zero. It was therefore assumed that the 865 nm vicarious calibration was equal to the value suggested in the NASDA Version-4 calibration (Fukushima, pers. comm.), and the 765 nm band was adjusted to force the atmospheric correction algorithm to select, on average, a maritime aerosol type over the MOBY site. This assumption is consistent with the typical aerosol-type retrievals derived from SeaWiFS data in the vicinity of MOBY. The entire vicarious calibration process can be performed in a single processing step in which the OCTS match-up data set is corrected to retrieve the normalized water-leaving radiances, the retrieved normalized water-leaving radiances are replaced with the *in situ* values, and the atmospheric correction algorithm is reversed to derive the theoretical top-of-atmosphere radiances. These theoretical radiances are divided by the observed radiances to derive correction factors for each in situ match-up point, and those ratios are averaged within each band to derive the vicarious calibration coefficients.

The final calibration coefficients are listed in the Table 3, with the equivalent NASDA Version-4 calibration shown for comparison. Considering that the two projects use different atmospheric correction algorithms (Fukushima et al., 1998) and different in situ measurements for calibration, the results are in good agreement.

Table 3.

Band	NASDA	SIMBIOS
1	1.14	1.13
2	1.03	1.01
3	0.9394	0.94
4	1.00	1.00
5	1.04	1.03
6	1.00	0.99
7	1.02	0.91
8	0.89	0.89

The largest difference is in the 765 nm band, which NASDA does not use for atmospheric correction (Shimada, 1998). Since SIMBIOS does make use of the 765 nm band for aerosol model selection, a correction for oxygen absorption was necessarily performed, which accounts for the discrepancy.

Validation Analyses

An extensive set of *in situ* data taken during the time of the OCTS mission was made available to the SIMBIOS project for match-up analysis from the SeaBASS database. Over 600 data points taken on 134 separate days exist in this set.

OCTS Satellite data used in the match-up analysis was obtained from two different sources and two different processing methods were used. Files in the U.S. Coastal archive which matched *in situ* data points were processed from Level 0 to Level 2 using the SIMBIOS algorithms and calibration described above. Level 1B data files supplied to the SIMBIOS Project by NASDA/EORC were processed to Level 2 using the SIMBIOS atmospheric correction algorithms and vicarious calibration. Level 2 data supplied by NASDA/EORC were also matched to *in situ* data, but these data were processed using Version 3 of the NASDA calibration and so results obtained are of historic interest only.

Normalized water-leaving radiance (nLw) values were extracted from the Level 2 records and acceptable pixels within a 1.05-km radius were weighted by the inverse of their distance to the match-up site and then averaged to derive nLw values for comparison to *in situ* data. This technique usually resulted in obtaining data from 9 pixels in a square centered about the *in situ* data point, although the actual number can vary due to the complex scan geometry of the OCTS instrument. Match-up values were also calculated for an area within a 2-km radius if there were not enough acceptable pixels within the 1.05-km limit.

The *in situ* water-leaving radiances were normalized using theoretical estimates of surface irradiance (E_s). The E_s values were calculated from the Solar radiance model of Neckel and Labs (Neckel and Labs, 1984), weighted by the OCTS band passes, and transmitted to the surface using measurements of the local ozone concentration, knowledge of the Rayleigh optical thickness, and estimates of the aerosol transmittance. The resulting nLw values were then compared to the weighted average nLw values from OCTS.

Where possible, the match-ups of satellite to in situ data were judged acceptable by the same criteria used to judge SeaWiFS match-ups to *in situ* data. Specifically, match-ups were rejected if:

- The time difference between satellite and in situ measurements was more than 4 hours (6 hours for chlorophyll).
- Difference in solar zenith angle was more than 15º
- In situ data were from a duplicate cast and had a lower K490 value than other casts.
- Wavelengths of *in situ* data differed from OCTS wavelengths by more than 5 nm.
- Satellite data coefficient of determination (the ratio of standard deviation to average) was greater than 0.5
- The usable number of satellite pixels was less than 5, after tests for clouds and sunglint.

For the data processed from NASDA Level 1B to Level 2 using SIMBIOS methods, 13 match-up points were deemed acceptable. An additional 10 match-up points were obtained from the Wallops Level 0 dataset. Data collected over the MOBY site were excluded from this analysis, since they were used to derive the vicarious calibration.

Table 4.

Band	Number of Match-ups	nLw ratio OCTS retrieval / in situ
1	18	1.20
2	18	1.06
3	19	1.01
4	13	0.998
5	9	1.04

The Table 4 summarizes the match-up results between in situ water-leaving radiance data (excluding MOBY) and OCTS retrievals processed using the SIMBIOS atmospheric correction algorithms.

Sargasso Sea Validation Study

Due to the small number of usable match-up *in situ* data in existence for the OCTS mission, additional validation of the SIMBIOS OCTS calibration was sought. A time series of averaged normalized water-leaving radiances derived from 27 scenes centered in the Sargasso Sea was generated and compared to nominal water-leaving radiances derived from MOBY *in situ* data and to a time series from one year later in the Sargasso Sea area created from SeaWiFS data.

The Sargasso Sea area was chosen for the OCTS data because it yielded the largest number of clear-water scenes within the OCTS data set acquired by the Wallops receiving station. In addition, six clear-water scenes centered over Bermuda were generated from the same archive and compared to *in situ* data from that area.

The SeaWiFS Sargasso time-series data was taken from the standard 8-day time-binned dataset, for a 3° square box centered at Latitude 25.5° and

Longitude -71.5° from 57 8-day periods between November 1997 and December 1998. The SeaWiFS time binning procedure averages all acceptable values over each time period on a pixel-by-pixel basis. The nominal clear-water radiances used for comparison were derived from MOBY *in situ* data tuned to the OCTS and SeaWiFS wavelengths respectively. *In situ* chlorophyll and water leaving radiances for the Bermuda site were taken from the Bermuda Atlantic Time Series (BATS) conducted by the Center for Remote Sensing and Environmental Optics at the University of California, Santa Barbara (Garver and Siegel, 1997). For each scene in the Sargasso Sea and Bermuda area, normalized water-leaving radiances were averaged, excluding values where chlorophyll was not within acceptable limits, *i.e.* data not between .0005 μg/L and .30 μg/L, as well as data of unacceptable quality, e.g., clouds, etc. The averaged Sargasso Sea nLw values were compared to nominal MOBY-derived OCTS nLw values and to SeaWiFS values from 1997-1998 while the Bermuda area nLw values were compared to nominal MOBY-derived nLw values and to contemporary *in situ* data from the BATS experiment. For both Sargasso Sea and Bermuda area data, chlorophyll values were computed from the average nLw using both the OC2 algorithm of O'Reilly et al. (1998) adjusted to the OCTS spectral bands and the standard NASDA OCTS-C algorithm (Kishino et al., 1998). In addition, pigment concentrations were computed using the Normalized Difference Pigment Index (Frouin, personal comm.).

The agreement in the general behavior of the OCTS data with the SeaWiFS data from one year later suggests that the variability seen in the Sargasso Sea nLw values is due to seasonal variation rather than instrument instability. The mean nLw values from OCTS agree reasonably well with MOBY-derived nominal nLw values, suggesting that the SIMBIOS calibration is working well. The three chlorophyll algorithms used on OCTS data agree in the average but the distribution of the chlorophyll derived by the OC2 algorithm is somewhat broader than that obtained using the NASDA chlorophyll or NDPI pigment algorithm. The results of this study were presented at the Alps ’99 Conference in Meribel, France in January, 1999

4.2 PRODUCT VALIDATION

The Project is comparing and validating SeaWiFS satellite measurements with *in situ* atmospheric and bio-optical measurements.

4.2.2 SeaWiFS AOT Comparisons

The theoretical basis of the SeaWiFS aerosol retrieval algorithm are described in both Gordon and Wang, (1994b) and Wang et al., (1999). In this section, we briefly outline our efforts in comparing and validating the SeaWiFS aerosol optical products with the in situ measurements mainly from the data of the Aerosol Robotic Network (AERONET) (Holben et al., 1998). The majority of the instruments within the AERONET network are in continental locations. The SIMBIOS Project augumented this network with coastal and island stations. Some other in situ measurements from calibration and validation campaigns within the SIMBIOS project are also analyzed. The primary objectives for these comparisons are to:

- validate the SeaWiFS aerosol optical thickness (AOT) products, and
- determine the validity of the suite of aerosol models currently used by SeaWiFS for atmospheric correction.

In Situ Data Acquisition

The ground-based measurements utilized for the aerosol optical thickness matchup analyses come from two primary sources: automated CIMEL sun/sky scanning radiometer managed as part of the AERONET network, and hand-held MicroTops II sunphotometers. A select group of the ground stations from the AERONET was chosen. These instruments were located at either coastal or island stations and were operational for a reasonable length of time after SeaWiFS went into operation. Table 1 provides the AERONET station name, location (latitude and longitude), and corresponding responsible AERONET principle investigator (PI). The hand-held MicroTops II sunphotometer data, on the other hand, were collected by various investigators in field campaigns associated with the SIMBIOS Project. Data from the MicroTops instruments are reprocessed from raw voltages using code adapted from the AERONET standard CIMEL processing code. This ensures that the t_a data derived from the MicroTops measurements will be comparable to the data provided by the AERONET.

SeaWiFS Data Acquisition

The SeaWiFS aerosol optical thickness data were obtained by spatially co-locating a 5x5 pixel grid box around the pixel containing the ground-base measurement station, thereby providing a maximum 25 SeaWiFS retrievals in each matchup. The SeaWiFS operational code has been modified to

output, at a pixel by pixel level, the aerosol optical thickness at wavelength 865 nm, values of retrieved two aerosol models, as well as the model partition ratio r_a value. Therefore, aerosol optical thicknesses at all the SeaWiFS wavelengths can be calculated (Wang et al., 1999).

Data Analyses

SeaWiFS data were obtained by averaging over a 5x5 pixel grid box spatially, whereas the t_a data from the CIMEL measurements were derived by a time-weighted averaging during the SeaWiFS overpass (± 1 hour). Usually, the CIMEL instruments routinely take one measurement every 15 minutes. Therefore, for a given SeaWiFS file there may be as many as eight AERONET measurements that qualify as a match for the 2-hour time window. The number of hand-held MicroTops II measurements that match a given SeaWiFS file, however, varies greatly since the measurement protocol for these instruments is not yet well-defined. In general, there should be a minimum of three MicroTops measurements per matched SeaWiFS file. The ground-based measurements are averaged after weighting by the time difference between the in situ measurement and the SeaWiFS overpass. Once averaged, the ground based measurements are compared with the SeaWiFS derived values on a band by band basis for each ground station. Due to a limited number of MicroTops data, these data are grouped together as one "station."

Preliminary Results

We compared the SeaWiFS derived aerosol optical thicknesses with those from the ground in situ measurements. Figure 2 provides an overall comparison results of $t_a(l)$ between SeaWiFS and CIMEL measurements at wavelength 865 nm (870 nm for CIMEL). The CIMEL measurements were from the AERONET stations listed in Table 5. The dotted lines in Figure 2 is the 1:1 line. Though the comparison results varying both in time and location, it appears that SeaWiFS has tendency of overestimating $t_a(l)$ with respect to the in situ measurements. Note that, however, since the SeaWiFS band 8 has not been absolutely calibrated on orbit, any error in calibration may contribute to the error in the $t_a(865)$ evaluations. On the other hand, some in situ data are suspected to be erroneous due to instrument calibration. Obviously, more studies are needed to understand all of these. We want to emphasize that all results are preliminary.

Similarly, the *in situ* MicroTops II data, which were from the various SIMBIOS calibration and validation campaigns, have been compared with the SeaWiFS measurements. Although this work is still in the initial phase, some results are promising. Table 6 shows three sample comparison results from three field experiments. In these three examples, the SeaWiFS results were almost all underestimated as compared with the MicroTops II measurements (Ratio < 1), though the three results usually agreed reasonable well.

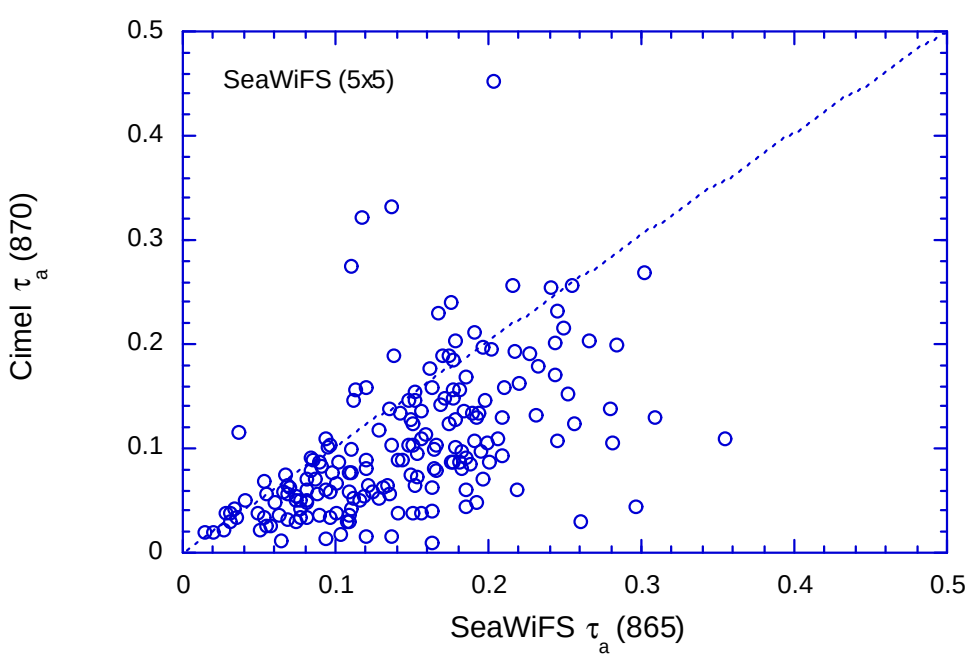


Figure 2. The retrival SeaWiFS aerosol optical thickness $t_a(l)$ compared with the ground *in situ* measurements from AERONET at 865 nm (870 nm for CIMEL Data).

Table 5. AERONET sites utilized for the aerosol matchup analyses.

AERONET Station	Latitude	Longitude	AERONET PI
Bahrain	26.32	50.50	Charles McClain*
Bermuda	32.37	-64.70	Brent Holben
Dry Tortugas	24.60	-82.80	Ken Voss/Howard Gordon
Kaashidhoo	4.97	73.47	Brent Holben
Lanai	20.83	-156.99	Charles McClain*
San Nicolas Island	33.26	-119.49	Robert Frouin

*SIMBIOS Project Office

Table 6. Three samples of MicroTops II data compared with SeaWiFS

Aerosol Optical Thickness $t_a(l)$						
λ (nm)	Jason Project G. Feldman		GOCAL97-98 J. Mueller		JULNAN98 B. Schieber and A. Subramaniam	
	SeaWiFS	Ratio	SeaWiFS	Ratio	SeaWiFS	Ratio
440	0.0555	0.7603	0.1635	0.8678	0.1775	0.9168
500	0.0509	0.9204	0.1469	0.9767	0.1538	0.9031
670	0.0395	0.8857	0.1076	1.1811	0.1013	0.9217
865	0.0304	0.9102	0.0774	0.8113	0.0641	0.8456

4.2.3 SeaBASS INTERFACE

The SeaWiFS Bio-optical Archive and Storage System (SeaBASS) was created by the SeaWiFS Project to provide a data archive for *in situ* products used in scientific analysis. This system has been expanded to additionally contain data sets of interest to the SIMBIOS Project.

The *in situ* data in SeaBASS include measurements of water-leaving radiance and other related optical and pigment measurements, from ships, moorings and drifters. Various methods are deployed in the collection of SeaBASS data, including the use of standard profiles, floating radiometers and above-water measurement devices. In addition to the optical and pigment products listed, measurements of total suspended matter (TSM), chromophoric dissolved organic matter (CDOM), and other typically non-plankton derived optical components are recorded in SeaBASS.

The products are used by the SIMBIOS Project in validation of SeaWiFS and other (OCTS, POLDER, etc.) postlaunch imagery and development of new operational chlorophyll algorithms. Additional uses under SIMBIOS will likely include field data calibration comparisons, algorithm workshops, and time series studies. A detailed description of the original SeaBASS design and scope is provided in the SeaWiFS Technical Report Series, specifically volume 20. A current description of the SeaBASS system is available via the World Wide Web at http://seabass.gsfc.nasa.gov.

Data Design

The SeaBASS system contains data from well over 150 separate experiments with thousands of files requiring over 22 megabytes of storage space. In addition, the historical optics database holds over 300,000 records related to phytoplankton pigments and is expected to grow as new pigment data is collected. Since the SeaBASS system is continuously growing with new data, a method for efficiently ingesting and storing field data was needed. It was deemed important that the data ingest be as straightforward and effortless as possible on the part of the contributing investigators, while still offering a useful and correct data archive for analysis efforts. The following aspects were considered to be the most important in the design of the system:

- Simple data format
- Global portability

- Data update simplicity
- Web accessible data holdings
- Support for existing Web standards

To accomplish the above goals, the SeaBASS system was designed to support standard ASCII files which can be managed from any computer platform. The files use a simple descriptive header format which contains descriptor=value pairs to explain the specifics ("metadata") of a data file. For example:

```
/begin_header
/affiliations = University_of_Maryland
/investigators = John_Creamer
/contact=johnc@umd.edu
/parameters=Ed,Lu,Kd,CHL
/north_latitude=59.10[DEG]
/south_latitude=58.65[DEG]
/east_longitude=-13.11[DEG]
/west_longitude=-13.50[DEG]
! Comments: data file to be updated
…
/end_header@
```

The header or metadata section is intended to fully describe the data in a file. Each header contains information on time and location of the *in situ* measurements, the investigators involved, values measured, comments, and other related descriptive information. Frequently, SeaBASS files will contain references to other files with additional descriptive details (e.g., README files).

Following the header information, the actual measured optics or pigment data is listed in columnar format. Typical data files include optical profiles, summary pigment files, or along track measurements. Specific information and examples of the formats can be referenced at the SeaBASS web site.

Following an series of redesign modifications in the first year of the SIMBIOS effort, the SeaBASS file formats have not changed significantly. However, additional changes may need to be made in the near future as new instrumentation and collection methods continue to populate the archive, some of which may warrant variations in the current data archive approach (i.e., hyper-spectral data).

Format Checking

Early in the development of the SeaBASS web site it was realized that each data provider can have very different views on data format or presentation. In order to establish a standard format for SeaBASS incoming data files which met the dual goals of simplicity and portability, feedback software was developed.

The primary component of this software is the FCHECK script. FCHECK is written in the PERL scripting language with connections to look-up tables and UNIX mail handling utilities. Data providers from any platform can test their data for compatibility with the SeaBASS format by simply e-mailing their file to fcheck@seabass.gsfc.nasa.gov. The FCHECK program will receive the incoming mail file from the system mail handler, parse the data, and thoroughly compare it to the established SeaBASS format. FCHECK will then report back to the data provider on the file's compliance. This file testing function happens automatically with no intervention required, but the SeaBASS administrator is sent a copy of all incoming data files, for review. The FCHECK program has been used by many SeaBASS data providers as a quick format checker and has saved many hours of processing time for both the SeaBASS administrator and contributing investigators.

Once the data provider is sure that their files will work with the SeaBASS archive, they can send the data, and related documents, to the SeaBASS archive via the file transfer protocol (FTP). From there, the SeaBASS administrator will move the files into their appropriate position in the archive and will initiate a database update to register the new data to the SeaBASS online system.

Data Security Issues

A concern of some contributors to SeaBASS involves outside user accessibility. Some investigators have been concerned that when data is quickly submitted to the archive, others may use the data without proper notification or acknowledgement. To address these concerns, and to afford continued rapid submission of data sets, the SeaBASS web server has been configured as a password protected system. Typically, only SeaWiFS or SIMBIOS authorized investigators who also submit data to the archive are allowed access. Others may be allowed access on a case-by-case basis. Additionally, the web server and SeaBASS software log all user activity. This information is available to contributing investigators. It is expected that all users who use data from the SeaBASS archive will offer collaboration or authorship to the data provider.

Specific Matchup Format

To expedite comparisons between *in situ* data and SeaWiFS (or other satellite) products, a specific file format has been developed. This file format, known as the "matchup" format, follows a similar logic to that of the other SeaBASS *in situ* files, that being a simple, easy to implement format in standard ASCII.

However, unlike the general format for SeaBASS data, the matchup format expects a strict adherence in the positions and units of data fields. This requirement is to allow for automated comparisons between *in situ*

and satellite data. The format is also used in interactions with the SeaWiFS/SIMBIOS satellite data archive. The matchup format is structured in standard ASCII columnar format with the following fields in each data record:

Year, Month, Day, Hour, Minute, Second, Latitude, Longitude, L_w412, L_w 443, L_w 490, L_w 510, L_w 555, L_w 670, E_s412, E_s 443, E_s 490, E_s 510, E_s 555, E_s 670, K_d490, Chl *a*

Where the time and location values identify when and where the measurement was taken. Water-leaving radiance (L_w) and downwelling irradiance (E_s) values may be extrapolated from below the surface or measured above the surface, depending upon the instrumentation used. The vertical attenuation of irradiance at 490 nm (K_d 490) as well as *in situ* measured values of chlorophyll a (Chl *a*) are also recorded if available. Missing data values are represented by a placeholder. As in the case of other SeaBASS submitted data, the matchup file also contains a metadata section to describe the enclosed *in situ* data.

Data Contributions

The SIMBIOS project funds numerous investigators in order to obtain *in situ* optical and pigment data for Case I (optically characterized solely by phytoplankton) water characterization. Additional investigators are also supported to develop new algorithms or scientific approaches in accordance with the goals of the SIMBIOS Project. As described above, the data and information provided are used for both internal analysis and satellite validation and to populate the SeaBASS archive for future activities and community use. Table 7 summarizes the data sets which have been received from investigators during the first year of funding. As shown in the table, the majority of funded principal investigators provide field data for the archive. However, some additional investigators were funded solely to develop algorithms or analysis techniques.

Future Plans

The SIMBIOS project has created an environment by which in situ data may be archived, accessed and analyzed to improve satellite retrievals through scientific data validation. In its first year of operation, the Project has implemented software and format standards which should greatly aid in future satellite efforts. Additionally, the Project's focus on thorough data documentation should aid in both current and future research activities. Subsequent years will focus on improving the usefulness of *in situ* data by continuing to improve the data ingest and data analysis approach.

Table 7. SIMBIOS supported data submitted to SeaBASS

Principle Investigator	**University or Laboratory**	**Optics Data**	**Pigment Data**	**Documentation Provided**	**Algorithm Development**
William Balch	Bigelow Labs	√	√	√	
J. Brock / C. Brown	USGS / NOAA	√	√	√	
Douglas Capone	U. MD	√	√	√	
Ken Carder	U. South Florida	√	√	√	
Francisco Chavez	Mont. Bay ARI	√		√	
Glenn Cota	ODU	√	√	√	
Tom Dickey	UC SantaBarbara	√		√	
Dave Eslinger	U. AK, NOAA/CSC	√	√	√	
Piotr Flatau	Scripps, UCSD			√	√
Robert Frouin	UCSD / Scripps	√		√	
Robert Green	JPL	√		√	
Watson Gregg	GSFC			√	√
Mark Miller	BNL	√		√	
Rick Miller	Stennis Space Ctr.	√			
Greg Mitchell	Scripps, UCSD	√	√	√	√
Jim Mueller	San Diego St. U.	√	√	√	
Frank Müller-Karger	U. South Florida	√	√	√	
John Porter	U. Hawaii	√		√	
Dave Siegel	UC Santa Barbara	√	√	√	√
Knut Stamnes	U. Alaska	√		√	√
Ron Zaneveld	OSU	√	√	√	

4.2.4 Support Services

In an effort to improve the quality and quantity of calibration and validation data sets, the SIMBIOS Project offers several support services to field investigators. These services include; scheduling of on-board Local Area Coverage (LAC) recording for SeaWiFS; overflight predictions for operational sensors (currently SeaWiFS, MOS-B and OCI); near real time SeaWiFS imagery for cruise locations; and optical instrumentation from a pool of investigator- and project-owned instruments. These services may be requested via the World Wide Web at http://simbios.gsfc.nasa.gov.

In return for these services, the SIMBIOS Project requests that the field investigators provide *in situ* validation data to the Project's bio-optical archive, SeaBASS. Since October of 1997, when these services were initially offered, the SIMBIOS Project has supported 81 cruises (Table 8).

SeaWiFS Scheduling

Since much of the worlds oceans are not covered by a SeaWiFS High Resolution Picture Transmission (HRPT) station, high-resolution data may be recorded onboard the SeaWiFS sensor. As a service to the science community, the SIMBIOS project in conjunction with the SeaWiFS project can schedule SeaWiFS onboard LAC for cruises that occur outside HRPT coverage. SeaWiFS has the ability to record a maximum of 10 minutes of high-resolution data per downlink. Typically, a 30-second interval is allotted for LAC target, which corresponds to 180 scan lines or approximately 200 km along track at nadir. Detailed information on LAC scheduling is available on the SIMBIOS web site.

Overflight Predictions

For calibration and validation purposes, *in situ* measurements should be made as close to the sensor overflight time as is possible. To aid investigators in determining when sampling should occur, the SIMBIOS project offers overflight predictions for all operational ocean color remote sensors. Currently, the sensors supported are SeaWiFS and MOS-B. With the successful launch of ROCSAT-1 on 26 January 1999, OCI is being added to this list. Detailed information on overflight predictions is available on the SIMBIOS web site.

Near-Real Time SeaWiFS Imagery

In addition to providing predictions for satellite overflight times, the SIMBIOS project offers near real time imagery of the operations SeaWiFS products in JPEG format to cruises at sea. These images provide field investigators with additional information with which they may maximize *in situ* sampling of transient oceanographic features. The default specifications for the images provided include:

- Available LAC, HRPT, and Global Area Coverage (GAC);
- Chlorophyll-a and pseudo-true color images;
- 2-degree box about a designated location or the entire designated region;
- Image Width: 600 pixels; and
- Minimum percent valid chlorophyll pixels: 5% .

Images may be customized to best accommodate individual investigators needs. Detailed information on near real time imagery is available on the SIMBIOS web site.

Table 8. Table of SIMBIOS supported cruises with services provided.

Cruise Location	Begin Date	End Date	On-board LAC	Over-flight Prediction	Near Real Time Imagery	Instrument Pool	Principal Investigator
Chesapeake Bay	09/28/1997	11/23/1997	√				Curt Davis
Black Sea	10/03/1997	10/13/1997		√			Oleg Kopelevich
Alaska	10/10/1997	10/17/1997				√	Glenn Cota
Gulf Of Maine	11/10/1997	11/21/1997		√	√		William Balch
Taiwan	11/23/1997	11/25/1997	√	√			Hsien-wen Li
Equatorial Pacific	09/27/1997	12/16/1997	√	√			Francisco Chavez
Ross Sea	10/01/1997	12/14/1997	√	√	√		Greg Mitchell
Equatorial Atlantic	11/14/1997	12/12/1997	√	√	√		C. Menkes
HOTS	12/01/1997	12/21/1997	√	√			John Porter

Cruise Location	Begin Date	End Date	On-board LAC	Over-flight Prediction	Near Real Time Imagery	Instrument Pool	Principal Investigator
Jamstec / Kaiyo	12/07/1997	12/26/1997	√	√	√		Marlon Lewis
Southern Polar Front	10/19/1997	02/15/1998			√	√	Greg Mitchell
HOTS Cruise	01/09/1998	01/12/1998	√	√			John Porter
Jamstec / Mirai	01/31/1998	02/11/1998	√	√	√		Marlon Lewis
SeaWiFS Initialization Cruise	01/26/1998	02/12/1998	√	√	√	√	Dennis Clark
Florida Bay	01/25/1998	02/07/1998	√	√			Eurico D'Sa
Antarctic	02/10/1998	03/18/1998		√	√	√	Greg Mitchell
Azores / Canary Islands	03/02/1998	03/27/1998	√	√			Marcel Wernand
Gulf of California	03/05/1998	03/16/1998	√	√	√	√	Jim Mueller
Gulf Of Maine	03/14/1998	03/27/1998	√	√	√		Bruce Monger
Indian Ocean	02/28/1998	03/15/1998	√	√			John Morrison
East China Sea	03/16/1998	03/27/1998	√	√	√		Gwo-Ching Gong
Bahamas	04/1/1998	04/07/1998	√	√		√	Robert Steward
HOTS	04/14/1998	04/16/1998		√	√		Craig Motell
Sicily Channel	03/27/1998	04/20/1998	√	√	√		M. Ribera d'Alcala'
California Coast	04/02/1998	04/24/1998		√		√	B.G. Mitchell
Yellow Sea	04/03/1998	04/23/1998	√	√	√		Sonia Gallegos
Sea Of Cortez	04/17/1998	04/26/1998		√	√	√	Gene Feldman
SW Pacific	03/24/1998	04/30/1998	√	√	√	√	Ajit Subramaniam
North Sea	04/6/1998	05/01/1998	√	√	√		Marcel Wernand
Atlantic Meridional Transect	04/6/1998	05/01/1998	√	√	√		Stan Hooker
Equatorial Pacific	04/26/1998	05/2/1998	√	√	√		Peter Strutton
Subtropical North Pacific	04/21/1998	05/06/1998	√	√	√		Jeffrey Polovina
HOTS	05/11/1998	05/15/1998		√		√	John Porter
Atlantic Ocean - Baltic Sea	05/01/1998	05/18/1998	√	√			Roland Doerffer
Gulf Of Cadiz	05/09/1998	05/19/1998	√	√			Andreas Neumann
Baltic Sea	05/26/1998	06/03/1998		√			Peter Land
Atlantic Meridional Transect	05/14/1998	06/18/1998	√	√	√		Stan Hooker
Gulf Of Maine	06/01/1998	06/15/1998		√	√	√	Bruce Bowler
Equatorial Pacific	06/6/1998	06/16/1998	√	√	√	√	Peter Strutton
Massachusetts Bay	07/05/1998	07/10/1998		√	√	√	Ajit Subramaniam
Labrador Sea	06/22/1998	07/10/1998		√	√	√	Glenn Cota
East China Sea	06/27/1998	07/08/1998	√	√	√		Gwo-Ching Gong
South China Sea	06/28/1998	07/03/1998	√	√			Hsien-Wen Li
Gulf Of Mexico	06/27/1998	07/03/1998			√		Andrew Thomas
Arctic Ocean	06/18/1998	07/20/1998	√	√			Dariusz Stramski
Resolute Bay	07/28/1998	08/25/1998	√	√		√	Glenn Cota
Equatorial Atlantic	07/15/1998	08/15/1998	√	√	√		C. Menkes
Long Island Sound	07/20/1998	07/30/1998		√			S. Papanikolaou
Puget Sound	06/04/1998	06/25/1998	√	√		√	Ron Zaneveld
Puget Sound	07/29/1998	08/22/1998	√	√		√	Ron Zaneveld
Arctic Ocean	08/05/1998	08/07/1998	√	√			Sergey Shirshov
Puget Sound	07/24/1998	08/22/1998	√	√	√		M.J. Perry
Taiwan Straits	08/10/1998	08/20/1998	√				Ming-Xia HE

Cruise Location	Begin Date	End Date	On-board LAC	Over-flight Prediction	Near Real Time Imagery	Instrument Pool	Principal Investigator
HOTS	08/08/1998	08/12/1998		√			John Porter
Gulf of Maine	08/14/1998	08/18/1998		√	√	√	Bruce Bowler
SE Bering Sea	08/15/1998	09/09/1998	√	√	√		Stephan Zeeman
South West U.S.	08/17/1998	09/25/1998	√	√	√		Edward Zalewski
South China Sea	09/11/1998	09/27/1998	√	√		√	Rick Miller
California Coast	09/13/1998	10/02/1998		√		√	Gregg Mitchell
North Pacific	08/30/1998	09/21/1998	√	√	√	√	Ron Zaneveld
HOTS	09/26/1998	09/30/1998	√	√			John Porter
North Pacific	10/01/1998	10/12/1998	√	√	√		Carrie Leonard
Atlantic Meridional Transect	9/14/1998	10/30/1998	√	√	√		Stan Hooker
Barents Sea	9/15/1998	10/10/1998	√	√			Oleg Kopelevich
U.S. East Coast	10/5/1998	10/13/1998		√	√		Stephan Howden
Gulf Of Maine	9/10/1998	10/31/1998	√	√	√	√	Bruce Bowler
HOTS	10/18/1998	10/20/1998		√			John Porter
East China Sea	10/15/1998	10/31/1998	√	√	√		Gwo-Ching Gong
Equatorial Pacific	10/23/1998	11/09/1998	√	√	√		Peter Strutton
HOTS	11/10/1998	11/12/1998	√	√			John Porter
South Atlantic Bight	10/27/1998	11/24/1998		√	√	√	Ajit Subramaniam
Gulf of California	11/25/1998	12/09/1998	√	√	√	√	Andrew Barnard
Gulf of Maine	12/02/1998	12/18/1998		√	√		Heidi Sosik
HOTS	12/13/1998	12/16/1998	√	√			John Porter
Indian Ocean	01/04/1999	02/23/1999	√	√	√		J. Le Fevre
Indian Ocean - INDOEX	01/14/1999	04/01/1999	√		√	√	Piotr Flatau
Southern Ocean	01/01/1999	04/01/1999	√		√		Steve Groom
California Coast	01/09/1999	01/31/1999		√	√		Greg Mitchell

Field Instrument Pool

The SIMBIOS project provided funding to several of the science team members for the purchase of in situ ocean optical instrumentation. The funding was provided with the stipulation that these instruments would be made available for three years to an instrument pool to be maintained by the Project Office. The Project augmented this instrument pool with atmospheric instrumentation. Table 10 summarizes the instruments available.

4.3 SENSOR ENGINEERING AND CALIBRATION

AERONET is a network of ground-based automated sun photometers owned by national agencies and universities. AERONET data provides globally distributed, near-real time observations of aerosol spectral optical depths, aerosol size distributions, and precipitable water. These data allow for algorithm validation of satellite aerosol retrievals as well as characterization of aerosol properties. Such validation and characterization are critical for atmospheric correction of ocean color sensors. The majority of the instruments within the AERONET network are in continental locations. The CIMEL Sun Photometer manufactured in France is the instrument used for AERONET.

The SIMBIOS Project augmented his instrument pool with atmospheric instruments by purchasing 12 MicroTops hand-held sun photometers, 2 PREDE (Japanese built) sun photometers, one micro-pulse lidar and the 12 CE318 CIMEL sun photometers.

Specifically, the 12 CIMEL instruments augment the AERONET network with coastal and island stations. These CIMEL instruments better withstand the corrosive marine environment after undergoing a robust re-engineering. These “hardened” CIMEL

instruments are placed, with other instruments, at sites near marine environments. Confirmed (delivered or negotiated) CIMEL sites include Lanai-Hawaii (with a backup in Honolulu), Ascension Island, Bahraine, Tahiti, Wallops Island (Virginia), South Korea, and Turkey (Black Sea).

CIMEL Re-engineering

In its normal configuration, the CIMEL Sun Photometer is not suitable for use in a corrosive marine environment. Meridian Engineering of Hanover (Maryland) under Tom Riley's guidance hardened these instruments for placement in locations where they may be subject to salt spray. The modifications include:

- Replacement of the base housing — The new base housing is welded and has more weather resistant connectors.
- Replace motor housing — The new housing is welded.
- Replace instrument housing — Again the new housing is welded.
- Cable and connectors — Connectors were replaced with military style connectors. Cables replaced with ones rated for this environment. The cables were then sealed with both 3M 2242 Linerless Electrical Rubber Splicing Tape and then 3M Scotch Super 88 Vinyl Electrical Tape.
- Hardened moisture sensor — The moisture sensor cable and connector were replaced.

The following devices were added to allow remote operation:

- Electronic boxes — The two electrical boxes (Control Box and Power Box) are now sealed plastic NEMA boxes and are painted white.
- Photovoltaic panel mount — The two photovoltaic panels and the moisture sensor are mounted on a fiberglass panel that is held to the power box with stainless steel hardware.
- Sun Shield — The Control Box also has a fiber glass sun shield held one inch above the box and has stainless steel hardware.
- Mounting Plate — A heavy galvanized steel mounting plate is now available.

Sun Photometer Calibration: Non-Polarized Channels

The calibration consists of using a sun photometer calibrated in high altitude conditions (Mauna Loa, Hawaii) and transferring the calibration to the other sun photometers by taking simultaneous sun direct measurements from ground during a clear day. The top of atmosphere (TOA) signals (V0) of the non-calibrated sun photometer are deduced from those of the CIMEL sun photometer. This method is currently applied to all the CIMEL sun photometers involved in the AERONET network (Holben et al., 1998).

The processing steps for analyzing the calibration measurements performed by a sun photometer are described below and summarized in Diagram 1:

- Download the raw signal of the uncalibrated sun photometer [Vu (i)] and of the calibrated sun photometer [Vr (i)].
- Select the simultaneous measurements (time difference lower than 36 seconds).
- Compute for each channel, the TOA signals for the un-calibrated sun photometer using the TOA signals of the calibrated sun photometer (obtained at Mauna Loa).
- The TOA signals, computed for each simultaneous event, are averaged

The comparison with the aerosol optical thickness (AOT) retrieved from the calibrated sun photometer allows for validation of the protocol. AOT are retrieved using the same steps as in Diagram 2 except for the Ozone retrieval. Total Ozone Mapping Spectrometer (TOMS) measurements are used for the computation of ozone contribution.

Currently, eight MicroTops, one SIMBAD and two PREDE sun photometers have been successfully transfer calibrated according to the inter-calibration method. The TOA signals of the MicroTops #3773, SIMBAD #972396 and PREDE #PS090063 are summarized during several transfers of calibration between August and December 1998 in Table 1. Means and standard deviation are presented for each channel of each instrument. The standard deviation of the TOA signal is overall lower than 2%. The results are especially good for the MicroTops and SIMBAD sun photometers, considering the long period used, the design (i.e., hand held) and affordable cost. The accuracy of the CIMEL sun photometer TOA signals (calibrated at Mauna Loa and used for our calibration transfer) is 0.5 % for the channels between 440 and 1020nm (Holben et al., 1998). The accuracy of the calibration transfer for the PREDE PS090063 is only presented on Table 11. Another PREDE (#PS090064) instrument, used between October and December 1998, is still under study.

Sun Photometer Calibration: Polarized Channels

The polarized version of the CIMEL sun photometers is composed of three channels at 870nm mounted on the filter wheel. Three polarizing sheets are located in front of the filters and are respectively adjusted according to 0, -60 and +60 degrees.

The polarization rate of the light is deduced from three measurements in these three channels.

The calibration of the polarized version of the CIMEL sun photometer is performed using a calibration device designed by the Laboratoire d'Optique Atmosphérique. The calibration device is located ahead of a non-polarized source and allows the polarization of the light in the output of the device. The reading of the angular position of the two SF11windows mounted inside the device allows for the computation of the polarization rate of the light. The calibration consists of plotting the computed polarization rate versus the measured one and determining the slope and the intercept of the trend line.

The calibration have been performed on six polarized instruments belonged to the AERONET group. The results are summarized in Table 12. The same calibration is scheduled for the SIMBIOS polarized CIMEL sun photometers. The calibration is performed for a polarization rate ranging between 0 to 65%, because of the dimensions of the device. The linear squared fit determined for the calibration of the six CIMEL sun photometers ranges between 0.9993 to 1.

Sun Photometer Data Processing

The data processing is applied to all SIMBIOS sun photometers (i.e., CIMEL, PREDE, MicroTops II and SIMBAD). The data processing principle is described below and summarized in Diagram 2:

1. Download the raw signal V_i corresponding to the measurements performed in the channel i.
2. Compute the ratio between the raw signal and the top of Atmosphere (TOA) signal V_{i0} provided by the calibration of the sun photometer, V_i/V_{i0}.
3. Compute the ratio between the averaged Sun-Earth distance and the Sun-Earth distance of the day, (d_0/d).
4. Compute the air mass m, according to the day, the date, the time and the location when/where the measurements were taken.
5. Compute the total optical thickness in the channel i, $\tau_{tot}(i)$.
6. According to the location, compute and remove from the total optical thickness the Rayleigh and the ozone optical depth for each channel, $\tau_R(i)$ and $\tau_O(i)$. The same equation and Dobson table is used for the data processing of all the sun photometers.
7. Compute the aerosol optical thickness (AOT), $\tau_A(i)$.

Several AOT measurements have been performed on the roof of a building at GSFC (from August to December 1998), from cruises during several campaigns and from ground, allowed performance comparisons with SeaWiFS sensor (Wang et al., 1999).

Calibration Round Robin

NASA personnel carried out the first SeaWiFS-SIMBIOS Intercalibration Round-Robin Experiment (SIRREX-6) from August 1997 to February 1998. SIRREX-6 was performed in a completely different manner from SIRREX-1 through SIRREX-5. In those tests, laboratory references were brought to a central location and tested against one another. In SIRREX-6, the same four common field instruments (e.g., Satlantic in-water radiometers) were taken to nine separate laboratories and tested using the laboratories' standards and procedures. Two of the sensors were seven-channel radiance heads and two were seven-channel irradiance heads. The calibration and data reductions procedures used at each site followed that laboratories' normal procedures. The reference lamps normally used for the calibration of these types of instruments by the various laboratories were also used for this experiment. NASA personnel processed the data to produce calibration parameters from the various laboratories for comparison. These tests showed an overall agreement at better than the +/-2% level. Test equipment, calibration procedures, data reduction, and specific handling procedures have been published in the Riley and Bailey (1998).

SXR-II

The first SeaWiFS Transfer Radiometer (SXR) was built for the SeaWiFS Project to verify and compare measurements of spectral radiance at six discrete wave-lengths in the visible and near infrared Johnson et al. (1998). In addition SXR is used to compare these sources to standards of spectral radiance maintained at the National Institute of Standards (NIST). SIMBIOS project had a second copy of the SeaWiFS Transfer Radiometer (SXR-II) built for use in the calibration round robin. This unit will supplement the first unit and is designed for easier travel. The SXR-II is currently being characterized and calibrated. It will be used in future SIRREX round robin experiments.

Additional SQMs

NASA developed a portable optical calibration source called the SeaWiFS Quality Monitor (SQM) with NIST. Last year, NASA provided limited financial support for the development of the SQM as a commercial product. Two companies elected to take advantage of the opportunity, Satlantic Instruments and Yankee Environmental Systems, Inc. The Satlantic version was evaluated by Dr. Stan Hooker.

The Yankee Environmental Systems, Optical Calibration Source prototype was evaluated at GSFC by Tom Riley. Their computer interface is a significant improvement over the earlier models. A number of small problems were uncovered and reported back to the manufacter who has taken corrective action.

4.4 SIMBIOS COMPUTING RESOURCES

The SIMBIOS computing facility contains many different types of equipment (Diagram 3). The main goal of the facility is to provide support for the following areas: 1) routine bulk data processing, 2) large scale analysis and match-up between sensors, 3) focused analysis on data subsets, and 4) storage of large sensor data sets.

To support these efforts, the facility has grown to include two large server systems, a 6 terabyte tape library, four desktop workstations, and numerous personal computers and printers. Co-location of the facility with the SeaWiFS Project has also made available other resources such as high-quality color printers, network equipment, and other supporting equipment. Large scale tasks such as bulk data processing and large scale analysis tasks are performed by two Silicon Graphics (SGI) Origin 2000 servers. To prepare for increased workload, the systems were upgraded to 6 processors each, and approximately 3 gigabytes (GB) of RAM. The influx of large data sets for additional sensors requires increasing amounts of space, especially when performing comparative analysis. The Data Processing server has been increased to 98 GB of disk, and the Data Analysis server has over 372 GB of total disk space. Long term storage of data sets is handled by the 6 terabyte (TB) tape library attached to the Data Analysis server.

Silicon Graphics O2 workstations are used for software development and more focused analysis tasks. The sizing of the workstations varies with the task requirements. One workstation has 320 megabytes (MB) of RAM and 28 GB of disk space, a second workstation has 640 MB of RAM combined with 72 GB of disk space. The third workstation has 640 MB of RAM and 50 GB of disk space. Acquisition of a fourth workstation is planned for this fiscal year.

SIMBIOS is connected to the Internet via a 100 megabit link, making network transfer of large data sets more feasible. Internal connections are also 100 megabit for rapid transfer of data between the servers and workstations. Data ingest for SIMBIOS is also done via removable media. The Project can read a wide variety of removable media including CD-ROM, 8 millimeter tape, 4 millimeter (DAT) tape, and DLT media up through DLT 7000.

Table 10. SIMBIOS Pool Instruments

Instrument	Quantity	Description	Manufacturer	Custodian(s)
MicroTops II Sunphotometer w/GPS	12	5 channel handheld sun photometer w/Garmin GPS-38	Solar Light Company	SIMBIOS Project
HISTAR Package	1	2 hyper-spectral absorption/beam attenuation meters mounted on a cage with a SeaBird CTD	WETLabs, Inc	Zaneveld/Pegau
Hydroscat 6	3	Backscattering meter	HOBILabs	Siegel Carder Mitchell
Pure Water System	3	Water purification system for calibration of WETLabs AC-9 and HISTAR absorption and attenuation meters	Barnstead	Zaneveld/Pegau
AC-9	3	Absorption/beam attenuation meter	WETLabs, Inc.	Cota Capone Muller-Karger
SIMBAD	2	5 channel radiometer and sun photometer		Frouin
SeaWiFS Multichannel Profiling Radiometer	2	Free-fall profiling radiometer measuring $L_u(z)$, $E_d(z)$, E_s, $L_u(1m)$ with cables, deck unit and PC with data acquisition and processing software	Satlantic, Inc.	Capone Chavez
Micropulse LIDAR	1	Continuous operation LIDAR system	SESI	SIMBIOS Project
Prede Sun Photometer	2	Automated ship-board sun photometer	Prede	SIMBIOS Project
CE 318 CIMEL Sun Photometer	12	Marine-hardened, automated sun photometer	Cimel	SIMBIOS Project

Table 11. Top of Atmosphere signals (V_0) of MicroTops, Simbad and Prede sun photometers determined by transfer calibration from a calibrated CIMEL at GSFC between August and December 1998.

MicroTops #3773	**440nm**	**500nm**	**675nm**	**870nm**	**940nm**
08/20/98 – Cimel # 37	1236.95±0.78	980.63±1.37	1214.27±0.98	821.80±1.12	1419.70±1.22
08/21/98 – Cimel # 37	1243.64±1.92	989.01±1.48	1220.24±0.86	825.59±0.76	1420.55±1.80
10/16/98 – Cimel # 27	1216.46±0.91	970.49±0.89	1187.49±0.77	822.38±0.58	1400.10±0.55
11/24/98 – Cimel # 27	1219.75±0.45	976.43±0.46	1191.42±0.34	821.64±0.61	1401.36±0.75
MEAN	1229.20	979.14	1203.35	822.85	1410.43
STD %	1.07	0.79	1.35	0.22	0.79
Simbad #972306					
08/20/98 – Cimel # 37	393564.40±1.89	482820.40±1.07	403245.16±0.35	420247.88±0.84	307582.92±0.59
08/21/98 – Cimel # 37	393525.05±3.13	481855.71±1.02	407705.35±0.41	423453.93±1.03	305498.45±0.56
10/16/98 – Cimel # 27	381894.63±1.25	469676.76±0.99	393682.49±1.82	409544.15±0.56	306692.23±0.98
11/24/98 – Cimel # 27	392974.50±0.89	477633.99±0.97	409380.37±1.16	412874.93±0.41	307275.49±0.17
12/14/98 – Cimel # 101	386234.51±0.95	471653.55±0.37	393092.41±0.21	409462.25±0.51	310487.83±0.22
MEAN	389638.62	476728.08	401421.16	415116.63	307507.39
STD %	1.36	1.24	1.91	1.54	0.60
Prede #PS090063					
08/20/98 – Cimel # 37	1.52E-04±3.38	2.86E-04±1.43	3.59E-04±2.22	2.81E-04±0.36	2.84E-04±2.63
08/21/98 – Cimel # 37	1.48E-04±1.13	2.84E-04±1.45	3.57E-04±1.75	2.81E-04±0.45	2.92E-04±2.30
MEAN	1.50E-04	2.82E-04	3.58E-04	2.81E-04	2.88E-04
STD %	1.48	0.51	0.27	0.11	1.87

Table 12: Slope (δp), intercept (p_0) and linear squared fit applied to the polarization rate given by the device and plotted versus the polarization rate measured by six polarized CIMEL sun photometers.

Instrument #	δp	p_0	R^2
92	1.1088	-0.1051	0.9996
25	1.2256	-0.0523	0.9977
111	1.0791	0.0476	1
45	1.0608x	0.2354	0.9998
43	1.1935x	- 0.7816	1
14	1.1665	-11.179	0.9993

Diagram 1. Sun photometer transfer calibration

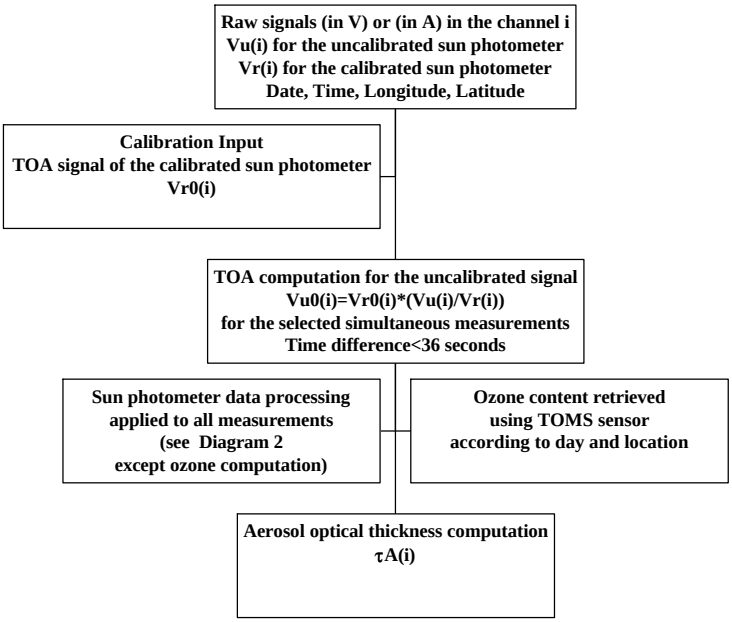
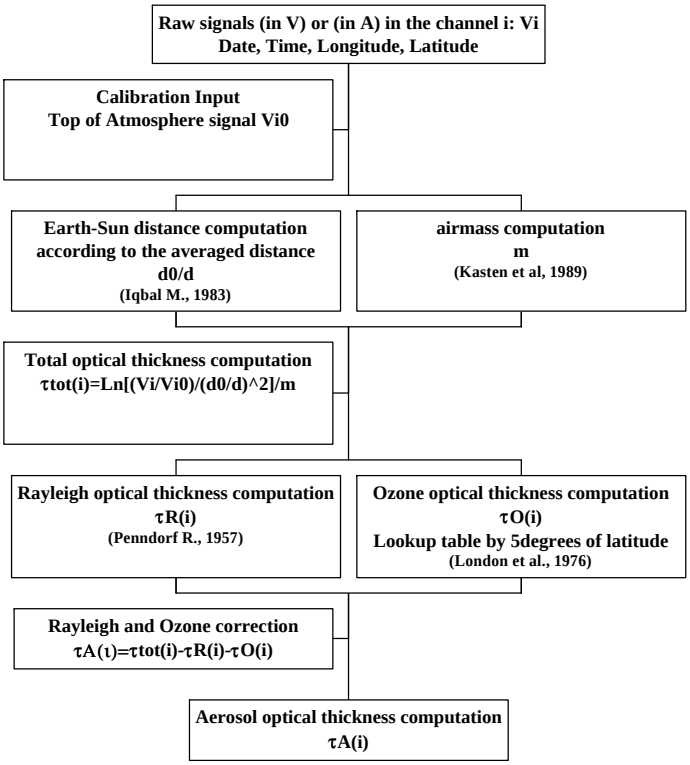


Diagram 2. Sun photometer data processing



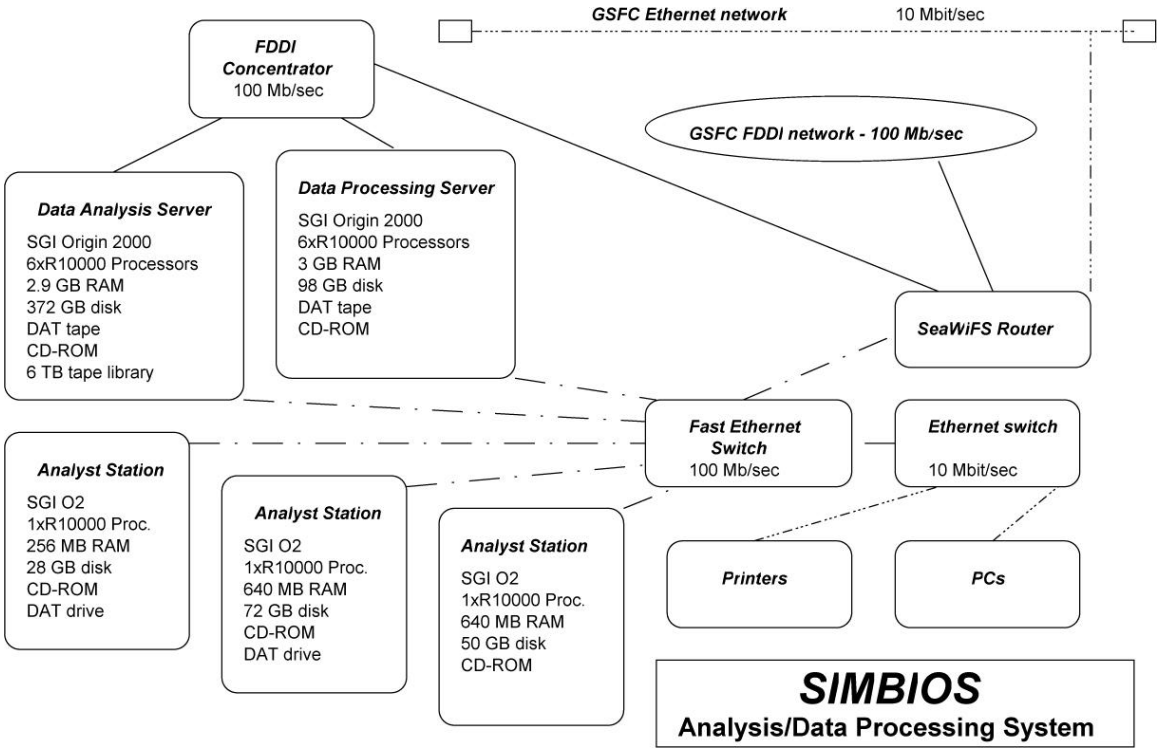


Diagram 3. SIMBIOS Analysis/Data Processing System

Chapter 5

Validation of Surface Bio-optical Properties in the Gulf of Maine as a Means for Improving Satellite Primary Production Estimates

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5.1 INTRODUCTION

There is a strong need to have sea-truth optical data in order to evaluate remotely-sensed ocean color. Our SIMBIOS contract is to use the M/S Scotian Prince ferry as a ship of opportunity, running between Portland, Maine and Yarmouth (NV). While the Gulf of Maine is cloudy and foggy more than it is clear; the climatology shows on average, about 1 in 4 days is completely clear and clear days are slightly more frequent in the late summer and early fall months. A ship of opportunity program (where one has choice of the days of sampling) provides much better flexibility to sample during clear periods with good satellite coverage. Measurements include continuous, surface, along-track fluorescence, light scattering, absorption, beam attenuation, above-water remote sensing reflectance, calcite-dependent light scattering, temperature, and salinity. Expendable Bathythermograph (XBT) drops allow acquisition of vertical temperature information, useful for defining isopycnal slope, which affects primary production. These data are comparable to a previous program from early 1982, where a Ship Of Opportunity Program (SOOP) was run on the truck ferry, M/V Marine Evangeline, which ran along the same transect (Boyd, 1985). These surface data were combined with satellite-derived sea surface temperature fields to examine the Maine coastal current (Bisagni et al., 1995). Unfortunately, this program stopped in 1982. The ongoing SIMBIOS results will dovetail nicely with the previous work (which also had CZCS coverage) for looking at any long-term changes in the Gulf of Maine hydrography or bio-optics.

The Gulf of Maine is an ideal site for gathering sea-truth optical data. It is a semi-enclosed basin with an average depth of about 150m. Isopycnal slope (and productivity) appears to be strongly topographically driven, with the water column becoming isothermal at the 60m isobath around Georges Bank. Integrated productivity in the region varies seasonally by a factor of 45x (0.1 to 4.4 gC m^{-2} d^{-1}; O'Reilly, 1987), greater than in the California Current (15x variability; 0.2-3.0 gC m^{-2} d^{-1}). The Marine resources Monitoring Assessment and Prediction (MARMAP) database along the eastern seaboard of the U.S. has been the equivalent to the California Cooperative Oceanic Fisheries Investigation (CalCOFI) database (West Coast) in terms of its sheer size and length of sampling. However, MARMAP does not maintain pigment or inherent optical property data. This SIMBIOS project attempts to provide this unique data for the region.

5.2 RESEARCH ACTIVITIES

We participated in several field cruises to field test equipment, and collect data. We have completed the following field activities:

- June '98-Second set of sea trials of sampling and underway system in the Gulf of Maine and Georges Bank (11d cruise).
- September-October '98-Eleven cruises aboard M/S Scotia Prince completed.

Real time enumeration of coccolithophores is essential to this work (as well as cell counts done after the cruise). We have an Olympus BH2 microscope with epi-fluorescence and polarization optics which allows us to quantify birefringent $CaCO_3$ coccoliths, empty coccospheres, and fluorescing, plated coccolithophore cells on board the ship. Due to limited time at each station, only about two samples typically can be enumerated. However, counts are recorded on video, which provides an important record for post-cruise comparison to the preserved counts, as well as for any retrospective analyses. We take preserved cell count samples at all stations (preserving with 4% buffered formalin) and, after the cruise, measure the concentration of detached coccoliths and plated coccolithophores (Utermöhl, 1931 and 1958).

The technique of Fernandez et al. (1993) is used to measure $CaCO_3$ concentrations. Briefly, samples are filtered onto 0.4μm polycarbonate filters, and rinsing first with filtered sea water, then borate buffer

(pH=8) to remove seawater calcium chloride. Filters are placed in trace metal free centrifuge tubes with 5 ml 0.5% Optima grade Nitric acid. Next, the Ca concentration is measured using graphite furnace atomic absorption spectrometry. The sensitivity of the technique, after correction to the volume of seawater filtered, is about 2ng Ca l^{-1}.

Particulate organic carbon and nitrogen are measured according to Sharp (1974; 1991). One liter sample bottles will be emptied via tygon tubing, through in-line pre-combusted glass fiber filters. Low vacuum will be maintained during filtration. These filters will be placed in plastic petri dishes using clean forceps, and stored at -20°C. Prior to running the samples, they will be fumed over HCl to remove any carbonates, then dried in a dessicator, and shipped on dry ice to the Bermuda Biological Laboratory for analysis. Chlorophyll is measured fluorometrically according to Strickland and Parsons (1972) and modified according to Joint Global Ocean Flux Study (JGOFS) (1996) which involves filtering 200 ml seawater with Gelman GFF filters, extracting overnight at 4°C in 10 ml of 90% acetone, and measuring fluorescence with a Turner 111 fluorometer.

We locate high densities of coccolithophores in the field with a flow-through system which estimates suspended $CaCO_3$ using an optical technique. A Wyatt Technologies laser-light scattering photometer (equipped with a flow-through cell) is used to measure optical volume scattering at 18 angles. Integration of this signal in the backward direction allows calculation of backscattering in real time. A pump injects weak acid every 4 minutes to dissolve the $CaCO_3$, and then backscattering is re-measured. The difference between the total b_b and the acidified b_b is called the "acid-labile b_b," and is calibrated to suspended $CaCO_3$ concentrations. The acidified b_b represents backscattering due to organic matter (which can be calibrated to CHN measurements). This value can be converted to POC concentration using our POC-specific backscattering coefficients (Balch et al., 1999). The system monitors chlorophyll fluorescence, pH, temperature, salinity and 18-channel volume scattering (with and without $CaCO_3$). An AC-9 provides estimates of absorption and attenuation, which by difference, also provides scattering. A Global Positioning System is interfaced, as well. The flow-through system has been field-tested over carbonate banks off of Florida, which provided data over 3 orders of magnitude in acid-labile b_b. Such high concentrations of suspended $CaCO_3$ are found in the most dense coccolithophore blooms that we have ever visited. During the Arabian Sea expedition, as well as 5 recent Gulf of Maine cruises, the instrument ran virtually flawlessly over thousands of kilometers, providing a wealth of data on the distribution of particulate inorganic and organic carbon (Balch et al., 1999). The final cruise of this year was completed in October; the raw data have been worked up and distributed to the NASA SIMBIOS Project. Discrete samples for suspended calcite, POC, PON, and coccolith counts were also taken, and will be processed over the coming months.

5.3 RESEARCH RESULTS

We completed 33 days at sea in 1998, with 11 trips aboard the M/S Scotia Prince ferry (Table 1). Two of 11 trips were cloudy (82% were sunny). In the Gulf of Maine, where 28% of the time it is sunny, we have demonstrated that we take full advantage of ferry as a ship of opportunity. For the year, we have processed about 147 stations in the Gulf of Maine and Georges Bank, and provided continuous underway data along 5000 miles of ship track for SeaWiFS calibration. Below are summarized the main sampling activities:

- R/V Delaware 10-21 November 1997 R/V Delaware, Gulf of Maine and Georges Bank. Underway data analysis completed and submitted to SeaBASS database. Data collected: underway fluorescence, backscattering and calcite-dependent backscattering (510 nm; Wyatt light scattering photometer, absolutely calibrated with a glass standard), absorption, scattering (AC-9; SeaWiFS bands; recently calibrated), temperature, salinity. Discrete measurements at 27 stations of suspended calcite, POC/PON, chlorophyll, coccolith and coccolithophore concentration. Discrete cell counts and analytical analyses are still being processed.
- R/V Albatross 3-12 June 1998, Gulf of Maine and Georges Bank. Data collected: underway fluorescence, backscattering and calcite-dependent backscattering (510 nm), absorption, scattering (AC-9: SeaWiFS bands), temperature, salinity, L_w and Ed at SeaWiFS wavelengths measured with Satlantic SAS system. Discrete measurements at 28 stations of suspended calcite, POC/PON, chlorophyll, coccolith and coccolithophore concentration.
- M/S Scotia Prince on a total of 1l cruises (Table 1). Data collected: underway fluorescence, backscattering and calcite-dependent backscattering (510 nm; Wyatt light scattering photometer, absolutely calibrated with a glass standard), absorption, scattering (AC-9; SeaWiFS bands; recently calibrated), temperature, salinity. L_w and E_d at SeaWiFS wavelengths measured with Satlantic SAS system. Microtops sun photometer measurments performed for overpasses. Discrete measurements at stations of suspended calcite, POC/PON, chlorophyll, coccolith and coccolitho-

phore concentration. Discrete cell counts and analytical analyses being processed.

5.4 WORK PLAN

Our contract calls for 20 ferry trips next year. We anticipate no problem completing these trips since our laboratory container and sample arm are already completed and ready.

Moreover, we anticipate no problems in timely data work-up and submission as our processing software is now streamlined for post-cruise calibrations.

Table 1. Summary of cruises and *in situ* data collected.

Cruise Location	Cruise Name	Date	Fluorescence	Backscattering	Calcite-dependent backscattering	Absorption	Scattering	Temperature and salinity	MicroTops sun photometer Stations	Stations	Suspended calcite	Chlorophyll	POC/PON	Coccolith and Coccolithoph. Con.	Discrete cell count	L_w and E_d (Satlantic SAS)
Delaware, Gulf of Maine and George Bank	10d	10-21 Nov 1997	√	√	√	√	√	√		*27*	√	√	√	√	√	
Gulf of Maine and George Bank	11d	3-12 June 1998	√	√	√	√	√	√		*28*	√	√	√	√		√
Portland, Maine and Yarmouth (NV)	Ferry 1	10-11 Sept. 1998				√	√	√	√	*2*	√	√	√	√	√	√
Portland, Maine and Yarmouth (NV)	Ferry 2	16-17 Sept. 1998	√	√	√	√	√	√	√	*10*	√	√	√	√	√	√
Portland, Maine and Yarmouth (NV)	Ferry 3	17-18 Sept. 1998	√	√	√	√	√	√	√	*9*	√	√	√	√	√	√
Portland, Maine and Yarmouth (NV)	Ferry 4	28-29 Sept. 1998	√	√	√	√	√	√	√	*9*	√	√	√	√	√	
Portland, Maine and Yarmouth (NV)	Ferry 5	3-4 Oct. 1998	√	√	√	√	√	√	√	*10*	√	√	√	√	√	
Portland, Maine and Yarmouth (NV)	Ferry 6	4-5 Oct. 1998	√	√	√	√	√	√	√	*10*	√	√	√	√	√	
Portland, Maine and Yarmouth (NV)	Ferry 7	11-12 Oct. 1998	√	√	√	√	√	√	√	*10*	√	√	√	√	√	
Portland, Maine and Yarmouth (NV)	Ferry 8	12-13 Oct. 1998	√	√	√	√	√	√	√	*8*	√	√	√	√	√	
Portland, Maine and Yarmouth (NV)	Ferry 9	16-17 Oct. 1998	√	√	√	√	√	√	√	*9*	√	√	√	√	√	√
Portland, Maine and Yarmouth (NV)	Ferry 10	17-18 Oct. 1998	√	√	√	√	√	√	√	*9*	√	√	√	√	√	
Portland, Maine and Yarmouth (NV)	Ferry 11	18-19 Oct. 1998	√	√	√	√	√	√	√	*8*	√	√	√	√	√	

Chapter 6

OCTS and SeaWiFS Bio-Optical Algorithm and Product Validation and Intercomparison in U.S. Coastal Waters

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6.1 INTRODUCTION

The launch of the National Space Development Agency of Japan (NASDA) Ocean Color and Temperature Sensor (OCTS) in August 1996, and the launch of Orbital Science Corporation's (OSC) SeaWiFS in August 1997 signaled the beginning of a new era for ocean color research and application. The ocean color data provided by these satellites promises the ability to remotely evaluate and monitor 1) water quality, 2) transport of sediments and adhered pollutants, 3) primary production, upon which commercial shellfish and finfish populations depend for food, and 4) harmful algal blooms which pose a threat to public health and economies of affected areas. Accordingly, several US government agencies have recently expressed interest in using optical remote sensing in US coastal waters for these purposes.

The goal of this project is to evaluate the performance of standard bio-optical algorithms and validate satellite ocean color products derived from OCTS and SeaWiFS data in Case I and Case II coastal US waters. To accomplish this goal, *in situ* bio-optical observations were collected and analyzed. This document briefly describes the methods used in sample collection and analysis, and presents preliminary results obtained during the first year of the project. As a result of the failure of the Japanese satellite on June 30, 1997, and the consequent termination of the OCTS data stream, we have been unable to evaluate the performance of OCTS algorithms and data products.

6.2 RESEARCH ACTIVITIES

In-situ bio-optical data were collected during eight cruises in diverse US Case I and Case II waters along the Atlantic coast and in the Great Lakes since OCTS became operational in November 1996 (Table 1). Optical instruments were deployed on cruises to measure surface spectral downwelling irradiance, in-water spectral downwelling irradiance and upwelling radiance. Deployment of other instruments and the collection of bottle samples enabled additional measurements that included temperature, chlorophyll fluorescence, light scattering, quantum scalar irradiance, total suspended solids concentration, chlorophyll and pigment concentrations from fluorometric and High Pressure Liquid Chromatography (HPLC) techniques, and absorption coefficients of colored dissolved organic matter and particles. Although sampling strategies and instrument packages varied between cruises, a Biospherical Instruments Profiling Reflectance Radiometer (PRR) cage was typically deployed off the stern of the boat in conjunction with a reference surface unit with matching channels. The PRR cage contains a split PRR600s that measures seven channels of downwelling irradiance, seven channels of upwelling radiance, depth, tilt, roll, and temperature. A reference surface unit PRR610 that measures seven matched channels of surface downwelling irradiance was also used. PRR600s channels 1 to 6 are narrow band (10-nanometer [nm], full width half maximum [FWHM]) centered at 380 nm, 412 nm, 443 nm, 490 nm, 510 nm, and 555 nm, while channel 7 on the downwelling sensor and PRR610 measures broad band Photosynthetically Available Radiation (PAR) (400 to 700 nm). In addition, the PRR cage contains a 10-centimeter pathlength, 660 nm Light Emitting Diode (LED) -based SeaTech transmissometer, a Biospherical Instruments Quantum Scalar Profiling sensor (QSP200), a SeaTech light scattering sensor (LSS), and a WETLabs Wetstar chlorophyll fluorometer. Water is drawn through the fluorometer using a Sea-Bird pump running at 2,000 revolutions per minute. The data from these instruments are multiplexed through the PRR600s such that each record contains a depth and the parameters from every instrument.

In some cases, a Hydro-Optics, Biology, and Instrumentation Laboratories, Inc. (HOBI Labs) Hydro-

Scat-6 spectral backscattering sensor was lowered by hand following the deployment of the PRR cage. Typically, an along-track system was used to measure the position (latitude, longitude), time, course and speed of the vessel, temperature, and salinity. *In situ* temperature, salinity, and density were also measured at some stations with a Conductivity-Temperature-Depth (CTD) instrument. Water samples for chlorophyll biomass, particulate, and dissolved absorption were obtained from a separate cast using a Niskin array. Discrete water samples were collected following the PRR cast, from just below the sea surface using a Niskin bottle.

Bio-Optical Data Processing

The PRR optical data was processed using the Bermuda Bio-Optics Project (BBOP) processing software (Siegel et al, 1995c). The data were separated into upcast and downcast profiles and then binned to 0.5 meter bins. Spectral attenuation coefficients were calculated for the optical channels over a five point moving window. Subsurface downwelling irradiance and upwelling radiance were extrapolated to just below the surface using data from the top 3 meters. The HydroScat-6 data were processed using software provided by HOBI Labs, Inc. The data were despiked, in two passes using a difference threshold, and a moving average was calculated for these channels. These data were also separated into upcast and downcast profiles and then binned to 0.5-m bins.

For fluorometric chlorophyll *a* and HPLC pigment determinations, water samples are filtered through glass fiber. The chlorophyll *a* samples are cold extracted in 10 ml of 90% acetone (10% water) for 24 hours in the dark, and the biomass is determined fluorometrically with a Turner Designs fluorometer using the method of Yentsch and Menzel (1963). Filtered HPLC pigment samples are cut into small pieces, ground, and extracted in a 1.5 ml microcentrifuge tube with 1.5 ml 90% acetone and are placed in a freezer overnight. They are centrifuged at 0°C for 15 minutes, 0.5 ml is filtered through a Nalgene nylon syringe filter, the samples are diluted to 60% acetone with the addition of 0.25 ml water, and 0.5 ml is injected into the HPLC. A Hewlett-Packard 1050 Series HPLC with a Phenomonex Sphericlone ODS (2) reverse-phase column (250 mm x 4.5 mm with 5 µm particles) is used with a ternary gradient to separate and identify the photosynthetic pigments (Wright et al, 1991). On cruises that included along-track measurements, water from about one meter below the sea surface was pumped through a hose into a bucket in which a Hydrolab Datasonde 3 Multiprobe logger was immersed. The Datasonde was used to measure temperature, specific conductivity, and salinity. Data from many of these cruises are made available via cruise reports (Culver et al. 1998, Subramaniam et al. 1997a, Subramaniam et al. 1997b, Subramaniam et al. 1997c, Subramaniam et al. 1998), and also through a website at the NOAA Coastal Services Center (http://www.csc.noaa.gov/crs/cruises/).

6.3 RESEARCH RESULTS

Our group has conducted eight cruises since the beginning of October 1996, including six cruises in the South Atlantic Bight (SAB), one in the Gulf of Maine, and one in the vicinity of Nantucket Shoals. Coverage of the SAB has been extensive due to productive collaboration with the NOAA Southeast Fisheries Science Center.

The SAB consists of a variety of environments including near-coastal and continental shelf regimes, the Gulf Stream, and the Sargasso Sea. Smooth transitions from low temperature waters with high pigment concentrations and attenuation coefficients, that are typical of nearshore environments, to the higher temperature waters with low pigment concentrations and attenuation coefficients, that are typical of offshore environments, are often disrupted by Gulf Stream eddies that appear on the continental shelf. The variability in the biological and optical characteristics of these regimes complicates temporal or spatial analyses of changes in, for example, phytoplankton species composition, primary production rates, colored dissolved organic matter (CDOM) concentration, suspended sediments, or temperature.

Coastal waters of the SAB can be classified as optical Case II waters. Data from the MAY97OB cruise (Subramaniam et al., 1998), on May 5, 1997 and May 8, 1997, indicate that the waters of Onslow Bay and especially Pamlico Sound were sediment-dominated. Data from the May cruise suggest that the OC2 algorithm (O'Reilly et al., 1998) over-estimated chlorophyll and pigment concentrations in these waters by a factor of at least 1.5 and up to 15. Chlorophyll *a* and total suspended solids concentrations in waters of the SAB during the APR98SAB cruise in April 1998 were highly variable. Chlorophyll *a* concentrations tended to be higher nearshore, and total suspended solids concentration showed no discernible geographic pattern, with high and low concentrations being measured at both nearshore and offshore stations. High attenuation coefficients for the blue wavelengths indicated the presence of high concentration of colored dissolved organic material near the coasts of South Carolina, Georgia, and Florida however, these high coefficients were not observed near North Carolina. Overall, the OC2 version 2 algorithm significantly over-estimated the chlorophyll *a* concentration by a factor of 4 and as much as a factor of 50, however, CZCS pigment concentration was estimated more successfully, with ratios of measured to estimated pigment ranging from 1 to 5.

Table 1. Summary of cruises.

Cruise Location	Date	Aircraft	Ship	Cruise Name
Southern California Bight	1/29/96 to 2/18/96	None	Jordan	JAN96CAL
Mid-Atlantic Bight	3/1/96 to 3/10/96	NASA P-3	Endeavour	MAR96OMP
South Atlantic Bight	4/22/96 to 4/26/96	None	Ferrel	APR96FER
New York Bight	5/13/96 to 5/16/96	None	Osprey	MAY96NY
Gulf of Maine	5/18/96 to 5/24/96	None	Gulf Challenger	MAY96ME
Lake Erie	8/26/96 to 8/30/96	None	R/V Bio Lab	AUG96GL
Beaufort, North Carolina	3/13/97 to 3/13/97	None	R/V Onslow Bay	MAR97OCC
Coastal North Carolina	5/5/97 to 5/8/97	None	R/V Onslow Bay	MAY97OB
Gulf of Maine	6/3/97 to 6/10/97	None	Gulf Challenger	JUN97ME
South Atlantic Bight	9/6/97 to 9/24/97	None	Cape Hatteras	SEP97SAB
South Atlantic Bight	11/4/97 to 11/6/97	None	R/V Palmetto	NOV97SAR
South Atlantic Bight	4/5/98 to 4/27/98	NOAA Twin Otter	Cape Hatteras	APR98SAB
Nantucket Shoals	7/6/98 to 7/10/98	None	Gulf Challenger	JUL98NAN
South Atlantic Bight	10/28/98 to 11/25/98	None	Cape Hatteras	NOV98SAB

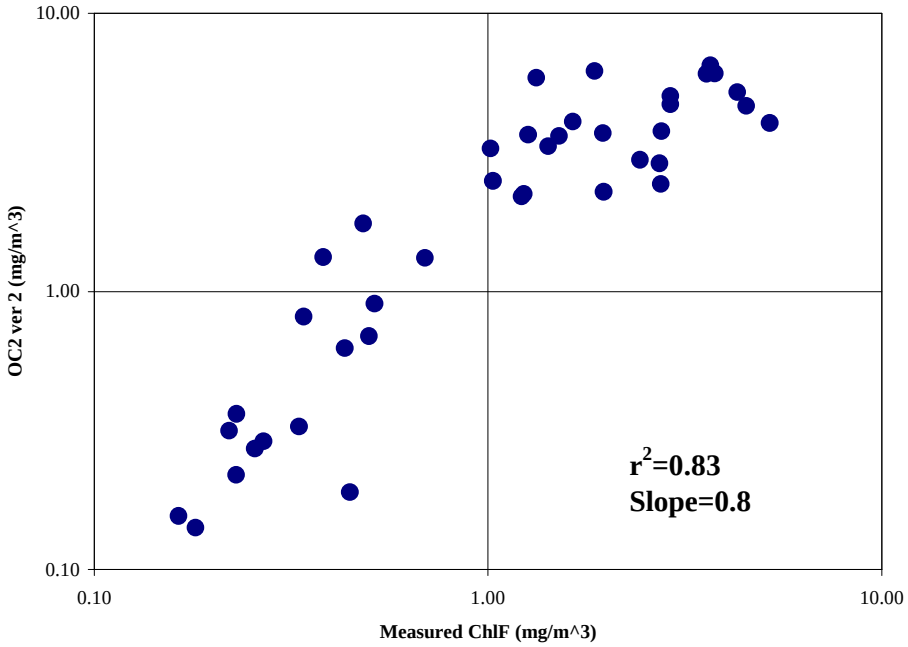

Figure 1. OC2 version 2 vs. fluorometric chlorophyll.

The results of cruise NOV97SAR (Culver et al, 1998), conducted from November 3 to 5, 1997, show that the OC2 algorithm performs reasonably well at stations well off-shore, although, in general the algorithm tends to over-predict chlorophyll concentrations in coastal waters. Also, we found good agreement between our *in situ* optical measurements of normalized water-leaving radiance and that measured by the SeaWiFS sensor. We interpret this to mean that our *in situ* measurements are of good quality, and that our goal of validating satellite chlorophyll algorithms using these measurements is reasonable and tractable.

The consistent overestimation of chlorophyll *a* concentration in the SAB by the standard algorithms is likely due to the influence of sediments and CDOM on ocean color. Preliminary analysis suggests that sediment may be the dominant factor near North Carolina, and CDOM may be the dominant factor for the southern waters.

When these components do not covary with chlorophyll *a*, the algorithms will overestimate chlorophyll *a* concentration. The agreement between our *in situ* optical measurements of normalized water-leaving radiance and that measured by the SeaWiFS sensor indicate that a chlorophyll algorithm for these waters is tractable, however, the coefficients will require adjustment to compensate for the effect of sediment and CDOM on the radiance measurements. Overall, our results show that it is necessary to establish empirical bio-optical relationships for separate coastal regions, such as the SAB.

There is a reasonable relationship between the OC2 algorithm-derived chlorophyll concentration and the fluorometrically measured chlorophyll concentration in the SAB (Figure 1). Small changes in the power equation coefficients should yield a better regional algorithm for the SAB. The relationship between HPLC-derived chlorophyll a and the OC2 algorithm is not as robust and requires further study.

6.4 WORK PLAN

The project plans to complete three additional cruises in the SAB during October 1998 through September 1999 in order to collect a more complete data set using our established sampling protocol. Given that analyses thus far have demonstrated that the OC2 Version 2 algorithm estimates of chlorophyll a concentration for SAB waters exceed acceptable error limits, our project will strive to develop a region-specific algorithm for SeaWiFS for these waters. During the recent NOV98SAB cruise, in addition to the deployment of the NOAA CSC PRR600, a Satlantic free falling profiler (SPMR), the SIMBAD, and an above water hyperspectral Spectrex instrument were used to obtain water leaving radiance data. This coincident multiple instrument data set will be used to compare the efficacy of each instrument in coastal Case II waters. In response to the observation that erroneous negative radiances occur in SeaWiFS data at 412 nm band, especially in late spring/early summer, sunphotometer data will be used to determine the suitability of the standard atmospheric correction algorithms for the SAB.

ACKNOWLEDGMENTS

We sincerely thank Drs. A. Subramaniam and M. Culver for their invaluable assistance in this project. In addition to collection and analysis of the data, they reviewed and suggested improvements in a previous version of this Technical Memorandum.

Chapter 7

Validation of Ocean Color Satellite Data Products in Under-Sampled Marine Areas

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7.1 INTRODUCTION

The marine diazotroph, *Trichodesmium* is a planktonic cyanobacterium which occurs throughout the tropical and sub-tropical oligotrophic seas. It can form large blooms and is thought to be responsible for the major fraction of N_2 fixation in the pelagic zone of world's oceans. The total rate of N_2 fixation by this organism has been thought to be about 10 Tg annually. However, estimates of *Trichodesmium*'s contribution to total marine N_2 fixation are relatively crude and other independent estimates suggest a higher rate of marine N_2 fixation. The annual rate was derived by scaling an average trichome N_2 fixation rate with biomass abundance and distribution data largely taken from historical plankton surveys. However, there are unique difficulties in quantifying the biomass of a buoyant, colonial alga such as *Trichodesmium* and the quantitative accuracy of many of these surveys are suspect. One of the most appealing prospects of using satellites in biological oceanography has been the potential to derive flux estimates from inventories of standing stock calculated from changes in optical properties of the ocean. Using algorithms to estimate global distributions of *Trichodesmium* biomass, we can calculate nitrogen fixed by this organism, and hence model its contribution to new production in the world oceans. Towards this goal, we proposed to use a previously developed hyperspectral optical model for the *Trichodesmium* to construct sensor specific biomass algorithms.

The goal of our proposed work was to develop sensor specific algorithms to quantify the biomass of *Trichodesmium* in the world oceans. The specific objectives of our proposal were to:

- Use a hyperspectral optical model for *Trichodesmium* to derive sensor specific *Trichodesmium* chlorophyll algorithms.
- Constrain and validate these algorithms using field measurements. Also use the field measurements to validate standard chlorophyll algorithms.
- Estimate the error in using standard algorithms to estimate chlorophyll in a *Trichodesmium* bloom. Develop flags for switching algorithms if necessary.

We were required by our contract to acquire and process data from at least one cruise per year. The data included measurements of vertical profiles of spectral downwelling irradiance, upwelling radiance, spectral attenuation and remote-sensing reflectance calculated from the profile data, photosynthetically active radiation, primary productivity, and concentrations of chlorophyll a and other pigments. We were required to purchase and make available to the instrument pool, an AC-9 instrument and a turnkey free-fall profiling radiometer system. Here we outline our progress during the first year of our SIMBIOS project to develop an algorithm for detection and quantification of *Trichodesmium* biomass for the SeaWiFS sensor. We also describe our field program for validating the OC2 algorithm and obtaining *in situ* bio-optical data in under-sampled marine areas.

7.2 RESEARCH RESULTS

The work detailed below is of an effort in progress and intended to provide an interim update to the SIMBIOS project. Our initial approach was to derive a *Trichodesmium* chlorophyll specific algorithm from an optical model, and then constrain this algorithm based on field data. Our optical model detailed in Subramaniam et al. (1999) showed that at low concentrations, *Trichodesmium* does not have singular enough optical properties to be uniquely identified (Figure 1). But as the concentration of *Trichodesmium* in the water column increases, its optical properties dominate and it is possible to identify and quantify

this organism (Figure 1). Therefore, we initially decided to develop a branching algorithm, where at low *Trichodesmium* concentrations the algorithm produced total chlorophyll (i.e. not *Trichodesmium* specific), but at higher *Trichodesmium* concentrations the algorithm resulted in *Trichodesmium* specific chlorophyll. We formulated the algorithm as (R_{555}-R_{490}/R_{510}) where R_{555}, R_{490}, R_{510} are the SeaWiFS remote sensing reflectance corresponding to bands 3, 4 and 5 respectively. We parameterized this formulation by fitting a power equation to the results of the previously developed remote-sensing reflectance based hyperspectral optical model for *Trichodesmium*. However, we were not satisfied by the results of this formulation and have been working on other approaches and band combinations.

Although the branching algorithm approach is very attractive for producing global maps of *Trichodesmium* abundance based on a sound theoretical model, it is essential to characterize the chlorophyll concentration threshold where the algorithm results in *Trichodesmium* specific chlorophyll concentration. The optical model suggested that this threshold was about 0.5 mg/m^3 *Trichodesmium* Chl *a*. While we did not encounter such high concentrations of *Trichodesmium* during the Trichonesia cruise, preliminary analysis of field data from a cruise in the South Atlantic Bight shows that this threshold is probably much higher – around 3 mg/m^3. We need more field data with *Trichodesmium* cell counts to characterize this threshold. In the meantime we have developed a flag to study global occurrence of *Trichodesmium* blooms. This flag is based on the combination of high reflectance at 555 nm, and absorption at 490 nm. We are comparing this to climatological data on *Trichodesmium* occurrence - in regions and seasons where *Trichodesmium* is known to occur historically. We think we are very close to completing an initial *Trichodesmium* chlorophyll algorithm and will communicate it to the SIMBIOS office as soon as we are satisfied with it.

Our 1998 field campaign was a 35-day research cruise in the South Western Pacific ocean. We left Lyttleton, New Zealand on the 24 March 1998 and arrived in Suva, Fiji on the 30 April 1998. We had requested cruise time in January-February when the organism is most abundant in this region. However, due to ship availability, our cruise was pushed to April. This, in combination with the effects of the El-Nino, resulted in our encountering lower *Trichodesmium* populations than we had anticipated. After our port call in New Caledonia on 30 March, we had to head north to avoid Cyclone Zumann. Thus we were under overcast skies during the portion of the cruise with some of the highest chlorophyll concentrations. In total, we occupied 51 stations and made 33 optics deployments including 2 diel deployments for Inherent Optical Property measurements. The *in situ* optical data, chlorophyll concentrations, and carbon and nitrogen fixation rates have been submitted to SeaBASS.

We acquired a Wetlabs AC-9 in January 1998. This instrument was field tested during a SIMBIOS cruise (CALCOFI 9802) and recalibrated after that cruise. This instrument was used on the Trichonesia cruise and is now available at CBL.

A Satlantic SeaWiFS Profiling Multispectral Radiometer (SPMR) with a matched SeaWiFS Multispectral Surface Reference (SMSR) was procured in March 1998. The SPMR is a 13 channel free falling profiler that measures *in situ* downwelling irradiance (Ed^-) and upwelling radiance (Lu^-) at 340, 380, 412, 443, 490, 510, 520, 555, 565, 619, 665, 670, and 683 nm. The SMSR is a floating reference that measures downwelling irradiance (Ed^+) just above water and upwelling radiance (Lu^-) 70 cm below the surface. The SPMR includes a 300-m power telemetry cable, 2 axis tilt sensors, and external temperature and conductivity sensors. The SMSR includes a 100-m power telemetry cable and 2 axis tilt sensors. The package includes a deckbox with computer interface and power supply, data logging and display software, and a Hitachi pentium laptop computer with an extra PCMCIA serial card and cables.

The SPMR was used on the Trichonesia cruise in March-May, on NOAA cruises in July and November, and a CALCOFI cruise in September. Initially there were problems with gain switching and some data from the Trichonesia cruise and JUL98NAN cruise were compromised because of this. This has been subsequently fixed by Satlantic. The instrument has been recalibrated twice at Satlantic and twice at UC Santa Barbara since March 1998. It has been shipped to the Indian Ocean for use in the Indian Ocean Experiment (INDOEX).

7.3 WORK PLAN

We will continue to work on refining the *Trichodesmium* algorithm. Specifically we will analyze the field data collected during the Trichonesia (1998) and INDOEX (1999) cruises to define the *Trichodesmium* specific chlorophyll concentration that can be detected by the algorithm and test the sensitivity of the algorithm. We will work on algorithms specific to the OCTS, the MOS, and the MODIS sensors. We will participate in the INDOEX cruise in March 1999 and a cruise off northern Australia in October 1999.

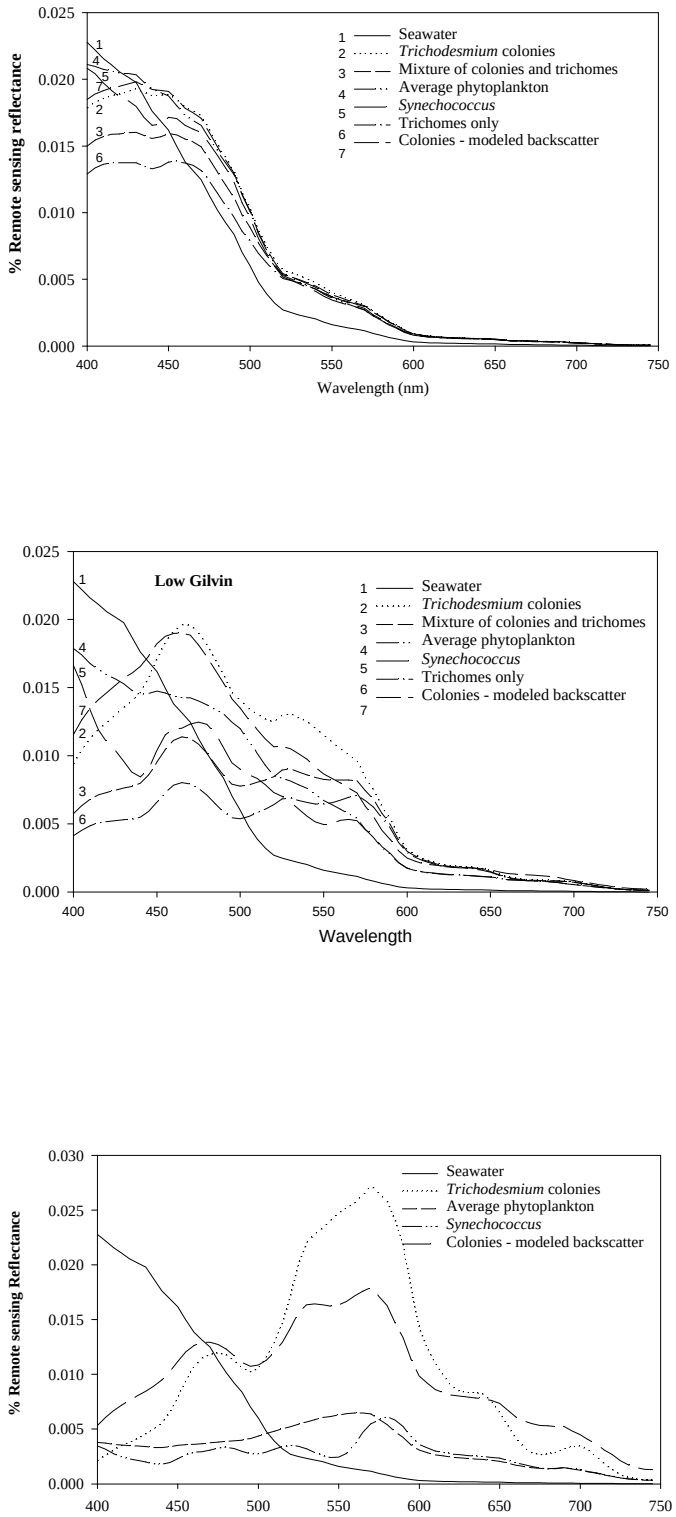

Figure 1. Optical model of *Trichodesium* remote sensing reflectance for a) 0.1 mg Chl/m^3, b) 1.0 mg Chl/ m^3, and c) 10.0 mg Chl/ m^3.

Chapter 8

Stray Light and Atmospheric Adjacency Effects for Large-FOV, Ocean-Viewing Space Sensors

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8.1 INTRODUCTION

The radiance of dark targets (e.g. oceans and lakes) when measured by large-field imagers such as MODIS and SeaWiFS can be enhanced by stray light within the sensor and by radiance atmospherically scattered from bright, adjacent targets. One of the goals of this project is evaluation of this stray light and estimation of its effect on derived products of remote color imagery.

8.2 RESEARCH ACTIVITIES

The first year of this project focused on collecting field data to evaluate the performance of SeaWiFS. To assure field data quality, a significant effort was expended in characterizing and calibrating field instruments as well as standardizing field methodology. Field sites were selected where adjacency artifacts would be likely. One site is a deep ocean canyon surrounded by bright carbonate banks, the Tongue of the Ocean (TOTO); another is Lake Okeechobee, Florida where dark water is surrounded by bright vegetation. With funding from other sources, additional field experiments were applied to this study and help with evaluation of SeaWiFS performance. These included sampling on Tampa Bay, the West Florida Shelf, Exuma Sound, the San Juan Islands in Puget Sound, and Lake Tahoe.

8.3 RESEARCH RESULTS

The degradation of SeaWiFS infrared bands, which are used to evaluate the type and amount of aerosol path radiance, caused a perturbation in the type of aerosol correction to be made by the SeaWiFS atmospheric correction scheme. This resulted in over estimation of the blue-richness of the aerosol scattering. Furthermore, high cirrus clouds have a tendency to exaggerate this effect, due to enhanced aerosol absorption in the oxygen band near 762 nm. To obviate the worst effects of both problems, we developed an aerosol-typing algorithm using bands 6 and 8 over clear waters. This approach forced the calibration of band 6 relative to band 8 to provide normalized water-leaving radiance values at band 6 consistent with the Gordon and Clark (1981) for scenes with known aerosol type. For scenes of unknown aerosols, the new 6-8 band combination delivered appropriate aerosol types with SEADAS. This prevented blue exaggeration of the aerosol type and prevented excessive removal of blue radiance from the scene, which otherwise would have resulted in blue-poor water-leaving radiance values. This approach provided atmospherically corrected scenes that did not became negative at blue wavelengths for gelbstoff-rich (blue-absorbing) areas. This approach also provided clear water, normalized water-leaving radiance values at 555 nm consistent with Gordon and Clark (1981) using the calibration factors distributed by the SeaWiFS Project on 6 January 1998. Furthermore, it provided a data distribution for clear waters using ratios of bands 1 and 2 versus bands 2 and 5 that are consistent with those found by Carder et al. (1999) using the SeaBASS in situ data set.

Using the above calibration scheme, SeaWiFS images of the TOTO, the West Florida Shelf, and regions between were compared to field data using the default NASA chlorophyll algorithm and the Carder et al. (1999), MODIS-like, semianalytic chlorophyll algorithm. For these spring scenes, the pigments were somewhat packaged with little in the way of photoprotective pigments. Both algorithms performed similarly (within 5%) for Case 1 waters. When gelbstoff absorption overwhelmed the pigment absorption, however, the semianalytic algorithm delivered chlorophyll values within 25% of measured values; while the default NASA algorithm overestimated chlorophyll by as much as a factor of 4. These scenes will be re-evaluated with the new calibration-degradation curves of SEADAS 3.2 during the next contract year, but the new results are not expected to deviate significantly from these results using the 6-8 band combination except for turbid waters.

In terms of evaluating atmospheric adjacency and stray light effects due to infrared radiance emanating from the bright foliage surrounding Lake Okeechobee

or blue-green light reflected from the bright shallow banks surrounding TOTO, our preliminary findings suggest the following:

- Lake Okeechobee has so much horizontal variability in the water-leaving radiance field at infrared wavelengths that it is at times an impractical site at which to evaluate stray infrared light from its surrounds. It does offer, however, so much gelbstoff absorption at 412 nm that we are considering performing atmospheric corrections based upon the blue end of the spectrum.

- Data we collected at the Friday Harbor Laboratory in the San Juan Islands suggest that this site provides a viable alternative to Lake Okeechobee for evaluation of stray infrared light and/or atmospheric adjacency effects. Hyperspectral Imager for Low Light Spectroscopy (PHILLS) aircraft data Curtis Davis (NRL) suggests that one can find a red-edge effect (exaggerated infrared light) in the water near sunlit tree lines in data collected at 10,000 feet and with visibility in excess of 50 km. These data will be evaluated next year along with SeaWiFS data collected at high resolution over Griffin Bay (San Juan Island) which is surrounded by forest land.

- Chlorophyll values farther than 2 pixels offshore and east from bright, shallow banks of the TOTO were not significantly different than those found farther offshore. Extreme caution must be taken, however, to avoid misinterpreting conditions where gelbstoff- and particle-laden waters from the shallows are transported offshore. Next year an evaluation of the electronic over-shoot, and/or hysteresis on the west sides of bright targets will also be evaluated on the eastern edge of the TOTO. More accurate calibration of the SeaWiFS sensor will help in this effort.

- A recently published paper by Reinersman et al. (1998) on calibration of aircraft and small footprint, spacecraft sensors using cloud shadows was dependent upon the development of a Monte Carlo model of radiance from single spherical clouds. This model is being modified to permit evaluation of atmospheric adjacency effects of clouds on radiance values received by a space sensor when viewing the ocean through an opening (elliptical cylinder) in a cloud bank. Algorithms that are more immune to the adjacency effects of clouds will be sought. Much of the light scattered into the sensor from clouds will be from molecules and stratospheric aerosols and thin cirrus clouds. A strategy using the effect of the oxygen absorption line on band 7 versus results from bands 6 and 8 may provide an indication of the effective height of any aerosol scattering for SeaWiFS, whereas MODIS has a cirrus discriminator built into its data processing scheme

8.4 WORK PLAN

The main goal of the project will remain the same, to evaluate stray light effects on derived products from ocean color imagery. Since MODIS and OCTS will not be available, the effort will be concentrated on SeaWiFS, Advanced Visible and Infrared Imaging Spectrometer (AVIRIS), and PHILLS.

The TOTO site will be visited in mid-April. It is planned to use PHILLS overflights of Griffin Bay, Tampa Bay, and the West Florida Shelf. The aircraft data will be used to refine techniques to detect atmospheric adjacency effects and bright infrared reflectance due to vegetation.

Chapter 9

Bio-Optical Measurements at Ocean Boundaries in Support of SIMBIOS

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9.1 INTRODUCTION

This project consists of a mooring program and supporting cruise-based measurements aimed at quantifying the spectrum of biological and chemical variability in the equatorial Pacific. The mooring program was designed to obtain continuous time series of biological and chemical properties on a time scale that is equivalent to measurements of currents, local winds and temperature structure.The project has the following general objectives:

- to understand the relationships between physical forcing, primary production, nutrient supply and the exchange of carbon dioxide between ocean and atmosphere in the equatorial Pacific;
- to describe the biological and chemical responses to climate and ocean variability;
- to describe the spatial, seasonal and interannual variability in near surface plant pigments, primary production, carbon dioxide and nutrient distributions, and
- to obtain near real-time bio-optical measurements to ground-truth satellite measurements of ocean color.

9.2 RESEARCH ACTIVITIES

Moorings

Bio-optical and chemical sensors were deployed on two moorings of the TAO array in the equatorial Pacific at 0°, 155°W and 2°S, 170°W. The following sensors formed the core set:

- A Biospherical PRR-620 located 3m above the water surface, to measure downwelling irradiance at 412, 443, 490, 510, 555, 656nm and PAR.
- A ΔpCO_2 system to measure the difference in partial pressure of CO_2 between ocean and atmosphere (supported by NOAA).
- Two Satlantic OCR-100s located approximately 1.5m below the surface, to measure upwelling radiance at 412, 443, 490, 510, 555, 670 and 683nm.
- Two Wetlabs miniature fluorometers at approximately 1.5m and 20m below the surface to measure stimulated *in vivo* fluorescence.
- Two Biospherical MCP-200s located at 10m and 30m below the surface to measure downwelling irradiance at 490nm.
- A Biospherical PRR-600 located 20m below the surface to measure downwelling irradiance at 412, 443, 490, 510, 555, 670nm and PAR, plus upwelling radiance at 412, 443, 490, 510, 555, 670 and 683nm.

Daily noon-time bio-optical data were delivered via service ARGOS in near real time to MBARI, and then via automated FTP to the SeaBASS database, after some processing and quality control. Higher frequency, publication-quality data (10 or 15-minute intervals) were recovered at approximately six month intervals, and sent to the SeaBASS database after processing and quality control. Some derived products, such as OC2V2 chlorophyll from surface upwelling radiances, and mean chlorophyll over the upper 20m of the water column (Morel, 1988) were included in these data files. Using simple algorithms derived from optical profile data the upwelling radiances measured by the moored radiometers have been converted to normalized water-leaving radiances (L_{wn}), for the SeaWiFS calibration/validation effort.

In addition to the two mooring installations described above, MBARI has also maintained smaller bio-optical packages at four sites in the equatorial Pacific: 2°N, 180°; 2°S, 140°W; 2°N, 140°W and 2°N, 110°W. These bio-optical packages produced measurements of downwelling incident irradiance at 490nm, upwelling radiance from ~1.5m depth at 412, 443, 490, 510, 555, 670 and 683nm, plus stimulated *in vivo* fluorescence. Data, including derived L_{wn} (see above) were delivered in near real time to MBARI and the SeaBASS database. A bug in the original software precluded collection of significant data prior to March of 1998.

In situ measurements

All cruises were undertaken aboard the NOAA ship *Ka'imimoana*, with the exception of GP6-98-RB aboard the NOAA ship *Ronald H. Brown* (Table 1). Essentially, the cruise-based measurements consisted of chlorophyll (using the fluorometric method described by Chavez et al., 1995) and nutrient profiles (8 depths, 0-200m) obtained at CTD stations between 8°N and 8°S across the Pacific from 95°W to 165°E. On selected cruises (primarily the 155°W and 170°W meridional transects), primary productivity measurements and optical profiles, using the Satlantic Profiling Multispectral Radiometer, were also performed. These data were archived at MBARI and the chlorophyll and optical profile measurements provided to NASA's SeaBASS database.

9.3 RESEARCH RESULTS

Chavez et al. (1998) describe the biological-physical coupling observed in the central equatorial Pacific during the onset of the 1997-98 El Niño. Figure 1 shows the time series of chlorophyll, SST and ΔpCO_2 from the mooring located at 0°, 155°W for the time period covering the peak of the 1997-98 El Niño and the subsequent recovery of the phytoplankton community. Our data from the four smaller bio-optical packages describe the physical and biological effects of the passage of Tropical Instability Waves. While the corresponding SeaWiFS data in large part agree closely with the mooring-derived chlorophyll concentrations, there are time periods where this is not the case. This may in part be due to the spatio-temporal averaging that is inherent in the SeaWiFS 9km/8-Day data. We have performed SeaWiFS chlorophyll comparisons with extracted chlorophyll concentrations for all of the 1998 equatorial Pacific cruises, with good agreement between the two data types.

9.4 WORK PLAN

During 1999 data collection will continue as for 1998. The two major mooring installations at 0°, 155°W and 2°S, 170°W are now operating well after some initial problems with damage and loss of instruments. The smaller bio-optical packages at four additional locations across the Pacific are also performing well and data collection at those sites, as described above, will also continue. The program of cruise-based measurements of chlorophyll, nutrients, primary productivity and bio-optical profiles will continue on up to eight equatorial Pacific cruises during 1999, with scheduled SeaWiFS LAC where possible, to enhance the probability of obtaining valid matchups.

The major data processing objective for 1999 is to automate the near real-time data provision to the SeaBASS database as much as possible to aid in the calibration/validation effort. In addition we aim to improve our data processing routines for the high resolution data that are downloaded from the 0°, 155°W and 2°S, 170°W moorings at approximately 6 month intervals. This should decrease the lag time between data download and provision of products to the SeaBASS database.

Table 1. Summary of cruises during which *in situ* data have been obtained by MBARI in support of SIMBIOS. All cruises were undertaken aboard the NOAA ship *Ka'imimoana*, with the exception of GP6-98-RB aboard the NOAA ship *Ronald H. Brown*. Meridional transects indicate the lines occupied by the ship. Along each line, CTD stations were performed approximately every degree of latitude from 8°N to 8°S. Measurements consisted of extracted chlorophyll (Chl) plus nitrate, phosphate and silicate (Nutrients) at 8 depths between 0 and 200m. On selected cruises, primary productivity (PP) measurements were also made using ^{14}C incubation techniques, and daily optical profiles with the Satlaintic Profiling Multispectral Radiometer (SPMR) were obtained. During GP7-98-KA, a SIMBAD radiometer was also used, on loan from the SIMBIOS instrument pool.

Cruise ID	Dates	Meridional transects	Measurements
GP6-97-KA	27-Sep-97 to 30-Oct-97	125°W and 140°W	Chl, PP, Nutrients, SPMR
GP7-97-KA	06-Nov-97 to 17-Dec-97	155°W, 170°W and 180°	Chl, PP, Nutrients, SPMR
GP1-98-KA	05-Feb-98 to 13-Mar-98	95°W and 110°W	Chl, Nutrients
GP2-98-KA	18-Apr-98 to 20-May-98	125°W and 140°W	Chl, Nutrients
GP3-98-KA	02-Jun-98 to 03-Jul-98	155°W and 170°W	Chl, PP, Nutrients, SPMR
GP4-98-KA	07-Jul-98 to 03-Aug-98	165°E and 180°	Chl, Nutrients
GP5-98-KA	05-Sep-98 to 09-Oct-98	125°W and 140°W	Chl, Nutrients
GP6-98-RB	11-Oct-98 to 13-Nov-98	95°W and 110°W	Chl, Nutrients
GP7-98-KA	19-Oct-98 to 13-Nov-98	155°W and 170°W	Chl, PP, Nutrients, SPMR
GP8-98-KA	18-Nov-98 to 12-Dec-98	180° and 170°W	Chl, Nutrients
GP1-99-KA	22-Jan-99 to 24-Feb-99	125°W and 140°W	Chl, Nutrients

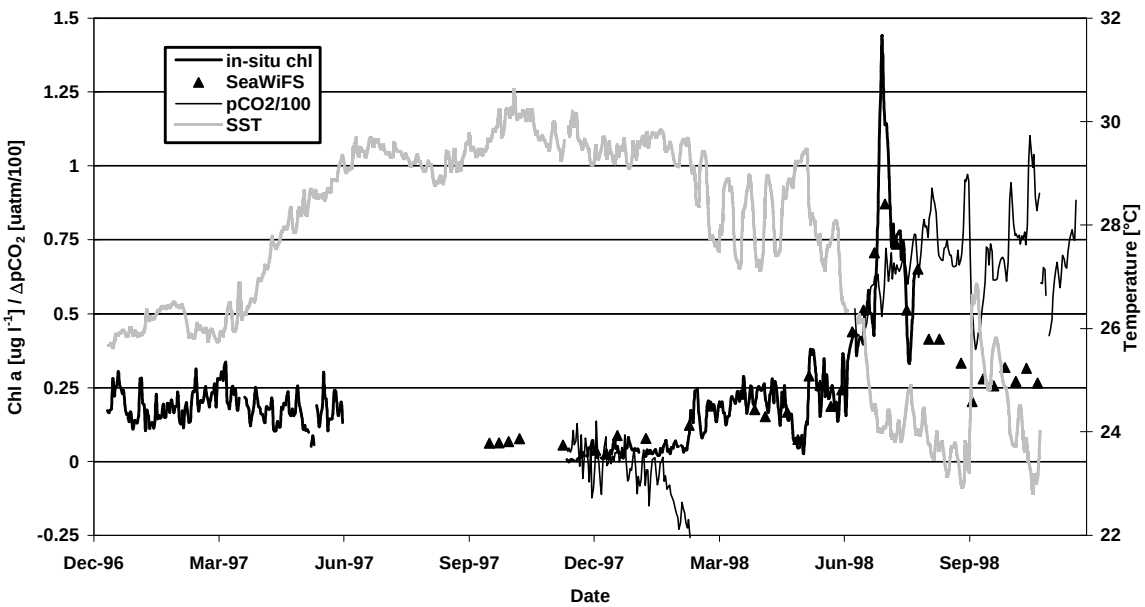

Figure 1. Time series of Sea Surface Temperature (SST – heavy shaded line), chlorophyll *a* averaged over the upper 20m of the water column from moored spectroradiometer data (heavy solid line) SeaWiFS OC2V2 chlorophyll (closed triangles) and ΔpCO_2 (thin solid line).

Chapter 10

Remote Sensing of Ocean Color in the Arctic: Algorithm Development and Comparative Validation

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10.1 INTRODUCTION

The Optical Research Consortium of the Arctic (ORCA) is a collaborative project between G.F. Cota of Old Dominion University (ODU), T. Platt and W.G. Harrison of the Bedford Institute of Oceanography (BIO), S. Sathyendranath of Dalhousie University and S. Saitoh of Hokkaido University. ORCA initiated bio-optical data collections in August, 1994 and has conducted 10 high latitude cruises in the Bering Sea (7/95 = Ber95, 7/96 = Ber96), the Labrador Sea (10-11/96 = Lab96, 5-6/97 = Lab97, 6-7/98 = Lab 98), the Gulf of Alaska (10/97 = Goa97), and in the Northwest Passage near Resolute Bay, NWT, Canada (8/94 = Res94, 8/95 = Res95, 8/96 = Res96, 8/98 = Res98). ORCA has now collected almost 500 in-water optical profiles and most of them have been submitted to NASA's SeaBASS database.

The ORCA program depends upon coordination and cooperation between international co-investigators with support from NASA, NASDA and Canadian sources. ODU has had primary responsibility for bio-optical and biogeochemical data collection with assistance from all collaborators. ODU has been responsible for data processing, distribution and submission to SeaBASS. Data analyses are being conducted by all co-investigators. Modeling is being done primarily by BIO and Dalhousie. Our algorithm development efforts encompass most of the potential data products listed for SeaWiFS, MODIS and GLI, and addresses product validation for a specific area of concern, i.e. high latitudes and coastal waters.

Observational suites depend primarily on field program duration, the sampling time, berths and personnel available. Longer, dedicated field programs (i.e. Resolute) include more comprehensive observations. Core observations always include in-water spectroradiometer profiles for apparent optical properties (AOPs) and discrete profiles of fluorometric chlorophyll. Absorption spectra for particulate, extracted particulates, and soluble materials are also available from most cruises. The observational suites for Resolute and the Labrador Sea are typically more comprehensive with in situ inherent optical property (IOPs) profiles (AC-9, Hydroscat-6: Resolute only), above-water spectral remote sensing reflectance $R_{rs}(\lambda)$, spectrophotometric and/or HPLC pigments, primary production and/or photosynthesis versus irradiance, inorganic nutrients, 15N-nutrient uptake, particulate organic carbon and nitrogen.

10.2 RESEARCH ACTIVITIES

From May, 1997 through August, 1998 four SIMBIOS validation cruises for OCTS or SeaWiFS were conducted with one on an early-start supplemental contract (Labrador Sea 5-6/97) and three under the main contract (Gulf of Alaska 10/97, Labrador Sea 6-7/98, and Resolute Bay 8/98). Our scheduled August, 1997 Resolute field program was cancelled because OCTS had failed and SeaWiFS was not yet operational.

Bio-optical, biogeochemical and experimental observations were made as frequently as logistical and weather considerations permitted. Data collections and processing for biogeochemical and optical observations conform closely to Joint Global Ocean Flux Studies (JGOFS, 1991) and SeaWiFS protocols (Mueller and Austin 1992, 1995).

Water column profiling consisted of a bottle or pump cast for discrete samples preceded or followed by optical casts. Discrete water samples were collected from standard depths and depths corresponding to features of particular interest such as fluorescence, beam attenuation and/or density maxima. Biogeochemical observations included fluorometric chlorophyll and phaeopigments, spectrophotometric (Resolute) or HPLC (Labrador Sea) pigments, absorption spectra of particulates, methanol-extracted particulates, and dissolved colored organic material (CDOM), inorganic nutrients, particulate organic carbon and nitrogen, and selected other observations such as total suspended matter and cell count samples. Experimental observations at Resolute and the Labrador Sea included ^{14}C and ^{13}C primary production and ^{15}N-nutrient uptake of nitrate and ammonium.

Optical stations include hand-held sun photometry and photographs of sea and sky conditions. In-

water optical observations were made with a Satlantic SeaWiFS Profiling Multichannel Radiometer (SPMR) and SeaWiFS Multichannel Surface Reference (SMSR). Downwelling irradiance $E_d(0^-,\lambda)$ and upwelling radiance $L_u(0^-,\lambda)$ were measured just below the sea surface at 13 wavebands with the SMSR sensors mounted on a floating, tethered buoy with an umbilical cable for power and data transmission. The SPMR also has 13 channels for vertical profiles of downwelling irradiance $E_d(z, \lambda)$ and upwelling radiance $L_u(z, \lambda)$, and was deployed in a free-fall mode with a kevlar cable for power and data transmission. The SPMR includes sensors for tilt and pitch, pressure, conductivity and temperature (Ocean Sensors), and fluorescence (WETLabs WetStar). The SMSR and SPMR measurements were always made concurrently and the sensors were deployed 20-100 m from the vessel to avoid ship-shadow effects. Above-water reflectance measurements of the sea surface were made with an Analytical Spectral Devices (ASD) Personal Spectrometer II (350-1050 nm, 1.4 nm bandpass,). Incident spectral irradiance $E_d(0^+,\lambda)$ was estimated with a gray Spectralon card (10% reflectance) and water-leaving radiance $L_u(0^+,\lambda)$ was corrected for reflected sky light (K. Carder and C. Davis, pers. Comm.). Spectrometers have been calibrated 1-2 times per year depending upon the number of field campaigns. Profiles of IOPs were measured with 1-2 WET Labs AC-9 absorption and beam attenuation meters with 9 channels and 25 cm path lengths for total and/or soluble constituents <0.2um. A HOBI Labs Hydroscat-6 was used to measure backscatter in 6 spectral bands. The latter three types of measurements were only made at Resolute.

AOPs, fluorometric chlorophyll and absorption spectra data from all cruises have been submitted to SeaBASS, except the Lab98 data set. The downwelling irradiance E_d sensor malfunctioned during Lab98, and the data processing will require modifications of Satlantic software or estimation of normalized water-leaving radiance L_{wn} from models. Additional ancillary data are also being submitted as they become available from our lab and collaborators.

10.3 RESEARCH RESULTS

High northern latitude waters have unique bio-optical properties compared with temperate data and models (Sathyendranath et al. 1999b). These waters have a large dynamic range of biomass, which must be considered in algorithm development.

Results to date reveal that diatoms usually dominate phytoplankton assemblages, but prymenesiophyte blooms may alter bio-optical signatures (Sathyendranath et al. 1999a). The relatively large diatom cells are highly packed with high chlorophyll-specific attenuation in the blue. Regional differences have been found in soluble attenuation with the highest values in the Canadian Arctic Archipelago. Blue-green band ratio algorithms provide reasonable chlorophyll and net daily primary production retrievals when properly tuned for high latitudes. However, the current SeaWiFS OC2 chlorophyll algorithm underestimates biomass at moderate to high concentrations (Figure 1). Solar-induced fluorescence should provide reasonable instantaneous estimates of primary production with robust backscatter corrections. The universality of any algorithms requires extensive evaluation and validation.

10.4 WORK PLANNED

Cruise plans for 1999 are not yet finalized, but should include a spring (May-June) Labrador Sea cruise and one more to be determined. With NOAA/NDBC, a time-series of bio-optical observations from the Chesapeake Light Tower is being initiated. As proposed ORCA is conducting 1-3 cruises per year, and contributing critical core observational data as well as a variety of ancillary bio-optical and biogeochemical data.

Core observations have been delivered within 90 days and include profiles of AOPs made with our Satlantic profiling spectroradiometer, fluorometric chlorophyll, and normally particulate and dissolved absorption spectra. Additional observations for which ODU has primary responsibility for are being delivered within 12 months, while contributions from international collaborators are submitted as they become available.

Our goal is to make raw data and derived products generally available via the web but our site is still under construction. Efforts in 1999 will concentrate on data analyses, modeling, and publication of results. Two manuscripts have been submitted and several more are in preparation.

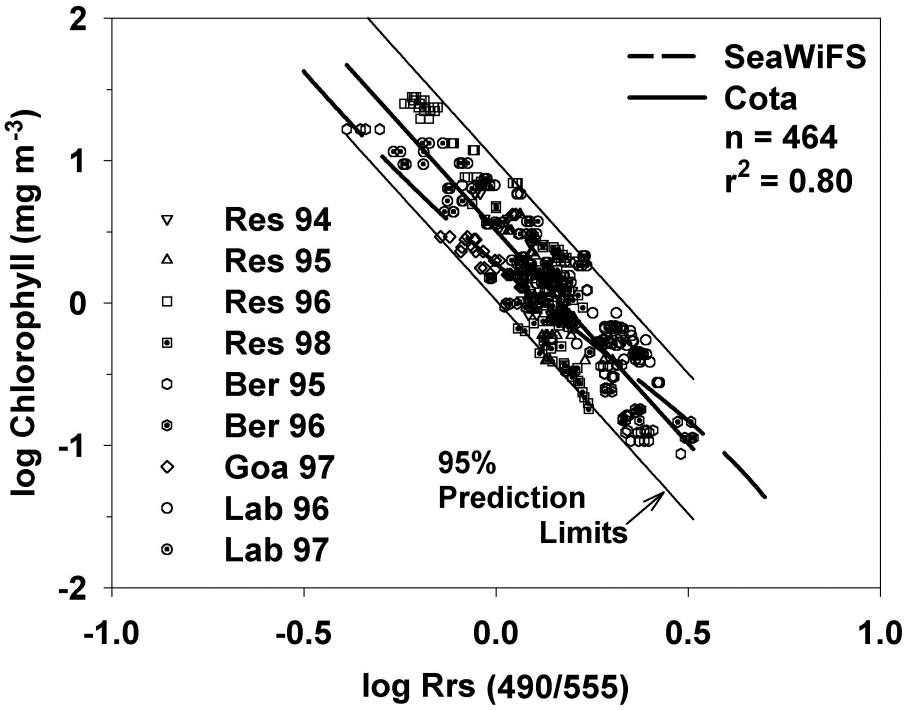

Figure 1. The current best-fit line of our high latitude data (minus Lab98) versus the current SeaWiFS OC2 chlorophyll algorithm.

Chapter 11

High Frequency, Long-Time Series Measurements from the Bermuda Testbed Mooring in Support of SIMBIOS

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11.1 INTRODUCTION

The primary goal of the present activity is to provide high frequency, long-term time series bio-optical data from the Bermuda Testbed Mooring (BTM) in support of SIMBIOS (Dickey et al., 1998). The site is located about 80km southeast of Bermuda at ~31° 43' N, 64° 10' W in waters of ~4530m depth.

The BTM study, which is funded by NASA, NSF, ONR, and NOPP, supports a variety of scientific research including SIMBIOS calibration and validation activities. Our study contributes to the development of methodologies and capabilities for synthesizing data derived from several satellite ocean color missions (Esaias et al., 1995), particularly SeaWiFS. Key NASA supported BTM optical measurements (every 15min during daylight) presently include: surface downwelling spectral irradiance (7 λ's, SeaWiFS matched) and subsurface (nominal depths of 14 and 32m) downwelling spectral irradiance and upwelling spectral radiance (7 λ's for each, SeaWiFS matched).

Products include: radiance and irradiance ratios, spectral attenuation coefficients, and upwelling spectral radiances just beneath the surface (0-). These data provide necessary links to and interpolation of radiometric data for remotely sensed observations of ocean color (suite of satellite color imagers) which can be used to estimate biomass and primary productivity globally.

Our newly developed telemetry system is now providing near real-time radiometric data to our lab. We are in the process of developing system software which will make key data available to the SIMBIOS project on a daily basis.

Highly complementary, value-added optical, meteorological, and physical data products are provided through our complementary NSF BTM study (e.g., Dickey et al., 1998). Our comprehensive measurements can be used to relate bio-optical signals to inherent optical properties and to biogeochemical measurements and to test interdisciplinary models of phytoplankton biomass and productivity and carbon flux.

11.2 RESEARCH ACTIVITIES

A major objective of the SIMBIOS program is to estimate normalized spectral water-leaving radiance, Lwn, by using in situ measurements. Our approach is to utilize moored instruments to obtain high temporal resolution measurements of fundamental radiometric variables to estimate upwelled spectral radiance just beneath the ocean surface, Lu(0-), which can be used to determine Lwn.

The mooring methodology, which allows for collection of very high temporal resolution, long-term data, has several advantages including the ability to obtain high numbers of "match-up" data for comparisons with SeaWiFS (e.g., Mueller and Austin, 1992). However, the use of moorings for obtaining optical data is a relatively new approach and has been used by very few groups (e.g., Dickey. 1991; Smith et al., 1991; Clark et al., 1997; Dickey et al., 1998).

Moored optical observations are more challenging than their ship-based counterparts for several reasons (e.g., less frequent calibration, biofouling, etc.). Thus, it is desirable to intercompare fundamental radiometric data and derived products based on nearly concurrent, co-located data from moored and ship-based instrumentation. We have been collaborating with Dr. David Siegel (UCSB), who has been collecting comparable vertical profile data during approximately monthly (every other week in springtime) shipboard cruises near the BTM site.

Our BTM data products are being intercompared with ship-based data collected as part of Dr. Siegel's Bermuda Bio-optical Program (BBOP) program (Siegel et al., 1995a,b; Siegel and Michaels, 1996). It should be noted that the BTM and BBOP measurements are displaced in space and to a lesser extent in time. In addition, there are several other significant differences. Thus, correlations between the BTM and BBOP data sets should not necessarily be expected to be great.

The BTM Deployment 7, 8, and 9 (May 3, 1997 - March 31, 1998) data sets encompass periods when 1) only the Japanese ocean color imager (OCTS) was collecting data, 2) neither OCTS nor SeaWiFS was

collecting data, and 3) when only SeaWiFS was collecting data. The time series of meteorological, physical, and optical data are described in Dickey et al. (1998). Time series measurements of surface and near surface optical properties were made using moored optical radiometer systems. Measurements include surface spectral downwelling irradiance (Ed (0+, λ) at λ = 412, 443, 490, 510, 555, 665, and 683nm (10nm bandwidth at half power) at 6Hz for 20sec every 15min during daylight and at midnight. Subsurface (nominal depths of 14 and 32m) downwelling irradiance (Ed (z, λ) and upwelling radiance, Lu (z, λ) data at λ = 412, 443, 490, 510, 555, 665, and 683nm are collected following the same regimen.

Our work is demonstrating that moored radiometric instrumentation can be used to provide a large number of in situ match-up data for comparisons with SeaWiFS observations in near real-time. The present approach uses a multi-purpose mooring, the BTM, and is relatively inexpensive. The use of such moorings for optical measurements is relatively new, and thus several complicating issues need to be considered and evaluated. We are working with data from the BTM and are doing statistical comparisons of data obtained from the BTM and those obtained nearly concurrently by the BBOP program. Despite several complicating factors, generally favorable correlations have been obtained for fundamental radiometric variables. Results including estimates of Lu(0-) have been transferred to the SeaBASS system. More detailed analyses and comparisons will continue to be done in the future. Particular areas of investigation will include calibration, sampling issues (e.g., BBOP spatial vs. BTM temporal), and biofouling. In addition, it is noteworthy that our near real-time data telemetry system has been functioning during the present Deployment 10. Lu(0-) estimates for this deployment have also been transferred to SeaBASS.

11.3 WORK PLAN

It is our intention to place an additional radiometer at 5-7m depth for a future deployment to determine if our estimates of Lu (0-) can be improved significantly. Deployment 10 full bandwidth data will be recovered in March 1999 and Deployment 11 will be initiated.

ACKNOWLEDGMENTS

We wish to thank David Siegel and Margaret O'Brien for sharing the BBOP data used for intercomparisons and for their assistance.

Chapter 12

The High-latitude Intercomparison and Validation Experiment (HIVE)

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12.1 INTRODUCTION

The HIVE project is a three-year series of cruises in both the Bering Sea and Prince William Sound/Gulf of Alaska. Both locations are at similar latitudes (~60°N) and have similar planktonic communities; however, the physical environments are dramatically different. These locations provide excellent test sites to determine the performance of bio-optical algorithms at high latitudes. We are making measurements of pigments (fluorometric and HPLC), radiometric profiles, total suspended matter, and ocean aerosols. The HIVE project builds on additional funding from the Japanese ADEOS program and the EXXON *Valdez* Oil Spill Trustee Council, which are supporting research projects in the Bering Sea and Prince William Sound, Alaska, respectively.

We are contracted to perform two or more cruises per year in the Gulf of Alaska, Prince William Sound, and/or Bering Sea depending on availability of sampling opportunities on US and Japanese vessels. In 1997, we received additional funding from the NASA SIMBIOS program to participate in a collaborative Japanese cruise in the Bering Sea prior to the start of the actual SIMBIOS project. In the first year of the SIMBIOS contract, we participated in three cruises, two in Prince William Sound and one in the Bering Sea. This technical memorandum reports on all four HIVE cruises to date.

The goal of the HIVE project is to validate high-latitude, satellite data products derived from imagery from different ocean color sensors. This goal is to be accomplished through meeting the following objectives:

- Make accurate measurements of *in situ* data fields of potential ocean color data products in northern-hemisphere, high-latitude waters.
- Compare measured data fields with data fields determined from ocean color satellites.
- Intercompare data fields retrieved from different ocean color satellites.
- Intercompare data fields retrieved from the same satellite at different times of day.

The failure of the ADEOS spacecraft precluded us from getting any match-up OCTS data during our 1997 cruise, which was prior to the SeaWiFS launch. In 1998, clouds, fog and poor weather have prevented any match-ups with the SeaWiFS data sets. Therefore poor weather and the ADEOS failure have prevented us from making any progress towards objectives 2 and 4. However, we have been successful in making field measurements, even under less-than-ideal conditions.

12.2 RESEARCH ACTIVITIES

We are making field measurements of phytoplankton pigments using both fluorometric and HPLC techniques, profiles of upwelling radiance and downwelling irradiance, total suspended matter, and ocean aerosols. These activities are described in detail below. We describe our activities in four cruises. The first occurred in July, 1997, in the Bering Sea, aboard the Japanese training ship *Oshoro Maru* and has a cruise identifier of OS97. The second was in June, 1998 was in Prince William Sound, AK, aboard a 58-foot charter vessel, the M/V *Auklet* and has a cruise identifier of AUK9806. The third was in July and was back to the Bering Sea aboard the T/S *Oshoro Maru* and has a cruise identifier of OS98. The fourth HIVE cruise was in August, again in Prince William Sound aboard the M/V *Auklet*, and has identifier AUK9808.

On all cruises, water samples were collected from 6 depths in the upper water column using Niskin bottles. During AUK9806, samples were taken from the surface and 5, 10, 15, 25 and 50 meter depths. During the OS97, OS98, and AUK9808 cruises, sampling depths were selected based on standard light levels and were generally taken at the depths corresponding to1, 10, 20, 36, 50, and 95% of surface light. Depths were altered when the water column was too shallow to permit sampling to the one-percent light level. Surface samples generally came from one-meter depth, but were occasionally deeper under rough sea conditions, when necessary to avoid firing bottles above the surface.

Phytoplankton Pigments

Water samples were filtered under low vacuum onto GF/F filters, followed by freezing in liquid nitrogen for HPLC, and by grinding and extraction in 90% acetone for immediate fluorometric analyses. Chlorophyll and phaeophytin concentrations were measured in the acetone extracts aboard the ship immediately after centrifugation using the technique of Strickland and Parsons (1972). HPLC samples were shipped in liquid nitrogen back to Fairbanks, where they were stored. Our group does not have the necessary facilities to perform HPLC analyses, therefore, after storage, samples from the first three cruises were shipped via FedEx to the Grice Marine Lab, Charleston, SC, for analysis. A combination of inadequate packing and shipment delays in both pick-up and transit led to the samples arriving in Charleston at room temperature. HPLC analysis of a subset of these filters indicated significant degradation of pigments had occurred and the samples were discarded. The filters from the fourth cruise remain in Fairbanks, in liquid nitrogen, while we determine exactly where the delays in handling and timing occurred and how to prevent them in the future.

Total Suspended Mater Concentrations

Water samples were taken for determination of total suspended matter (TSM) according to the JGOFS procedures (JGOFS, 1991) as outlined in the SeaWiFS protocols (Mueller and Austin, 1995). A modification of this was to use pre-combusted glass fiber filters. Filtered samples were dried and returned to Fairbanks for weighing on a precision analytical balance. Weighed dry filters were then recombusted and reweighed to give both total suspended matter and organic and inorganic fractions.

Radiance and Irradiance Profiles

For OS97, we were able to borrow a Biospherical Instruments MER-2048 system from the NOAA Coastal Services Center. Using this MER, we made measurements of E_d at 340, 380, 395, 412, 443, 455, 490, 510, 532, 555, 565, and 671 nm. E_u and L_u profiles measurements were made at 380, 412, 443, 490, 510, 555, and 683 nm. For surface reference, E_s was measured at 340, 380, 395, 412, 443, 490, 510, 555, 565, 671, 780, and 875 nm. Temperature was also measured during these profiles.

For AUK9806 cruise Satlantic loaned us an SPMR system (serial # 022). The profiler measured E_D at 405.4, 411.9, 435.6, 442.8, 455.4, 489.6, 510.4, 531.9, 554.8, 590.5, 665.6, 669.6, 700.4 nm and L_u at 405.1, 411.9, 435.1, 443.5, 456.3, 489.4, 510.3, 531.5, 554.3, 590.5, 665.3, 670.2, and 700.3 nm. The surface reference measured L_s at 406.5, 412.2, 435.3, 443.4, 455.9, 489.9, 510.4, 531.6, 554.6, 590.3, 665.1, 670.0, and 700.6 nm and E_s 405.1, 412.4, 435.6, 442.9, 456.1, 489.3, 510.4, 531.5, 554.5, 590.4, 664.8, 670.0, and 700.6 nm. This system was only used for the AUK9806 cruise. Due to failure of a PCMCIA serial port card, both the profiler and surface reference could not be used simultaneously. Instead, we made a measurement of E_s and L_s, did three profiles, and then repeated the surface reference measurements. Given the heavy overcast conditions during this cruise, we do not expect the surface light values to have varied significantly during the time we were profiling.

For the OS98 and AUK9808 cruises, we used our newly purchased SPMR system, which simultaneously measured E_d, L_u, E_s temperature, conductivity, and *in vivo* fluorescence profiles. E_d was measured at 412.3, 443.1, 490.7, 510.0, 555.1, 665.6 and 682.4 nm. L_u was measured 412.3, 442.1, 490.9, 510.1, 554.9, 665.4, and 682.9 nm. E_s was measured at 412.3, 442.6, 490.3, 510.2, 554.4, 665.0, and 683.8 nm.

Instrument Calibration

All instruments have been calibrated as required by the SeaWiFS protocol and SIMBIOS contract. Calibration files have been submitted with the bio-optical data to SeaBASS.

12.3 RESEARCH RESULTS

Table 1 summarizes the cruise time, location, station, and measurement data. All cruises had complete overcast at almost every station. Although these high latitudes are generally cloudy, this was an exceptionally bad year for our cruises. In 1994 through 1996 cruises, we had much better weather at these times and expected similar intermittent clouds these last two years.

12.4 WORK PLAN

This last year we participated in three cruises instead of only the two in which we were contracted to participate. Next year, we plan to consolidate our two 5-day Prince William Sound cruises into one 10-day cruise. By increasing our at-sea time to ten days, we hope to get the satellite match-ups that we have missed up to the present time. At the present, we plan to schedule the cruise for middle to late April, to capture the high, spring-bloom phytoplankton concentrations. However, we will review the previous years AVHRR data to try and determine if expecting cloud-free days during this time period is realistic. We will still plan to participate in the T/S *Oshoro Maru* cruise in July.

Table 1. Summary of cruises and *in situ* data collected.

Cruise ID	**Location**	**Cruise Dates**	**Number of Stations**	**Non-optical measurements***
OS97	Bering Sea	18 July –2 Aug.1997	20	Pigments (fluor), TSM, T
AUK9806	Prince William Sound	5 –9 June 1998	21	Pigments (fluor), TSM, T
OS98	Bering Sea	18 July –1 Aug. 1998	17	Pigments (fluor), TSM, T, S, Fluor
AUK9808	Prince William Sound	8 Aug. – 2 Sept., 1998	15	Pigments (fluor & HPLC), TSM, T, S, Fluor
* TSM = Total Suspended Matter, T = temperature profile, S = Conductivity profile, Fluor = *in vivo* fluorescence profile				

Chapter 13

Satellite Ocean Color Validation Using Merchant Ships

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13.1 INTRODUCTION

The usual approach to satellite ocean color validation is to organize dedicated experiments at sea, e.g. in regions that are likely to cause atmospheric correction errors, and to measure concomitantly water-leaving radiance and aerosol optical properties at the time of satellite overpass (Clark et al., 1997). The data are necessary not only to compare satellite estimates with in situ measurements, but also to interpret the differences and, eventually, adjust atmospheric correction algorithms. These experiments, unfortunately, are expensive; they cannot be carried out over the full range of expected atmospheric and oceanic conditions. Furthermore, because of cloud cover only a few match-ups are generally obtained during a campaign, making the approach even less cost-effective.

A complementary approach --and the focus of the present project-- is to use ships of opportunity, in particular, merchant ships traveling routes in the world's oceans. For the approach to be cost-effective, the ships must participate on a volunteer basis or at a very small cost, and the measurement program must not interfere with the ship's activities. Importantly, the ship should not be required to stop, i.e. one should be able to collect the data en route, while the ship is steaming. Because of these limitations, one cannot expect to measure the full set of ocean-color variables using ships of opportunity. Still, to be useful the measurement program should meet the basic requirements for satellite ocean color validation.

It is in this context, and also according to a study of the measurements required for satellite ocean-color validation (Schwindling et al., 1998), that the SIMBAD concept was developed. SIMBAD is a portable radiometer designed for use onboard ships of opportunity. It measures normalized water-leaving radiance (or diffuse marine reflectance) and aerosol optical thickness in typical spectral bands of satellite ocean color sensors. Knowledge of both variables is needed and generally sufficient to evaluate atmospheric correction algorithms (Schwindling et al., 1998). The instrument is easy to operate, so that any ordinary crew can learn quickly how to make measurements. To achieve adequate sampling, i.e. acquire data in a wide range of oceanic and atmospheric conditions, a series of ten radiometers was built for use in two complementary networks of ships/routes, one operated by the Scripps Institution of Oceanography, the other by the University of Lille.

13.2 RESEARCH ACTIVITIES

The SIMBAD radiometer was designed and built by the Laboratoire d'Optique Atmospherique (LOA) of the University of Lille. It measures water-leaving radiance from above the surface as opposed to below the surface the usual way. This eliminates constraints associated with deploying underwater instruments at sea, e.g. stopping the ship. Viewing of the ocean surface is made from the side of the ship lit by the sun, outside the glitter region, at a nadir angle of 45 degrees. A vertical polarizer reduces the skylight reflected by the surface in the instrument's field-of-view. The best location to operate the instrument is generally the bow, making it easy to avoid ship-generated foam. The radiometer also measures aerosol optical thickness, by viewing the sun like a standard sun photometer. The same optics (2.5 degree field-of-view) and detectors are used in both ocean- and sun-viewing modes, but at different electronic gain.

The radiometric measurements are made simultaneously in five spectral bands centered at 443, 490, 560, 670, and 865 nm. These bands are not exactly those of the ocean color sensors that are flying or scheduled to fly, but result from a compromise. They constitute, however, a basic set of bands for atmospheric correction and bio-optical algorithms. Viewing of the ocean and sun is made sequentially, but the non-simultaneity of the measurements is not limiting. SIMBAD does not measure incoming solar irradiance, a variable that must be known to normalize water-

leaving radiance. It is calculated accurately in clear sky conditions or when the sky is partly cloudy (<30%) with the sun not obscured by clouds. This defines the sky conditions under which SIMBAD should be operated. In addition to radiometry, SIMBAD automatically acquires viewing angles (using a magnetometer and two inclinometers), time and geographic location (using a GPS), pressure, and temperature. It requires about 15 minutes to collect a complete data set (ocean, sun, optical zero), including deploying the instrument and logging ancillary data (wind speed, sea state, cloud cover, etc.). Internal memory and batteries allow for 3 months of operations in normal mode (typically 5 sets of measurements per day). At the end of the campaign or voyage, after the ship returns to port, the data are downloaded onto computer disk and diskette and the radiometer is calibrated. In the case of long campaigns, the data are mailed from selected ports along the ship's route, allowing for a more rapid data turnover.

Justification and Verification

The principle of the SIMBAD radiometer, in particular its ability to reduce reflected skylight with the help of a vertical polarizer, has been justified theoretically and verified experimentally (Fougnie et al., 1999b). Theoretical calculations show that, for a nadir angle of 45 degrees and a relative azimuth angle between solar and viewing directions of 135 degrees, the recommended geometry, reflected skylight is reduced to typically 10^{-3} in reflectance units at 443 nm. This represents 2 to 10% of the diffuse marine reflectance, the signal of interest. Furthermore, the effects of surface roughness on skylight reflection and, hence, uncertainties in sea state (wind speed) are minimized. Taking into account typical uncertainties in wind speed and geometry, the residual reflected skylight are correctable to a few 10^{-4} in reflectance units. For most oceanic waters, the resulting error on the diffuse marine reflectance in the blue and green is less than 1%. The theoretical results have been verified experimentally at the Scripps Institution of Oceanography pier, by viewing the ocean surface with a scanning polarization radiometer (Fougnie et al., 1999b). The various angular and spectral effects predicted by theory have been evidenced in the measurements.

Since the water body polarizes incident sunlight (e.g., Ivanoff, 1975, Frouin et al., 1994), the measured polarized radiance differs from the total radiance. For the recommended geometry, the underwater scattering angle varies only between 148 and 158 degrees, and the maximum polarization factor varies between 0.83 and 0.92 (Fougnie et al., 1999b). One should be able to correct the polarization effects to within 5% relative accuracy, which compares with other errors, such as those due to bi-directional effects and radiometric calibration.

The SIMBAD radiometer was evaluated at sea, during California Cooperative Fisheries Investigation (CalCOFI) cruises in the southern California Bight. The diffuse marine reflectance measured by the radiometer was compared with that measured by an underwater MER optical system. The agreement between the two types of measurements was good, to within 1.6 10^{-3} in reflectance units. Aerosol optical thickness measured by the SIMBAD radiometer also compared well with that measured by sun photometers during the October-November 1996 CalCOFI cruise (Nakajima et al., 1999) and during the Second Aerosol Characterization Experiment (ACE-II).

The SIMBAD radiometer proved useful to check vicariously the radiometric sensitivity of the Polarization and Directionality of the Earth's Reflectance (POLDER) instrument onboard ADEOS (Fougnie et al., 1999a). The satellite radiance was compared with that computed for the same geometry using a radiation-transfer model. SIMBAD measurements of aerosol optical thickness and marine reflectance at the time of satellite overpass were used as input to the model. The accuracy of the vicarious calibration coefficients was estimated to be better than 3%. A large decrease of the POLDER instrument response was found in the blue, confirming the results previously obtained using alternative calibration techniques.

Data Format

The SIMBAD data sets are fairly complete for satellite ocean color validation. They include near-concurrent values of spectral aerosol optical thickness and diffuse marine reflectance, necessary variables for checking radiometric calibration and evaluating atmospheric correction algorithms. They also include fractional cloud coverage and wind speed (useful to estimate whitecap reflectance). The data sets can be accessed at the following web addresses: http://genius.ucsd.edu/~frouin/ and http://www-loa-univ-lille1.fr/~poteau/.

13.3 RESEARCH RESULTS

Since the launch of the SeaWiFS in September 1997 and until December 1998, SIMBAD measurements have been made during 12 research cruises and 9 merchant ship voyages (Table 1). A total of 156 SIMBAD data sets have been collected under clear or mostly clear sky (fractional cloud coverage less than 0.2) within a few hours of satellite overpass. A variety of oceanic and atmospheric conditions have been sampled, but no data have been acquired in the South Atlantic and Indian Oceans. The research cruises and merchant ship voyages are listed below in chronological order with location or route, date, name of the SIMBAD operator, and network (SIO or LOA).

Table 1. SIMBAD cruise measurements from 9/1997 to 12/1999

CalCOFI 9709, Southern California Bight, 09/20/98-10/08/98, Wieland, SIO.
M/V Asian Challenger, Valparaiso-Auckland, 10/12/98-10/18/98, Cutchin, SIO.
R/V Melville, San Diego-Acapulco-Callao-Valparaiso-Easter-Papeete-Honolulu, 11/02/97-06/07/98,Comer, SIO.
M/V Nacre, Honolulu-Coronel, 12/20/98-01/02/98, Cutchin, SIO.
CalCOFI 9802, Southern California Bight, 01/23/98-02/10/98, Subranamian, SIO.
CalCOFI 9804, Southern California Bight, 04/02/98-04/24/98, Mitchell, SIO.
R/V Revelle, Eastern Tropical Pacific Ocean, 04/09/98-04/27/98, Dupouy, LOA.
M/V Toucan, Le Havre-Cayenne-le Havre, 05/04/98-05/23/98, Poteau, LOA.
M/V Chevron Mississippi, Honolulu-Valdez, 05/18/98-05/23/98, Cutchin, SIO.
M/V Toucan, Le Havre-Cayenne-le Havre, 06/08/98-06/20/98, Poteau, LOA.
CalCOFI 9807, Southern California Bight, 07/09/98-07/27/98, Wieland, SIO.
ATMARA 9807, English Channel, 07/21/98-08/06/98, Wartel, LOA.
NAN 9807, Cape Cod, 07/06/98-07/10/98, Shieber, SIO.
M/V Mokihana, Oakland-Guam-Taiwan-Japan-Oakland, 07/20/98-08/15/98,Bousseloub, SIO.
CalCOFI 9809, Southern California Bight, 09/13/98-10/01/98, Wieland, SIO.
BREST 9809, Northeastern Atlantic Ocean, 09/25/98-10/01/98, Gohin, LOA.
M/V Mokihana, Oakland-Guam-Taiwan-Japan-Oakland, 08/25/98-09/08/98, Bousseloub, SIO.
M/V Micronesian Navigator, California-Micronesia-Philippines-California,08/25/98-10/28/98, Sumogat, SIO.
R/V Cape Hatteras, Beaufort-Jacksonville, 10/21/98-12/01/98, Subranamian, SIO.
M/V Micronesian Navigator, California-Micronesia-Philippines-California, 10/30/98-12/31/98, Sumogat, SIO.
R/V Ka'imimoana, Honolulu-Fiji-Honolulu, 10/19/98-12/11/98, Strutton, SIO.

13.4 WORK PLAN

A collaborative LOA-SIO measurement program for satellite ocean color validation based on ships of opportunity has been developed. This has been accomplished in a series of successive, logical steps. First, a study of validation requirements was performed, indicating that measurements of spectral water-leaving radiance and aerosol optical thickness at the time of satellite overpass are generally sufficient to evaluate satellite-derived ocean color (Schwindling et al., 1999). Second, in view of the study and limitations of dedicated validation experiments at sea, the SIMBAD radiometer was designed, for use of ships on opportunity such as merchant ships traveling regular routes in the world's oceans. Third, the instrument's innovative principle (use of a vertical polarizer to reduce skylight reflection) was verified experimentally at the Scripps Institution of Oceanography pier (Fougnie et al., 1999b). Fourth, the instrument was tested at sea, on station and en route, during various oceanographic campaigns (Fougnie, 1998, Nakajima et al., 1999). Fifth, suitable merchant ships and routes in the Pacific and Atlantic Oceans were identified and selected officers were trained. Some of the ships, for example M/V Micronesian Navigator (SIO network) and M/V Toucan (LOA network), are now providing SIMBAD data routinely. Sixth, SIMBAD data were used to check vicariously the radiometric calibration of the POLDER instrument onboard ADEOS (Fougnie et al., 1999a).

Regarding measurement opportunities, the program's focus has been on research campaigns during which water-leaving radiance and/or aerosol optical thickness were measured by other instrumentation (e.g., CalCOFI campaigns), so that comparisons could be made. Although more evaluation of the SIMBAD data is necessary, and should be done on a continuous basis, in order to increase the number of surface/satellite match-ups the focus should be shifted to ships that do not carry out the same type of measurements as the SIMBAD radiometer (e.g., more merchant ships). The program also needs to be extended to ships traveling in other oceanic regions, in particular the southern Oceans and the Indian Ocean, to complement the present coverage. There are many possibilities, and the demand for SIMBAD radiometers has been increasing. The realization of a new series of radiometers is envisioned, with the instruments available for the next generation of satellite ocean color sensors.

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Chapter 14

High Attitude Measurements of Radiance at High Spectral and Spatial Resolution for SIMBIOS Sensor Calibration, Validation and Intercomparisons

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14.1 INTRODUCTION

The successful combination of data from different ocean color sensors depends on the correct interpretation of signal from each of these sensors. Ideally, the sensor measured signals are calibrated to geophysical units of spectral radiance, and sensor artifacts are removed and corrected. The calibration process resamples the signal into a common radiometric data space so that subsequent ocean color algorithms that are applied to the data are based in physical processes and inherently sensor independent. The objective of this SIMBIOS effort: "High Altitude Measurements of Radiance at High Spectral and Spatial Resolution For SIMBIOS Sensor Calibration, Validation, and Intercomparisons is to conduct a series of direct calibration comparisons using the NASA Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)," is to assess the calibration of the satellite sensors which participate in SIMBIOS.

The AVIRIS sensor flies at 20 km altitude on a NASA ER-2 near the top of the absorbing and scattering portions of the atmosphere. AVIRIS measures the solar reflected spectrum from 370 nm to 2500 nm through 224 contiguous 10 nm wide spectral channels. Data are acquired as images of 11 by up to 800 km extent with 20 m spatial resolution. The stability and repeatability of AVIRIS calibration has been and continues to be validated through a series of inflight calibration experiments. With pre and post flight calibrations of AVIRIS, coupled with the on-board calibrator, calibration accuracy of better than 2% spectral, 3% radiometric and 3% spatial have been achieved.

The activities and results presented here are primarily for SeaWiFS. However, related work has been carried out for ADEOS OCTS. In the future, it is planned that AVIRIS will underfly EOS.

14.2 RESEARCH ACTIVITIES

On the 2nd of October 1997 AVIRIS under flew the SeaWiFS sensor of the coast of Southern California near latitude 35° and longitude 127°. The SeaWiFS sensor was tilted to the Northeast to avoid sun glint. In order for the AVIRIS spectral images to overlap the area, the azimuth, and the zenith angles of the SeaWiFS measurements, AVIRIS was flown in a circle beneath SeaWiFS. The AVIRIS scan angle (± 15 degrees) plus the aircraft roll angle (20 degrees) assured overlap of both area and observation geometry. The AVIRIS data from the 2nd of October 1997 flight were spectrally, radiometrically and spatially calibrated through the AVIRIS data system algorithms. The SeaWiFS data and the SEADAS processing software were requested and received. Both the AVIRIS and the SEAWIFS data sets include the position and pointing information at the time of acquisition. The simultaneous acquisition of the AVIRIS and SeaWiFS with overlapping observation geometry provides the essential data set to complete the calibration objective.

14.3 RESEARCH RESULTS

Determination of the areas of the SeaWiFS and AVIRIS images with the same observation geometries requires projection of the data based on the position and pointing knowledge of the sensor. A set of algorithms were developed to accept the SeaWiFS position and point information and calculate the azimuth and zenith angles for the 2nd of October SeaWiFS data. All angles were calculated from the perspective of the surface. The observation geometry at the surface is the correct geometry for calibration comparison. AVIRIS receives and records both Global Positioning System (GPS) and Inertial Navigation System (INS) information from the ER-2 aircraft. The GPS provides latitude, longitude and altitude information, while the INS provides roll, pitch, and yaw information. These position and pointing data were used with an analogous set of algorithms to calculate the AVIRIS spectral image azimuth and zenith angles were calculated. With both the AVIRIS and SeaWiFS image azimuth and zenith angles determined, the target area of overlapping observation geometry was identified.

This area contains the AVIRIS spectra and SeaWiFS multi spectral data of the same area on the surface with the same observation azimuth and zenith (Table 1).

The average AVIRIS spectrum from the area of observational and temporal coincidence was extracted. A correction factor was applied to the AVIRIS spectra for the transmittance from the 20 km AVIRIS altitude to the top of the atmosphere. This correction factor was calculated with the MODTRAN radiative transfer code using Ozone values from the TOMS total ozone archive for the area.

The SeaWiFS multi spectral band data were extracted directly for this target. A graphical comparison of the AVIRIS spectrum and SeaWiFS bands showed good agreement. In order to quantitatively compare the AVIRIS and SeaWiFS data, a convolution algorithm was developed to convolved the AVIRIS spectra to the SeaWiFS bands. The algorithm was applied to the AVIRIS spectra for the target area and the AVIRIS predicted radiances compared to the SeaWiFS reported radiances (Table 2). These results are preliminary. A review of the version of SEADAS used to process the SeaWiFS data is underway. A high priority activity has begun to review and compare the absolute radiometric standard used for SeaWiFS calibration and AVIRIS calibration.

The primary objective of this SIMBIOS effort has been achieved. On the 2nd of October 1997, AVIRIS underflew the SeaWiFS sensor. The data set was acquired such that the observation geometries of SeaWiFS and AVIRIS could be match for direct comparison of measured radiance. A set of algorithms were developed to calculate the surface azimuth and zenith angles for both the SeaWiFS and AVIRIS data sets.

These algorithms required as input position and pointing information for the two sensors. The initial graphical comparison of the AVIRIS spectrum and SeaWiFS bands showed good agreement for the ocean target of overlapping observation geometry. An additional set of algorithms were developed to convolved the AVIRIS spectra to the SeaWiFS spectral bands. Direct comparison of the AVIRIS measured and SeaWiFS measured radiance shows the agreement is best for SeaWiFS bands 3,4,5, and 6 and least good for SeaWiFS bands 1, 2, 7, and 8. These are initial, preliminary results and additional review and uncertainty analysis is required to strengthen the basis of comparison. Never-the-less, these initial results validate the objective, approach, and activities of this SIMBIOS Project.

14.4 WORK PLAN

In 1999 three additional underflights of SEAWIFS are planned. The first underflight is planned for the Spring of 1999 from the west coast. A second underflight will be attempted from the east coast in the late Spring or early Summer. The third underflight is planned for the west coast in the late summer early fall time frame. Each underflight will include two flight circle acquisitions to assure a match to the SeaWiFS viewing geometry. The first flight circle will be timed to coincide with the satellite overpass. The second flight circle acquisition enables investigation of the time sensitivity of the measurements. Efforts will be made to coordinate all underflights with other participating SIMBIOS investigators. Following each successful underflight, the AVIRIS runway calibration standard will be used to place the maximum accuracy on the AVIRIS radiometric calibration for the SeaWiFS underflight. In April of 1999, the new SIMBIOS SXR-II transfer radiometer will be used at JPL to further compare the SIMBIOS and AVIRIS radiometric standards. Results of all the 1999 activities of this project will be provided to SIMBIOS. Work will proceed on writing up the 1998 and 1999 results for publication.

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Table 1. Preliminary results of AVIRIS and SeaWiFS radiance comparison.

BAND	SeaWiFS Radiance	AVIRIS Radiance	AVIRIS Uncertainty	Difference
1	7.800	6.791	5.1%	12.9%
2	6.852	6.311	3.5%	7.9%
3	4.899	4.861	2.1%	0.8%
4	3.995	3.972	2.5%	0.6%
5	2.753	2.711	2.9%	1.5%
6	1.248	1.193	2.3%	4.5%
7	0.641	0.601	3.6%	6.2%
8	0.449	0.412	3.5%	8.3%

The units of radiance are microWatts/cm^2/nm/sr.

Table 2. Website locations for AVIRIS SeaWiFS match up example

1 First AVIRIS flight circle. ftp://makalu.jpl.nasa.gov/pub/rog/seawifs/pic01.jpg
2 Corresponding SeaWIFS image ftp://makalu.jpl.nasa.gov/pub/rog/seawifs/pic04.jpg
3 SeaWIFS azimuth ftp://makalu.jpl.nasa.gov/pub/rog/seawifs/pic05.jpg
4 SeaWIFS zenith ftp://makalu.jpl.nasa.gov/pub/rog/seawifs/pic06.jpg
5 AVIRIS azimuth ftp://makalu.jpl.nasa.gov/pub/rog/seawifs/pic07.jpg
6 AVIRIS zenith ftp://makalu.jpl.nasa.gov/pub/rog/seawifs/pic08.jpg
7 AVIRIS and SeaWIFS data measured within 5 seconds.

`ftp://makalu.jpl.nasa.gov/pub/rog/seawifs/pic09.jpg`

Chapter 15

Merging Ocean Color Data from Multiple Missions

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15.1 INTRODUCTION

In response to the potential importance of phytoplankton in the global carbon cycle and the lack of comprehensive data, the National Aeronautics and Space Administration (NASA) and the international community have established high priority satellite missions designed to acquire and produce high quality ocean color data. Seven of the missions are routine global observational missions: the Ocean Color and Temperature Sensor (OCTS), the Polarization and Directionality of the Earth's Reflectances sensor (POLDER), SeaWiFS, Moderate Resolution Imaging Spectrometer-AM (MODIS-AM), Medium Resolution Imaging Spectrometer (MERIS), Global Imager (GLI), and MODIS-PM. In addition, there are several other missions capable of providing ocean color data on smaller scales.

Any individual ocean color mission is limited in ocean coverage due to sun glint and clouds. For example, one of the first proposed missions, the SeaWiFS, can provide about 45% coverage of the global ocean in four days and only about 15% in one day (Gregg and Patt, 1994).

The proliferation of missions suggests that better ocean coverage can be obtained in less time if the data are combined. In addition to improved, and faster coverage, data can be taken from different local times of day if the missions are placed in different orbits, which they are. This can potentially lead to information on diel variability of phytoplankton abundances.

We propose to investigate, develop, and test algorithms for merging ocean color data from multiple missions. We seek general algorithms that are applicable to any retrieved ocean color data products, and that maximize the amount of information available in the combination of data from multiple missions. Most importantly, we will investigate merging methods that produce the most complete coverage in the smallest amount of time, nominally, global daily coverage. We will also assess the ability to produce fuller coverage in larger time increments, including 4-day, 8-day (weekly), monthly, seasonal and annual. Secondarily, we will investigate the ability of the missions to produce coverage at different times of day, for diel variability and dynamical evaluations, and develop algorithms to produce this information.

15.2 RESEARCH ACTIVITIES

Work in the first two years has focused on: a) defining the problems and opportunities provided by the existence of multiple sensors; b) analysis of past sensors to provide insights into the characteristics, drawbacks, and advantages of individual sensor responses in the context of merging; and c) analysis, development, and testing of candidate merger algorithms.

a) Defining the Problems

First we assessed the global coverage improvements possible by the six global missions. These results show that significant scientific advantages can accrue from assembling and merging data from the multiple satellite platforms proposed for ocean color in the next decade. The principal advantages are increased ocean coverage in less time, and new observations of the daily dynamics of phytoplankton abundances, resulting from different observation times of co-located ocean areas. Data from three satellites as opposed to one, can increase ocean coverage by 58% for one day, and 45% for four days. Additional satellites produce diminishing returns, however. This latter point is not necessarily an adverse finding, since each mission has a limited life expectancy and in-flight problems are, unfortunately, still not rare in the satellite business. Using observations from pairs of missions, as much as 14 hour time differences at co-located points can be realistically achieved at high latitudes, even considering the distribution of land masses and ice cover. Smaller time differences are observed at lower latitudes, but 5 to 7 hour differences are still available. Furthermore, massive numbers of these co-located pairs are available, suggesting that routine scientific studies of diel phytoplankton variability can be supported (Gregg et al., 1998). More detailed analyses emphasized seasonal and regional coverage improvements and was limited to the SeaWiFS/MODIS combination, since these are the two missions planned for next launch. The results showed that the launch of EOS AM-1 provides an opportunity to improve ocean color observations by combining data from the SeaWiFS and MODIS mis-

sions. The sensors have different scanning characteristics and are flying on different platforms in different orbits. The results suggested that very large improvements in coverage frequency (daily to four-day) can be obtained by combining data from both sensors: 40-47% increases in global coverage over SeaWiFS alone in one day, and > 100% in areas near the solar declination. Four-day increases are slightly smaller for global coverage, 29-35%, but meridional percent increases are similar to the one-day case. These differences are due to reduced sun glint contamination obtained by tilting (SeaWiFS), and scanning away from the maximum glint region (MODIS),due to its 10:30 AM equator crossing time, and due to the large scan width of MODIS. The results show that SeaWiFS and MODIS are very complementary ocean color missions that can provide more complete observations of ocean processes at high frequency if data are combined (Gregg and Woodward, 1998). A more detailed paper with more fully defined results was published as a NASA TM (Woodward and Gregg, 1998). Third, assessed potential capability for improving ocean color observations by selecting complementary mission orbits. Considering that observations are severely hampered by cloud cover and sun glint, a possibility exists for using multiple missions to improve the coverage of the oceans in shorter time scales. In fact, only about 10-18% of the oceans are observed in a single day, even by so-called global observational missions, due to these two ocean color contaminants. Analysis of a 7-day period of cloud cover from the International Satellite Cloud Climatology Project (ISCCP), show that 12% new surface area is available for viewing each day. This translates to an increase of about 0.5% per hour of separation in viewing times. Thus if the ocean could be viewed by 2 different satellites 4 hours apart, 2% more ocean area could be observed. This represents a coverage increase of about 13%. If 2 satellites were placed in Earth orbit with equator crossing times 4 hours apart, the improvement in coverage by these 2 satellites over a single one is about 60%. Furthermore, by managing the orbits of the 2 satellites, nearly complete sun glint avoidance can be achieved, further improving the ocean coverage. The best improvements can be made by 2 satellites in the same node, whose orbital positions are adjusted to view the sun glint contaminated areas of the other. If scan edges are useful for quantitative ocean color observations (the validity of which is unknown at this time), then only 2 polar-orbiting satellites are necessary. If not, a third satellite is necessary, preferably in a low inclination orbit where losses in coverage in the tropics by the polar orbiters can be best compensated (polar orbiters overlap coverage at high latitudes, and the scan edges are necessary only near the equator). However, the best configuration is 3 geostationary satellites, which provide complete global coverage routinely with a viewing time separation that can maximize cloud and sun glint avoidance, with a single polar orbiter to provide high latitude coverage (Gregg, 1999a).

b) Analysis of Past Sensors

We continued investigations into OCTS data. These investigations began before the failure of ADEOS, in an effort to characterize OCTS data for use with a merging activity with SeaWiFS. The loss of data from the sensor precludes its use in merging, but the similarity of some aspects of sensor design with MODIS suggests that significant understanding of the capabilities and deficiencies of MODIS data can be facilitated through a thorough analysis of OCTS data. In fact, we have found this to be true. Initial observations just after failure of OCTS suggested 6 problem areas: band registration, image striping, cloud noise, navigation, calibration, and bright target response. Analysis of the first three led to solutions that improved imagery substantially (Gregg, 1998; Gregg, 1999b). Particularly the methods for reducing image striping is a useful method for a problem expected to occur in MODIS imagery. Analysis of geolocation, radiometric stability and accuracy, and bright target responses were characterized and submitted for publication (Gregg et al.,1999). The results here also have implications for MODIS.

c) Merging Algorithms

Efforts have began on developing merging algorithms. We are investigating 4 possible approaches: a) simple splicing, where 1 data set is deemed superior and the other is patched into gaps, b) sensor weighting, where specific dependences and deficiencies are identified and co-located observations are merged using different weighting functions for the sensors, c) the Conditional Relaxation Analysis Method, where the best data are selected as interior boundary conditions into a merged set using Poisson's equation (Reynolds, 1988), and d) optimum interpolation, where merging occurs by weighting individual sensor data to minimize spatial covariance function. The Conditional Relaxation Analysis Method (CRAM) was implemented and tested using CZCS data and in-situ data. Although these results were funded by separate grant, the results enabled us to begin to understand the strengths and weaknesses of the method and its potential use for satellite data (Gregg and Conkright, 1999). Several modifications are required before effective use with in-situ data, but it is not clear at this time whether these modifications will be necessary for merging of multiple satellite data, since data paucity may not be an issue. It may be an issue, however, if significant deficiencies are identified.

Chapter 16

Validation of Bio-optical Properties in Coastal Waters: a Joint NASA - Navy Project

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16.1 INTRODUCTION

This project is a joint effort between NASA's Earth System Science Office and the Naval Oceanographic Office (NAVOCEANO) at the John C. Stennis Space Center, MS. The collaboration reflects a partnership developed by NASA and NAVOCEANO over six years to share resources and expertise in the collection of ocean optics, hydrographic, biological, and remotely sensed data to support each agency's goals in coastal research. NAVOCEANO provides ship time, instrumentation, and operational support during oceanographic surveys while NASA provides expertise in data collection, computer programming and modeling, and data processing and analysis. This SIMBIOS project was established to provide data collected in the South China Sea, Gulf of Thailand and adjacent coastal waters. This project is designed to provide NASA with cost-effective access to in-water optics and ancillary data in coastal waters representing diverse turbid environments, and if successful, will help provide an effective mechanism for interagency cooperation and data exchange.

16.2 RESEARCH ACTIVITIES

NAVOCEANO hydrographic surveys 260797 (27 April - 19 May) and 260897 (23 May - 16 June) were completed in the South China Sea, and the Gulf of Thailand / South China Sea, respectively. The SIMBIOS project investigators comprise the optics team of these surveys, one of three primary operations: optics, bioluminescence, and basic hydrography. Vertical profiles were acquired by each operations team at a dense grid of selected stations. In addition, XBTs were dropped at regular intervals along the cruise track between the profiling stations. Three optics packages were deployed. These were designated as the day (IOPs and radiometer), night (IOPs), and the Satlantic system. The day and night packages (Table 1) used the Mermaid II data acquisition system (Miller et al., 1995). System power and communications network for the day and night packages were provided by MODAPS (Wet Labs, Inc.).

Vertical Profiles and IOP

Several power and communication problems were encountered with the MODAPS deck and subunits of each package. Power delivery from the subunit to the MER 1032 failed after 11 profiles and hence the combined package was abandoned. The subunit for the IOP package could not establish communications with the Seabird CTD. The CTD was disconnected from the MODAPS system and was deployed in standard profiling mode (internal data collection). CTD Data were downloaded independently following each cast. Unfortunately, this approach decoupled the CTD and AC-9 data streams. A program was developed and used to interactively merge AC-9 and CTD profiles during preprocessing and quality control. Two AC-9s were on the IOP package. The inflow tubes of one AC-9 were fitted with 0.2 μm inline filters at several stations to partition the total spectral absorption and beam attenuation into dissolved and particulate fractions. At these stations, total (unfiltered) and dissolved (filtered) a and c profiles were obtained. A comparision / calibration of the AC-9s were performed when both AC-9s were unfiltered. The IOP package was deployed at 54 stations (111 profiles) and 120 stations (248 profiles), during survey 260797 and survey 260897, respectively. Two PC-based programs were written in IDL 5.0 (castDisplay, castMapper) to apply quality control checks and routine data correction and display. Temperature, salinity and scattering corrections were applied to all AC-9 data. Scattering corrections used either Method 1 of the Zaneveld Method (AC-9 User Guide, Wet Labs, Inc). A branching algorithm was used based on the a715 nm / b715 nm ratio to select which scattering method was applied. Method 1 was used for ratios greater than 0.35. The Zaneveld Method was used for ratio values <= 0.35. The castDisplay and castMapper (a geographic contouring package for vertical profiles) will be used on subsequate surveys for near-realtime processing and analysis. All data have been translated to SeaBASS format.

Satlantic Profiles

A SeaWiFS Profiling Multichannel Radiometer (SPMR) and a SeaWiFS Multichannel Surface Reference (SMSR) instrument were deployed at 42 and 36 stations during survey 26079 and 260897, respectively. In general, three profiles were acquired at each station. The central wavelengths for the SMPR and SMSR channels were: 405.3, 412.9, 435.1, 443.8, 456.2, 490.9, 509.1, 532.7, 555.2, 590.5, 665.8, 683.8, and 700.4 nm. Satlantic's Prosoft 4.0 (revision f) was used to produce derived products of K, Reflectance, R_{rs}, L_{wn}, and modeled pigments. The Satlantic system performed without problems.

Discrete Water Samples

At most stations, discrete water samples were collected at select depths (based on profiling transmissometer and fluorometer data) using Niskin Bottles mounted on the hydrographic CTD rosette. These water samples were filtered for analysis of fluorometric chlorophyll *a* and phaeopigments, HPLC pigments, CDOM absorption, particle absorption (QFT), and total suspended mater. All samples were collected and processed following the procedures of Mueller and Austin (1995). HPLC pigments determined were chlorophyll *a*, chlorophyll *b*, peridinin, fucoxanthin, 19 hex, prasinoxanthin, alloxantin, lutein, zeaxanthin, diadinoxanthin, canthaxantin, and β-carotene. Absorption spectra were determined for total, detrital, and phytoplankton components following the hot-methanol extraction technique (Kishino et al., 1985). Corrections for path-elongation were performed following the method of Mitchell (1990). CDOM absorption spectra were collected using a Perkin-Elmer Lambda 3 spectrophotometer. The number of samples collected for each analysis were (Survey 260797; 260897): HPLC (71; 100), fluorometic chl *a* (86; 149), total suspended mater (50; 50), CDOM absorption (5; 20), and particle absorption (0; 61).

16.3 RESEARCH RESULTS

The project was able to follow the proposed work plan with regards to data collection and processing. In general, instrument calibration and data collection followed the guidelines provided by the proposal with the exception that the MER 1032 needed to be phased out of the instrument suite. The problems with the MODAPS created unexpected delays in preprocessing and analysis. In addition to collection problems and limitations, considerable effort was invested to develop a reliable and robust method to merge CTD and AC-9 data. Raw and intermediate data products were created for most profiler data. The volume of data collected at sea exceeded our expectations. This resulted in a significant increase in the time required to process data. The NAVOCEANO provide operational support to the US fleet by conducting military surveys worldwide. These surveys are conducted under the provisions of military ordinances, and as such, do not require diplomatic permission from local governments.

The data collected during this project were mostly obtained in the Exclusive Economic Zone (EEZ) of several countries. Therefore, as a consequence of "The Law of the Sea", these data are currently restricted to DOD and DOD contractors use only. Hence, specific results and findings can not be presented at this time.

Members of the project team at NASA and NAVOCEANO are actively engaged in determining how these data may be made available to the SIMBIOS project office. It is the project's intent to establish a precedent for the release and use of this data for civilian projects without compromising the Navy's international agreements and mandates. If successful, this project may establish the means by which an important resource of oceanographic data may be made available to the research community.

16.4 WORK PLAN

The project will follow the proposed project plan with the exceptions that above water estimates of Rrs (λ) will be obtained using a GER (Geophysical Environmental Research, Inc.) 1500 hand-held spectroradiometer (300 -100 nm, effective 1 nm bandwidth) and the MER 1032 will not be used.

A survey to the South China Sea and Gulf of Thailand is planned for the summer 1999. A duplicate Satlantic system has been purchased to provide system redundancy. A Wet Labs WetStar profiling fluorometer will be configured on a profiling package to direct the selection of depths for discrete water samples. SeaWiFS LAC data will be requested during filed activites and upon processing using SeaDAS will be compared with in situ observations.

The project has acquired a AC-9 to ensure calibration history and performance for project deployments. A MicroTops II sun photometer will be used during future cruises. Increased effort will be devoted to secure the release of the data for SIMBIOS project use.

Table 1. Profiling Instrument Packages.

INSTRUMENTS	***MEASUREMENTS***
Day Package	
MER 1032 In-water Radiometer[1]	Spectral Upwelled and Downwelled Irradiance, and Spectral Upwelled Radiance
MER 21 Deck Radiometer[1b]	Surface Incident Irradiance
AC-9[2]	Spectral absorption and beam attenuation coefficients
LS-6000 Light Scattering Sensor[3]	Light scattering at 880 nm
Sea-Bird SBE 19 CTD[4]	Conductivity, temperature, and depth
PSA-900 Sonar Altimeter[5]	Height (m) of package above bottom
Night Package	
AC-9[2] (x2)	Spectral absorption, beam attenuation, backscattering coefficients
LS-6000 Light Scattering Sensor[3]	Light scattering at 880 nm
Sea-Bird SBE 19 CTD[4]	Conductivity, temperature, and depth
PSA-900 Sonar Altimeter[5]	Height (m) of package above bottom
Remote - Tethered Package	
SeaWiFS Profiling Multichannel Radiometer[6]	Spectral Upwelled Radiance, Spectral Downwelled Irradiance
SeaWiFS Multichannel Surface Reference[6]	Downwelled Spectral Surface Irradiance

[1]Biospherical Instruments, Inc.; [1b]Biospherical Instruments, Inc., MER 21 is a deck-mounted sensor;
[2]WET Labs, Inc. (Western Environmental Technology Laboratories, Inc); [3]Sea Tech, Inc.;
[4]Sea-Bird Electronics, Inc.;[5]Datasonics, Inc.; [6]Satlantic, Inc.

Chapter 17

Bio-Optical Measurement and Modeling of the California Current and Polar Oceans

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17.1 INTRODUCTION

This SIMBIOS project contract supports *in situ* oceanic optical observations in the California Current and Southern Ocean. The principal objectives of this research are to validate standard or experimental products through detailed bio-optical and biogeochemical measurements, and to combine ocean optical observations with advanced radiative transfer modeling to contribute to satellite vicarious radiometric calibration and algorithm development.

Our sampling efforts have been directed towards obtaining measurements in both the California Current and Antarctic polar waters, with the purpose of generating a high-quality, methodologically consistent data set encompassing a wide-range of oceanic conditions. The combined data base includes stations which cover the clearest oligotrophic waters to highly eutrophic blooms and red-tides, and provides a coherent set of observations to validate bio-optical algorithms for pigments and primary production. This unique and comprehensive data is utilized for development of experimental algorithms (e.g. high-low latitude pigment transition; phytoplankton absorption, photosynthesis, cDOM.

17.2 RESEARCH ACTIVITIES

The Southern California Bight region, from San Diego to just north of Point Conception, has one of the longest, most comprehensive time-series of marine observations; the California Cooperative Oceanic Fisheries Investigation (CalCOFI). This region experiences a large dynamic range of coastal and open ocean trophic structure, and has been extensively studied with respect to its regional optical properties in an effort to develop regional ocean color algorithms (e.g. Smith and Baker 1978, Mitchell and Kiefer 1988, Sosik and Mitchell 1995). During the first year of our contract, we participated in 4 quarterly cruises in the California Current region as part of the CalCOFI program.

The Southern Ocean is a large, remote region which plays a major role in global biogeochemical cycling. Despite evidence that bio-optical relationships in these waters can diverge significantly from lower-latitude waters (e.g. Mitchell and Holm-Hansen 1991), Antarctic waters have not been represented in the databases (e.g. SeaBAM) used to formulate and test modern ocean color algorithms. During the past year, we participated in 3 cruises to the Southern Ocean as part of the US JGOFS program. One cruise was located within the Ross Sea Polyna during the annual spring phytoplankton bloom, with two subsequent cruises covering the region of Antarctic Polar Front Zone along 170° W.

On all cruises, an integrated underwater profiling system was used to collect optical data and to characterize the water column. The system included an underwater radiometer (Biospherical Instruments MER-2040 or MER-2048) measuring depth, downwelling spectral irradiance (E_d) and upwelling radiance (L_u) in 13 spectral bands. A MER-2041 deck-mounted reference radiometer (Biospherical Instruments Inc) provided simultaneous measurements of above-surface downwelling irradiance. Details of the profiling procedure, characterization and calibration of the radiometers, data processing and quality control are described in Mitchell and Kahru (1998). The underwater radiometer was also interfaced with 25 cm transmissometers (SeaTech or WetLabs), a fluorometer, and SeaBird conductivity and temperature probes. When available, additional instrumentation integrated onto the profiling package included AC9 absorption and attenuation meters (Wetlabs Inc.), and a Hydroscat-6 backscattering meter (HobiLabs).

In conjuction with *in situ* optical measurements, discrete water samples were collected from a CTD-Rosette immediately before or after each profile for additional optical and biogeochemical analyses. Pigment concentrations were determined flurometrically and with HPLC. Spectral absorption coefficients (300-800 nm) of particulate material were estimated by scanning particles concentrated onto Whatman GF/F (Mitchell 1990) in a dual-beam spectrophotometer (Varian Cary 1). Absorption of soluble material was measured in 10cm cuvettes after filtering seawater samples through 0.2 um pore size polycarbonate filters.

17.3 RESEARCH RESULTS

Validation of satellite-retrieved normalized water-leaving radiances (L_{WN}) was done by comparing SeaWiFS images with *in situ* data collected concurrently (± 4 hours). Satellite data received at the Monterey Bay Research Institute, the University of California Santa Barbara (CalCOFI region) and McMurdo Station, Antarctica (Southern Ocean region) were processed to L_{WN} using SeaDAS 3.2 software (Fu et al. 1998). A total of 16 matching sets of L_{WN} were found between 2-Oct-1997 and 21-Apr-1998 for the CalCOFI region. Because of persistent cloud cover in the Southern Ocean, only 3 matchups were possible in the Ross Sea region (all on 1-Dec-1997). Satellite values were derived as averages over 3 x 3 pixel areas centered at the *in situ* measurement.

In both regions, these comparisons reveal significant under-estimation of the SeaWiFS-retrieved L_{WN} compared to *in situ* measurements. The differences were generally smallest in the 555 nm band, and largest at shorter wavelengths. The magnitude of underestimation in the shorter wavlength bands increases at high Chl concentration.

O'Reilly et al. (1998) describe the Ocean Color 2 (OC2) chlorophyll algorithm that is used by NASA in the operational processing of SeaWiFS data (Fu et al. 1998). This algorithm uses the ratio of remote sensing reflectances (R_{rs}) at 490 and 555 nm to estimate chlorophyll a concentration, with the coefficients derived by a statistical fit to a data set of 919 bio-optical measurements comprising the SeaBAM data set. More recently (August 1998), NASA announced a revised version of the OC2 (OC2-v2) which was intended to reduce the drastic over-estimation of Chl in high biomass waters produced by the original OC2 algorithm.

Figure 1 compares the performance of the OC2-v2 algorithm with our present data base of measurements from CalCOFI and the Southern Ocean. When applied to the CalCOFI data, this algorithm overestimates chl a at very high chl a and underestimates elsewhere (with the exception of the extreme low chl a). A similar pattern is seen with the Southern Ocean data, although in general the degree of underestimation is greater and the transition to overestimation occurs at lower Chl. These results underscore the eventual need for specific regional empirical algorithms to obtain more accuate estimates of Chl and primary production from ocean color remote sensing. We have recently developed an improved empirical chlorophyll algorithm for the California Current (CAL-P6), which utilizes a sixth order polynomial of the ratio of L_{WN} at 490 and 555nm (Kahru and Mitchell, 1999).

17.4 WORK PLAN

Our participation in the quarterly CalCOFI cruises in the California Current will continue throughout the next period. We are also initiating field programs in the Indian Ocean (INDOEX) and the Sea of Japan (JES) to increase the regional scope of our data base. Modeling efforts include the pursuit of regional bio-optical algorithms for in water optical properties and their relationship to biogeochemical parameters, as well as the development of semi-analytical models for the retrieval of inherent optical properties from satellite data. We anticipate that these efforts will lead to an improved understanding of the variability observed in empirical satellite algorithms. We will also initiate analyses to determine the elements of the SeaWiFS processing that lead to the underestimates of L_{wn}, which is of particular concern for high chlorophyll waters.

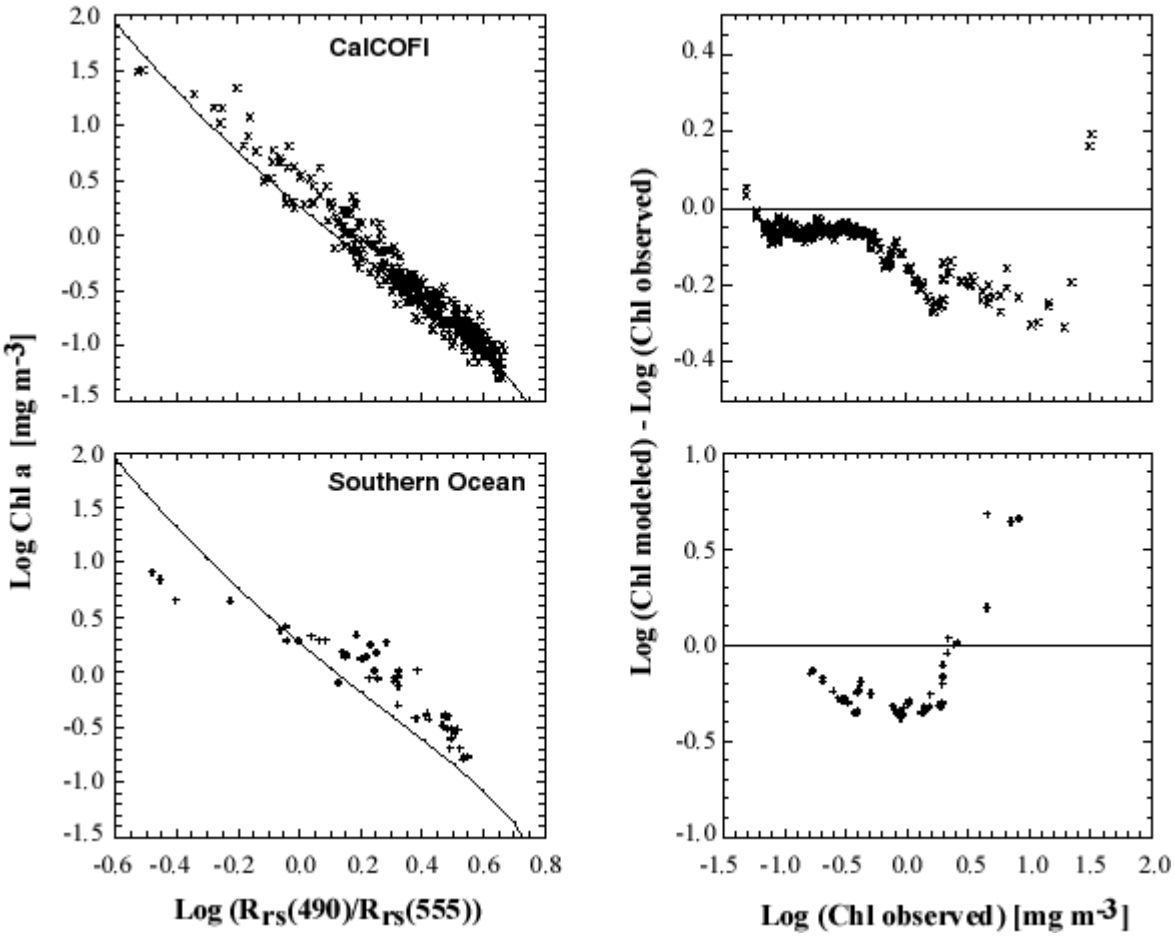

Figure 1. A comparison of the OC2-v2 algorithm (solid line in left panels) with *in situ* measurements of chlorophyll a from CalCOFI and the Southern Ocean. The right panels illustrate quantile-quantile plots of the differences between modeled and measured chlorophyll *a*.

Chapter 18

SIMBIOS Normalized Water Leaving Radiance Calibration and Validation: Sensor Responses, Atmospheric Corrections, Stray Light and Sun Glint

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18.1 INTRODUCTION

The objectives of research under this contract are to improve the uncertainty budgets and protocols for normalized water leaving radiances $L_{wN}(\lambda)$ and remote sensing reflectance $R_{rsN}(\lambda)$ determined from *in situ* measurements, and to apply in situ reflectance measurements to validate $L_{wN}(\lambda)$ and $R_{rsN}(\lambda)$ determined from radiances measured by the SIMBIOS ensemble of orbiting ocean color sensors (i.e. SeaWiFS, MODIS, GLI, POLDER and others). Our approach to these objectives includes protocol experiments to evaluate uncertainties in reflectances derived from above-water and in-water radiometry, field expeditions to acquire *in situ* radiometric, optical and biological ground truth data for validating SIMBIOS satellite ocean color sensors and match-up analyses, combining the *in situ* data with satellite radiometric data and derived parameters for vicarious radiometric calibration, and for evaluating sun glint effects and stray light artifacts in the image data.

18.2 RESEARCH ACTIVITIES

There is a general consensus that poorly understood optical variability associated with surface waves contributes strongly to the persistently significant discrepancies between remote sensing reflectances determined from above-water and underwater radiometric measurements. In above-water radiance measurements, wave roughness modifies the surface reflectance relative to a flat surface. Wave roughening also widens the effective field-of-view of reflected skylight components of the measured signal, and thus may incorporate angular variability in skylight which is not quantified by measurements using current protocols (Mueller and Austin, 1995). Finally, wave slope variations repolarize reflected skylight in ways which may not be properly accounted for using these and proposed alternative protocols.

In underwater radiometric profiles near the sea surface, surface waves radomly focus and defocus incident radiance and introduce "noise" which increases exponentially with proximity to the surface. Additional uncertainties result from strong wave-induced accelerations on an underwater radiometric package, which accelerations also increase exponentially with proximity to the surface and introduce quasi-random, difficult to measure fluctuations in sensor orientation. It is very difficult to separate these wave-related sources of uncertainty in comparing reflectances calculated from in-water and above-water measurements. It is correspondingly difficult, therefore, to partition the overall observed uncertainty between the two types of measurement. We are working towards comparative outdoor tank and field measurements which attempt to separately quantify near-surface in-water and above-water wave related uncertainties under semi-controlled conditions.

To support the difficult measurements associated with these protocol experiments, we are developing a unique hyperspectral above-water and profiling spectroradiometer and inherent optical property (IOP) system. The system is designed to allow repeated radiometric and IOP profiling at controlled ascent and descent rates, concurrent with measurements of above-water irradiance and radiance. The profiler package is built around a tethered variable buoyancy Autonomous Profiling Vehicle (APV) manufactured by Ocean Sensors Inc. of San Diego. In addition to the APV's built-in Conductivity, Temperature and Depth (CTD) sensors, sensors are attached to the profiler package to measure irradiance $E_d(\lambda,z)$, radiance $L_u(\lambda,z)$, absorption $a(\lambda,z)$, beam attenuation $c(\lambda,z)$ and chlorophyll a fluorescence. $E_d(\lambda,z)$ and $L_u(\lambda,z)$ are measured at 3.3 nm intervals from approximately 380 to 800 nm using radiometers based on Zeiss miniature fiber-optic spectrometers. Chlorophyll a fluorescence is measured using a WETSTAR fluorometer, and $a(\lambda,z)$ and $c(\lambda,z)$ are measured at 3.3 nm intervals using a HISTAR underwater spectrophotometer – both instruments are manufactured by WETLABS of Philomath, Oregon. (The WETSTAR and HISTAR are obtained under a ONR/ECOHAB research grant at CHORS.) Additional radiometers

are being integrated into the system for above-water measurements of irradiance $E_s(\lambda,z)$, total water-leaving radiance $L_{sfc}(\lambda,z)$ and sky radiance $L_{sky}(\lambda,z)$.

Validation Field Experiments

We are acquiring *in situ* data for validating SeaWiFS (and in the future MODIS and other ocean color sensors) data during field expeditions aboard the Mexican Research Vessel Francisco de Ulloa (FdU) in the Gulf of California (GoCAL). The GoCAL cruises are in collaboration with Drs. Ron Zaneveld and Scott Pegau of Oregon State University (SIMBIOS contract NAS5-97129) and Mexican scientists (Drs. Helmut Maske, Ruben Lara-Lara, Saul Alvarez-Borrego, and their students) at CICESE (an oceanography PhD granting postgraduate university in Ensenada, BC, Mexico).

The FdU is owned and operated by CICESE, and they have thus far contributed ship time for cruises in October 1997 (GoCal-97), March 1998 (GoCal-98A) and Nov-Dec 1998 (GoCal-98B). Measurements on each cruise include profiles of $E_d(\lambda,z)$ and $L_u(\lambda,z)$ at SeaWiFS wavelengths, fluorometric chlorophyll a, and HPLC pigments. IOP measurements are made by the OSU investigators, and additional bio-optical and ancillary measurements are contributed by CICESE. The next GoCal cruise aboard the FdU (GoCal-99A) is tentatively scheduled for 21 April – 2 May 1999.

All radiometric, optical and phytoplankton pigment measurement and data analysis procedures follow protocols in Mueller and Austin (1995). Radiometric profiles are analysed to obtain $E_s(\lambda,0^+)$, $E_d(\lambda),0^+)$, and $L_u(\lambda,0^+)$, using the integral method of Mueller (1995), as implemented using the CHORS interactive Kfit routine.

We are also planning to acquire validation data during day-cruises near San Diego and other California coastal sites using a small research boat. We have recently ordered and will outfit a trailerable research boat (a Parker-25 sport-fishing boat) to support this and other research projects at CHORS. Electronic equipment will be installed in the boat's enclosed pilothouse and forward cabin, while water sampling/filtering stations will be installed aft of the pilothouse under a permanent awning. Costs (acquisition, maintenance, and operating) associated with the CHORS research boat will be shared between this contract, other CHORS research projects using the boat, and SDSUF cost-sharing funds.

Calibration and Characterization

To support these experiments and analyses, CHORS carries out calibrations and characterizations of radiometers used in this project, including those of our collaborators at OSU and CICESE. NIST traceability of CHORS calibrations is maintained through tertiary standards (Optronics, Inc) and assured through participation in SIRREX and independent comparisons with other laboratories calibrating SIMBIOS instruments.

18.3 RESEARCH RESULTS

Radiometric data from GoCal-97 and GoCal-98A (including the results of the CHORS KFIT analysis of OSU's SPMR profiles) have been processed, analysed and archived in SeaBASS. Pigment data analyses and quality control have recently been completed for these two cruises, and the data will be archived in SeaBASS after appropriate reformatting and insertion of metadata. Processing and analysis of data from GoCal-98B (24 Nov through 8 Dec 1998) are in progress.

18.4 WORK PLAN

During the current contract year we will complete work in progress including:

- data processing, analysis and SeaBASS archival/documentation of data from GoCal-98B;
- Analysis and publication, in collaboration with investigators from CICESE and OSU, of data from completed GoCal cruises in 1995, 1996, 1997, 1998A and 1998B, (including SeaWiFS data for the 1997 and 1998 periods);
- Integration, laboratory characterization and calibration, and field-testing of the CHORS hyperspectral radiometric and IOP profiling and reflectance system;
- Continued routine calibrations of radiometers used by CHORS and our collaborators (OSU and CICESE) in this project.

During the current contract year, planned field campaigns include:

- GoCal-99A aboard the FdU in the Gulf of California between 20 April and 2 May 1999; and
- Day cruise, clear-sky validation sorties (within 20 nautical miles of the California coast) aboard the CHORS research boat (circa June 1999).

Reflectance protocol experiments will include tank and field in-water versus above-water reflectance measurement comparisons, as well as experimental evaluations of plaque reflectance versus direct measurements of incident irradiance and instrument self-shading tests.

Chapter 19

Validation of Carbon Flux and Related Products for SIMBIOS: the CARIACO Continental Margin Time Series

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19.1 INTRODUCTION

This SIMBIOS investigation focuses on validating ocean color satellite products from waters near continental margins. Specifically, our program focuses on collecting monthly observations within a coastal upwelling site, and seasonal extreme measurements within the plume of the Orinoco River, which is classified as having the third largest discharge in the world.

Initial focus of this project has been on setting up the logistics for field data collection and initiating routine observations. The program incorporates an effort to validate SeaWiFS products and products from the future MODIS (AM and PM), MISR, MERIS, GLI, and ROCSAT missions. Our goals are to evaluate algorithms used to compute biological and geophysical data products, develop new products aimed at assessing carbon flux, estimate the spatial and temporal errors in these products, and identify strategies that will help minimize such errors and eliminate possible biases between data sets from different missions.

19.2 RESEARCH ACTIVITIES

The core of this SIMBIOS project is an established oceanographic time series stations in the CARIOCO basin. In November 1995, the U.S. National Science Foundation, in collaboration with the Consejo Nacional de Investigaciones Cientificas y Tecnologicas (CONICIT) of Venezuela, implemented a comprehensive program of continuous observations in the Cariaco Basin, which is located in the southeastern Caribbean Sea. This multidisciplinary program is referred to as the CArbon Retention In A Colored Ocean (CARIACO) program. Specifically, the program conducts monthly observations at a station located at 10.5 N, 64.67 W.

The importance of the Cariaco Basin as a natural laboratory to study seasonal upwelling, sediments and anoxic effects has been appreciated for over 40 years. The CARIACO Program seeks to define a budget which assesses the total CO2 upwelled with deep, nutrient-rich water with respect to the annual export of organic carbon from surface waters along this continental margin. This basin is ideal for a carbon flux study because it is a large depression on a continental shelf which experiences vigorous wind-driven upwelling, and oligotrophic conditions at different times of the year. As the circulation below 200 m in this basin is restricted, it forms a natural sediment trap. The Cariaco Basin is the only permanently anoxic oceanic basin, and as such serves as an oceanic analog of the Black Sea.The series station is located at 10.50 N, 64.66 W and consists of:

- 1 to 3 monthly cruises with a fully-equipped, modern oceanographic vessel;
- Mooring with 4 sediment traps (200, 400, 800, 1200 m; capturing bi-weekly sample integrations);
- Varved (laminated) sediment core analyses.

The monthly oceanographic cruises provide information on:

- Composition, levels, and light absorption properties of organic particulate and dissolved matter;
- Pigments, HPLC, taxonomy of phytoplankton and general classification of bacteria;
- Biological productivity (phytopl. and bacteria);
- The physical/chemical characteristics of the water, including nutrient and oxygen levels;
- Carbonate system.

Shore-based, continuous meteorological and tide gauge observations are available, and we are trying to obtain these in collaboration with the local Air Force, Navy, and Environment Ministries. This project incorporates subsurface and above-surface spectral radiance, irradiance, and aerosol optical thickness measurements to the CARIACO series. The in situ bio-optical observations are all done following the SeaWiFS protocols. We have also participated in other SIMBIOS activities, including the first SIMBIOS PI meeting in Salomon's Island and a cal/val cruise to the Bahamas organized under Ken Carder's SIMBIOS program.

19.3 RESEARCH RESULTS

Each month since December 1995, bio-optical measurements have been part of the suite of measurements made at the CARIACO site. These observations were initially limited to above-water hyperspectral reflectance measurements. MER casts were performed only a few months out of this period because there was no continuous access to such an instrument.

Since October 1997, our suite of observations has included MER subsurface radiance/irradiance profiles. The optical measurements are used to validate SeaWiFS. The measurements are scheduled around the time of the SeaWiFS overflight. The monthly cruises last about 2 days each.

During each cruise, we collect bio-optical measurements using the underwater profiling Biospherical Instruments MER2048 in conjunction with a MER2041 Deck Cell. Above water measurements are made with a Photo Research Hyperspectral Colorimeter Model PR650, which is a calibrated, hand-held radiometer (8 nm resolution). Derived products include Lw (Water-Leaving Radiance), Rrs (Remote-sensed reflectance) and K (attenuation coefficient). In addition, a full suite of measurements is made which includes: particulate material and pigment absorption, HPLC, fluorometric determinations of Chl concentration, pH, Alkalinity, Primary Productivity, POC, DOC absorption and concentration, nutrients, sun photometry, oxygen, and salinity.

Cruise reports for each cruise starting in September 1997, have been submitted to the SIMBIOS Project. Approximately two years of bio-optical data have been submitted to the SeaBASS archive.

Preliminary results suggest marked seasonal changes in optical properties occur in this basin as phytoplankton concentration increases and decreases in response to coastal upwelling. Figure 1 shows the seasonal variation in surface hyperspectral remote sensing reflectance at the Cariaco station. A clear progression is seen from clear water conditions during boreal summer to blue-poor reflectances during boreal winter-spring, the time of upwelling. The decrease in blue reflectance is accompanied by a marked increase at 683 nm, clearly defining the signal of solar-stimulated fluorescence. We plan to examine this feature in relation to the primary productivity data collected concurrently during our CARIACO cruises.

We also find that there is a close correlation between phytoplankton specific absorption coefficients, primary productivity, and chlorophyll a. These data clearly are preliminary and need to be examined closely to understand variations from season to season.

The Orinoco River Plume

Above-water spectral remote-sensing reflectance (Rrs 380-700 nm) was measured including corrections for sky-radiance. We also conducted underwater measurements of remote sensing reflectance at 7 wavelengths (412, 443, 455, 475, 490, 510, 532, 560, 589, 625, 671, 683, and 700 nm) using submersible MER2048 instrumentation (Biospherical Instr.). Some observations were conducted away from the coast, where the color of the plume is influenced by colored dissolved organic matter as well as phytoplankton, but where suspended terrestrial material is expected to be minimal. We also collected data very close to the coast where the plume is extremely turbid. As of February 1, 1999, we are currently submitting bio-optical data collected during the first and second 1998 Orinoco plume cruises to SeaBASS

The Orinoco Plume data span a very broad range of remote sensing reflectance values. The river plume data are also being used by Joe Salisbury and Charles Vorosmarty at the University of New Hampshire for automated modeling of river water impact off the continent of South America, in a model linked to terrestrial hydrology.

19.4 WORK PLAN

We will continue to occupy the CARIACO station on a monthly basis. In addition, we plan to conduct two cruises to the Orinoco River plume, specifically in February and October 1999. Analysis of data and samples will continue. We are currently finalizing a manuscript that describes the seasonal cycle in hydrographic properties, phytoplankton biomass and productivity, and vertical carbon flux at the CARIACO station. We will now initiate work on a manuscript that summarizes the bio-optical data from this location.

ACKNOWLEDGMENTS

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cional de Investigaciones Cientificas y Tecnologicas (CONICIT, Venezuela). Many people have contributed substantially to the success of this program, and if they are not mentioned here it is by plain oversight on the author's part. We are indebted to the personnel of the Fundacion La Salle de Ciencias Naturales/Estacion de Investigaciones Marinas Isla Margarita (FLASA/EDIMAR) for their enthusiasm and professional support. In particular we thank FLASA's Director, Dr. Hermano Gines, for his confidence in our activities and the crew of the *R/V Hermano Gines* (FLASA) for their able support at sea. Field bio-optical measurements were conducted primarily by Natasha Rondon and John Akl of FLASA. They, and Yrene Astor and Ana Lucia Odriozola have processed the majority of the data to satisfy the seabass report formats. Jonathan Garcia (also at FLASA) has processed the samples for particulate and dissolved absorption coefficients. Juan Capelo and Javier Gutierrez (FLASA) have assisted with the primary production observations. Robert Thunell and Eric Tappa (U. South Carolina) maintain the sediment trapping program and process our particulate samples (POC, PON). Mary Scranton and Gordon Taylor (SUNY) conduct bacteria productivity studies. Dissolved Organic Carbon samples were processed by Ed Peltzer (formerly at the Woods Hole Oceanographic Institution and currently at the Monterrey Bay Aquarium Research Institute), and lately by David J. Hirschberg of State University of New York at Stony Brook.

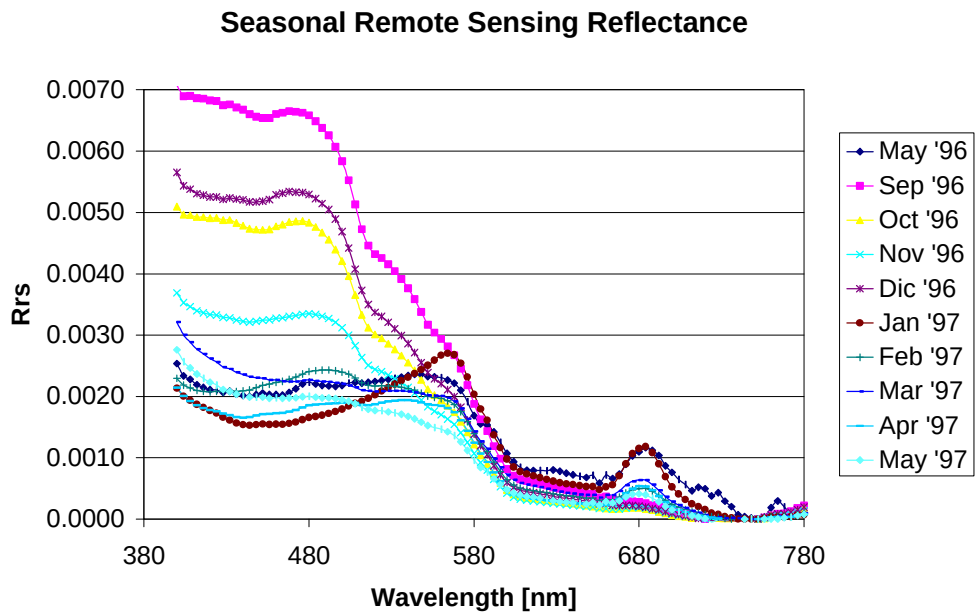

Figure 1. Remote sensing reflectance at the Cariaco station over the course of one year.

Chapter 20

Bermuda Bio-Optics Program (BBOP)

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20.1 INTRODUCTION

The Bermuda BioOptics Project (BBOP) is a collaborative effort between the Institute for Computational Earth System Science (ICESS) at the University of California at Santa Barbara (UCSB) and the Bermuda Biological Station for Research (BBSR, D. A. Siegel [UCSB] and N. B. Nelson [BBSR] P.I.'s). This research program is designed to characterize light availability and utilization in the Sargasso Sea and in doing so, provide an optical link by which biogeochemical observations may be used to evaluate bio-optical models for pigment concentration, primary production, and sinking particle fluxes from satellite-based ocean color sensors.

20.2 RESEARCH ACTIVITIES

The Bermuda Bio-Optics Program (BBOP) collects detailed profiles of AOPs and IOPs in conjunction with the US JGOFS Bermuda Atlantic Time-series Study (BATS) at 31°50' N, 64° 10' W in the mesotrophic waters of the Sargasso Sea. There are up to 16 cruises per year, conducted monthly with additional cruises during the spring bloom period, January through May.

Continuous profiles of apparent optical properties (AOPs) are collected in the upper 200m using a Multispectral Environmental Radiometer (MER-2040/2041, Biospherical Instruments Inc., San Diego CA; Smith et al., 1984). The primary optical measurements are downwelling vector irradiance and upwelling radiance, $E_d(z,t,\lambda)$ and $L_u(z,t, \lambda)$, respectively. The instrument samples these properties at 12 wavebands (including SeaWiFS wavelengths) plus broadband natural fluorescence. The BBOP sampling package also includes sensors for temperature and conductivity (SeaBird, Bellevue WA) chlorophyll fluorescence and red beam transmission (SeaTech, Corvallis OR) and a second mast-mounted spectroradiometer (MER-2041) with wavebands similar to those on the underwater instrument for measuring incident downwelling vector irradiance, $E_d(0^+,t, \lambda)$. Instrument deployments are planned to optimize match-ups with the BATS primary production incubations and, when possible, with SeaWiFS overpasses.

The BBOP group also collects several measurements of inherent optical properties (IOPs). Continuous profiles of spectral beam absorption and attenuation, $a(z, \lambda)$ and $c(z, \lambda)$, are measured using the WET Labs AC-9 (Brody, 1998), and discrete samples for determining the absorption spectra of particulates, $a_{ph}(z, \lambda)$ and $a_d(z, \lambda)$, and CDOM ($a_g(z, \lambda)$) are collected according to Nelson et al (1998). Spectral beam absorption measurements have been hampered by the fact that the baseline absorption of Sargasso Sea water is nearly the same as that of the deionized water used for the calibration. Particulate absorption spectra are determined using the quantitative filter technique (Mitchell, 1990) and CDOM absorption according to Nelson et al (1998). In 1997, we initiated the collection of above water $R_{rs}^{+}(l)$ spectra using the Analytical Spectral Devices FieldSpec spectrometer (ASD, Boulder Colorado). We are currently comparing this data set with values of $R_{rs}^{+}(l)$ calculated from MER data to evaluate its usefulness for SIMBIOS.

The profiling radiometers are calibrated three times per year at UCSB and have demonstrated remarkable calibration stability for several years, allowing the use of long-term averages for calibration coefficients (O'Brien et al., 1999). This stability, combined with streamlined procedures for data analysis, has made it possible for us to report many of our derived products with ~98% reliability in near-real time, including profiles of remote sensing reflectance ($R_{rs}(z, \lambda) = L_u(z, \lambda)/E_d(z, \lambda)$), and down- and upwelled attenuation coefficients ($K_d(z, \lambda)$, $K_u(z, \lambda)$). Our analysis procedures are fully documented in Siegel et al. (1995b). In addition to radiometer data, samples for fluorometric chlorophyll-a are collected before dawn and near noon (local time) and results are delivered to the SIMBIOS project with the AOP data, usually within one week after a cruise. Table 1 contains a list of data products collected by BBOP and/or BATS, which are relevant to SIMBIOS. A total of 472 AOP, 16 IOP and 36 pigment profiles were deliv-

ered from the start of this contract (July 1997) through 1998.

20.3 RESEARCH RESULTS

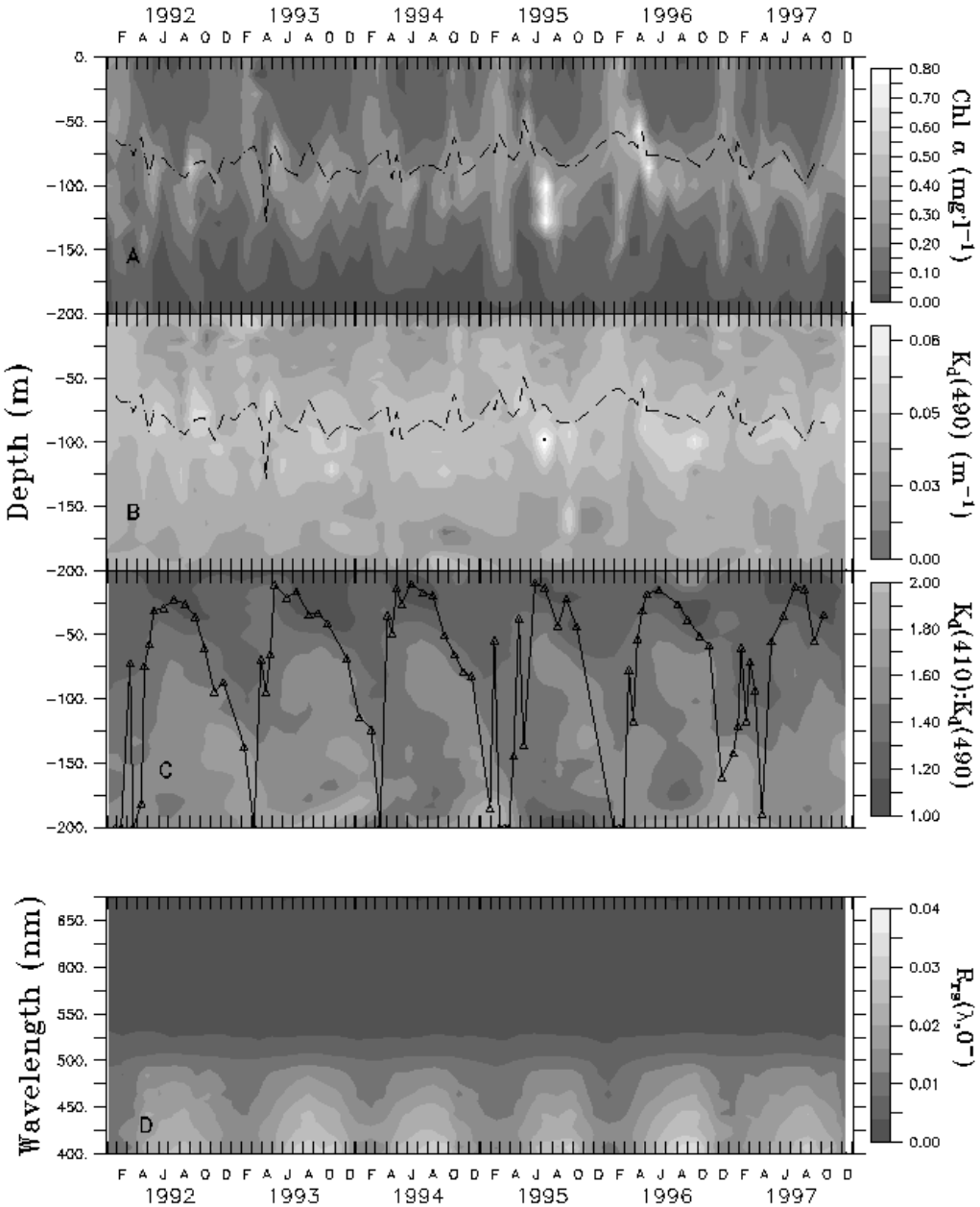
Since its inception in 1992, BBOP has made a number of important contributions toward the scientific understanding of the relationship between light and ocean biogeochemistry. The Sargasso Sea near Bermuda is mesotrophic, characterized by both eutrophic and oligotrophic conditions during different times of the year. Although low chlorophyll *a* stocks and primary production rates prevail for the most of the year, there is a short spring bloom characterized by somewhat higher concentrations and rates which is controlled by winter mixing and the associated nutrient influx.

Our research has shown that the BATS/BBOP site has an interesting and important ocean color signal associated with its colored dissolved organic material (CDOM) content. We have found that CDOM may comprise up to 50% of the light attenuation budget ($K_d(\lambda)$) at 410 nm (Siegel *et al*. 1995a, Siegel and Michaels 1996) and that CDOM concentrations can be determined from *in situ* ocean color spectra (Garver and Siegel, 1997). The ratio of $K_d(410)$ to $K_d(488)$ can be used as an index of CDOM concentration to illustrate its time-depth dynamics (Siegel *et al.* 1995a, Siegel and Michaels 1996). During the summer, CDOM is simultaneously produced within the seasonal pycnocline and photo-oxidized in the surface mixed layer (Figure 1c). Fall and winter mixing homogenizes the profile. The seasonal distribution of CDOM is unrelated to the those of chlorophyll or dissolved organic carbon, however it may be that the summer CDOM source is microbial (Siegel and Michaels 1996, Nelson et al. 1998). Since CDOM is a significant source of light attenuation in the Sargasso Sea that varies independently of chlorophyll, it appears that the optical definition of Case I waters which is based solely on chlorophyll should be reconsidered.

Table 1. A partial list of measurements made by BBOP and BATS

Direct Measurements:	
$E_d(z, \lambda)$	Downwelling vector irradiance (410,441,465,488,510,520,555,565,589,625,665 & 683 nm)
$E_d(0^+,\lambda)$	Incident irradiance (340,390,410,441,465,488,520,545,565,589,625,665 & 683 & 350-1050 nm)
$L_u(z, \lambda)$	Upwelling radiance (410,441,465,488,510,520,555,565,589,625,665 & 683 nm)
$a(z, \lambda)$	*In situ* absorption spectrum using WetLabs AC-9 (410,440,490,520,565,650,676&715 nm)
$c(z, \lambda)$	*In situ* beam attenuation spectrum (same λ's as above)
$a_{tp}(\lambda)$	Particulate absorption spectrum by QFT
$a_d(\lambda)$	Detrital particle absorption spectrum by MeOH extraction
$a_{ys}(\lambda)$	Colored dissolved absorption spectrum
$E_o(z, \lambda)$	Scalar irradiance at 441 and 488 nm
$F_f(z)$	Natural chlorophyll fluorescence using a broadband upwelled radiance sensor
chl-fl(z)	Chlorophyll fluorescence with a SeaTech fluorometer
c(z,660)	Beam attenuation coefficient at 660 nm with SeaTech 25 cm transmissometer
T(z) & S(z)	Temperature and conductivity with SeaBird probes
chl-a(z)	Discrete chlorophyll *a* determinations via Turner fluorometry (for next day delivery)
Primary Derived Products:	
$L_{wN}(\lambda)$	Normalized water leaving radiance (410,441,465,488,510,520,555,565,589,625,665 & 683 nm)
$R_{RS}(0^-,\lambda)$	In-water remote sensing reflectance (410,441,465,488,510,520,555,565,589,625,665 & 683nm)
$R_{RS}(0^+,\lambda)$	Above-water remote sensing reflectance (350 to 1050 nm)
$a_{ph}(\lambda)$	Phytoplankton absorption spectrum (= $a_p(\lambda) - a_{det}(\lambda)$)
$K_d(z, \lambda)$	Attenuation coefficient for $E_d(z, \lambda)$ (410,441,465,488,510,520,555,565,589,625,665 & 683 nm)
$K_L(z, \lambda)$	Attenuation coefficient for $L_u(z, \lambda)$ (410,441,465,488,510,520,555,565,589,625,665 & 683 nm)
<PAR(z)>	Daily mean photosynthetically available radiation at depths of the *in situ* C^{14} incubations
$b(z, \lambda)$	Spectral scattering coefficient (= $c(z, \lambda) - a(z, \lambda)$)

Figure 1. A-C: Time-depth contours of a) Chlorophyll-*a* (HPLC), b) $K_d(z,t,490)$, c) the ratio of $K_d(z,t,410):K_d(z,t,490)$ and D) time series of remote-sensing reflectance spectra ($R_{rs}(t,0^-,\lambda)$).



Chapter 21

SIMBIOS Data Product and Algorithm Validation with Emphasis on the Biogeochemical and Inherent Optical Properties

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21.1 INTRODUCTION

The purpose of the SIMBIOS program is to provide routine, long-term ocean color data from the various international ocean color missions. Our funded component of this program is to address and quantify the relative accuracies of the products from the international missions by means of product and algorithm validation. Our long-term objectives are to a) collect optical and biochemical data in oceanic and coastal regions including a cooperative international bio-optical monitoring program in the Gulf of California; b) provide collected data to the NASA database, SIMBIOS project office, and other interested users; and c) determine spatial and temporal error fields for the biological and geophysical data products from the various ocean color missions.

21.1 RESEARCH ACTIVITIES

Over the past 4 years we have been involved in a multi-national research effort focused on determining the physical and biogeochemical variability in the Gulf of California. This research is done in coordination with Drs. J. Mueller and C. Trees from San Diego State University (SDSU), Drs. S Alvarez Borrego, R. Lara-Lara, G. Gaxiola and H. Maske from the Centro de Investigacion Cientifica y de Educacion Superor de Ensenada (CICESE), Ensenada, Mexico, and Dr. E. Valdez from the University of Sonora, Hermosillo, Mexico. Our component has been to measure the inherent and apparent optical properties as well as the traditional CTD parameters on vertical scales less than 0.5 m. We have completed 5 cruises in the Gulf of California, with 3 of these cruises occurring in the last year and half during our SIMBIOS contract period. Optical data collected during these cruises are currently being used to validate SeaWiFS algorithms. We have also completed a cruise of opportunity offshore of Oregon in September 1998. Data from this cruise is currently being processed and analyzed.

Two sampling platforms are typically used during these cruises; a SLOW Descent Rate Optical Profiler (SLOWDROP) to measure the inherent optical properties as well as the physical parameters, and a profiling radiometer system to measure the downwelling irradiance and upwelling radiance. Typically, SLOWDROP and radiometer profiles are made within an hour of each other at the same location.

The SLOWDROP platform is free-falling and slightly negatively buoyant and provides 10-20 cm scale vertical resolution. A typical instrument configuration includes a SeaBird SBE-25 CTD for measuring physical parameters, a fluorometer, and two WETLabs ac-9 (9 wavelength absorption and attenuation meters) for measuring particulate and dissolved component of the inherent optical properties (IOP). CTD and IOP data are collected simultaneously during a single profile using a Wet Labs, Inc. MODAPS system for data collection and integration. Calibrations of the ac-9 instruments were performed several times during the contract period. Field calibrations of the ac-9 meters were typically done once per sampling day using a clean water standard produced using a Barnstead nanopure water system according to the SIMBIOS protocols for this instrument.

A Satlantic Inc. SPMR system is used to measure profiles of the apparent optical properties (AOP) including downwelling irradiance and upwelling radiance at 412, 444, 490, 533, 555, 590, and 684 nm. The Satlantic radiometer is calibrated at SDSU by Drs. Mueller and Pegau following NIST protocols and calibrated twice a year by Satlantic Inc. The optical filters on this radiometer were upgraded by the manufacturer (Satlantic) over the past year.

One meter binned profiles of all of the data, are provided to the SeaBASS database within 90 days of completion of each cruise. Also provided are the calibration histories of the ac-9's and the radiometer, and a detailed logbook. In the future we plan to make these data sets available via the web.

The dates of each cruise and the number of profiles made using each system are listed in Table 1.

Cruises in 1997 and 1998 were SIMBIOS supported. Figure 1 shows the station locations sampled during each cruise. Data collected during the fall cruise in 1998 is currently being processed and quality controlled. As is such, the locations of the profiles are not shown on Figure 1. Currently, we are receiving all of the SeaWiFS HRPT Level 1A data for the West Coast of North America including the Gulf of California from the DAAC. This data is being archived and processed to various levels for use in the validation of ocean color products. We have been contracted to maintain an optical profiling system for use in the SWIMBIOS instrument pool. The system contains two hyperspectral absorption and attenuation meters (WET Labs Histars), a CTD (SeaBird Electronics 25), a data acquisition system (WET Labs MODAPS+), cage, and necessary cabling. We have assembled the above system and have been testing the system in various local environments. Currently there are still some issues to be resolved as to the HiStar measurements in comparison to the ac-9 measurements, which at this point seems to be calibration dependent. We are currently working closely with WET Labs to resolve these issues. A full time technician has been hired to accompany this system, to assist users in deployment and operation and to process the data. We also maintain 3 deionizing water filtration systems (Barnstead Nanopure) which are for use by the SIMBIOS authorized users. These systems are used to produce a clean water standard for ac-9 and HiStar field calibrations. These systems are currently in hand and each has been tested and is ready for general use. We expect that the calibration issues with the profiling package will be fully addressed and the system ready for general usage by the SIMBIOS authorized users by late February 1999.

21.3 RESEARCH RESULTS

Over the past contract period, we have begun analyzing our field data collected over the past 4 years. Data collected in the Gulf of California as well as other locations were used to examine the spectral relationships between the inherent optical properties in Barnard et al. (1998). The results of this research were used to compare and contrast the inherent optical properties observed in the Gulf of California. In the shallow northwest region of the Gulf, Case II waters are consistently observed due to the resuspension of sediments. In the central portion of the Gulf, the largest variability in optical properties is associated with coastal upwelling. Away from the coasts the spectral optical properties are fairly constant. Validation of the normalized water leaving radiance measured by SeaWiFS in the Gulf of California during the 1997 and spring 1998 cruises was examined. The results of this research indicated that atmospheric correction was problematic, often causing negative water leaving radiances at 412 nm.

In coordination with our SeaWiFS funding, we have undertaken the development of a new remote sensing algorithm involving the triple ratio of the remote sensing reflectance. We have also compared the in situ radiance with the upwelling radiance resolved by the OCTS sensor off the northeastern U.S. coast.

21.4 WORK PLAN

We will be participating in two research cruises in the Gulf of California during 1999, tentatively planned for the spring and fall. We anticipate participating in other cruises in the next year, as the opportunity arises. We will also be working on the installation of an in-line fluorometer on the trans-Gulf ferry to provide a monthly transect of chlorophyll fluorescence and beam transmission data in the Gulf of California.

In the next year, we anticipate that the hyperspectral profiling package will receive a high amount of usage by the authorized users. We plan to maintain these systems as well as provide technical support to the users. Again we anticipate that this system will be available for general use by the end of February 1999. We plan to continue to investigate the inherent and apparent optical properties of the Gulf of California, as well as continuing our work with ocean color algorithm validation and development. We will also be addressing issues of atmospheric correction over the Gulf of California, which have been found to be problematic.

Table 1 Dates and number of profiles made during each of the Gulf of California cruises.

Cruise Name	Dates	# IOP profiles	# AOP profiles
GOC95fall	11/25/95 to 12/6/95	28	69
GOC96fall	10/30/96 to 11/7/96	25	25
GOC97fall	10/16/97 to 10/29/97	39	24
GOC98spring	3/6/98 to 3/16/98	27	7
GOC98fall	11/27/98 to 12/6/98	45	11

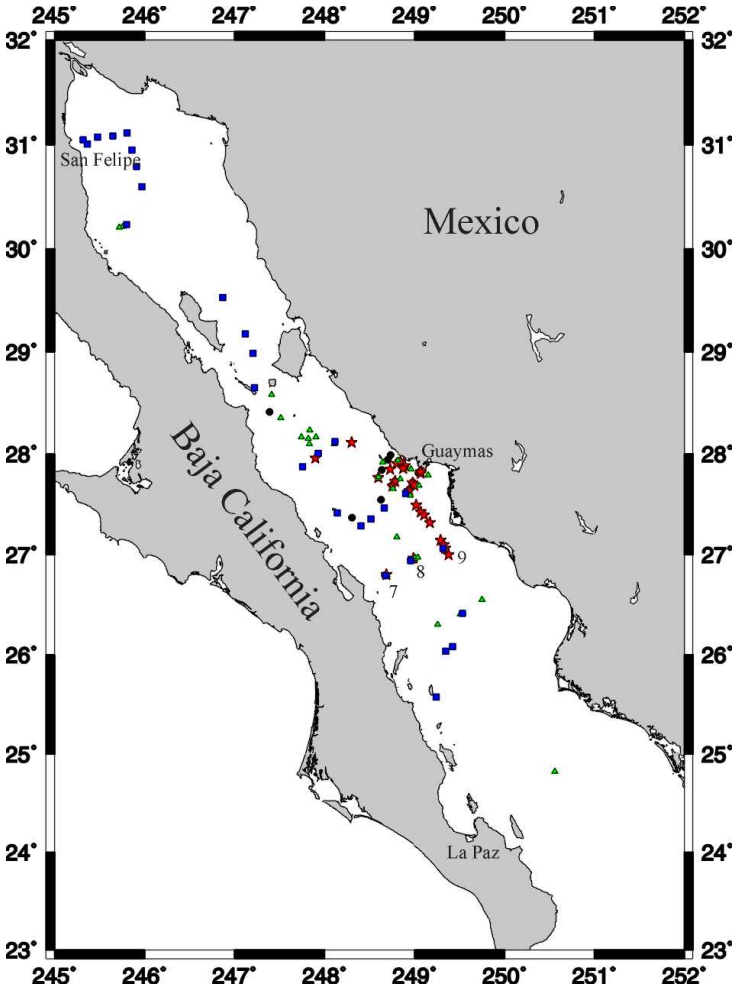

Figure 1. Map of the Gulf of California with sampling locations. The circles denote sampling locations during the 1995 cruise, the stars the 1996 cruise, the triangles the 1997 cruise, and the squares are for the spring 1998

Chapter 22

Validation of the SeaWiFS Atmospheric Correction Scheme Using Measurements of Aerosol Optical Properties

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22.1 INTRODUCTION

The focus of the research described below is comparisons between surface and satellite measurements of aerosol optical properties as a medium for validating the assumptions made in the aerosol models used in the retrieval of water-leaving radiance. Two research projects are being conducted as part of the SIMBIOS contract: The first project is to develop a Marine Fast Rotating Shadow-band Spectral Radiometer (MFRSSR) that can be used for continuous, ship-board measurements of the spectral aerosol optical depth and the spectral direct-normal and spectral diffuse irradiance. The second project is to measure and interpret aerosol properties in regions under surveillance by an ocean color satellite, thereby providing a data set from which to evaluate the atmospheric correction algorithm. This second project entails the use of AERONET and ship-board photometers and radiometers. Progress toward the completion of each of these projects and work planned for the next period is described in the subsections below.

22.2 RESEARCH ACTIVITIES

MFRSSR

There are two primary techniques used to measure the aerosol optical depth: sun photometry and rotating shadow-band radiometry. Just as sun photometers must be accurately oriented toward the sun, an obvious pitfall at sea, conventional shadow-band radiometers have required exact orientation. The development of fast-rotating, shadow-band radiometers, a hybrid form of the original shadow-band technique, has removed orientation requirement, whereupon shipboard use of shadow-band radiometers has been encouraged. As compared to land-based units, shipboard fast-rotating shadow-band radiometers require much faster rotation of the occulting arm, fast-response silicon detectors, higher data sampling rates, and more sophisticated data analysis. As part of a multi-agency effort between the Department of Energy (DOE) and NASA SIMBIOS, the Brookhaven National Laboratory has developed an MFRSSR. It measures spectral global and spectral diffuse irradiance, which are used to calculate the spectral direct-normal irradiance as a function of solar zenith angle. From these data, the aerosol optical thickness can be computed during clear periods using the Langley regression technique, or continuously if high quality extraterrestrial calibration coefficients are known.

Initial data comparisons of optical depths from hand held sunphotometers have been encouraging and an example of a time series of optical depth from the MFRSSR and MicroTops is shown in Figure 1. In this case, a well-defined decrease in the optical depth during a 9-hour measurement period was observed by both instruments. Periods of noisy optical thickness are the result of clouds, which have not been filtered in this plot. The MFRSSR is designed to operate for long periods with minimal attention and it is scheduled, along with two new units, to be at sea for a total of 7-8 months during 1999. During this period measurements will be taken over three oceans aboard the R/V Ron Brown and other ships, and from an island in the Tropical Western Pacific. At the conclusion of these cruises, all three units will spend several weeks at Mauna Loa for calibration. An important element of the MFRSSR design philosophy is automated operation and timely data analysis. Toward this end, efforts have been made to develop a cloud-filtering algorithm that can be used to identify cloud-free conditions. The initial version of this algorithm was based on the work of Long et al. (1999), but it has since been modified for more efficient use in a marine environment.

AERONET SeaWiFS Comparisons

Another approach to validating the atmospheric correction algorithms is to use land-based sunphotometers deployed in coastal locations, such as AERONET. These systems make a full range of measurements that can be used to compute the atmos-

pheric correction parameters defined by Gordon et al. (1980). It is not possible, with current instrumentation, to measure the full range of variables necessary to compute the atmospheric correction parameters at sea. One drawback of the land-based approach, however, is that near-shore measurements may not faithfully represent conditions further from the coast, whereupon an approach that combines ship-board and AERONET measurements is probably the best alternative. Both approaches are part of this study.

The AERONET and SeaWiFS optical properties for some selected locations are being compared using the SeaWiFS/AERONET match-up code developed at NASA GSFC. The initial form of this code selects dates and times of coincident SeaWiFS and AERONET measurement and extracts the aerosol optical depth from the respective data files, providing the following are true: (1) AERONET data that have passed a cloud filter algorithm are available during the two-hour period centered on the satellite overpass time, and (2) the SeaWiFS data in each individual pixel in a scene pass all quality control checks.

The match-up code identifies coincident SeaWiFs and AERONET measurement times at several locations and detailed examinations of these data are in progress. There are several points to be made. At present, we have analyzed the matchup data for the following locations: Dry Tortugas, Bermuda, San Nicholas Island, Lanai, Kaashidoo, and Bahrain. Preliminary results suggest that the pixel-to-pixel variability in the aerosol optical thickness at most of the sites is unrealistically large, perhaps due to an inadequate cloud filtering algorithm applied to the SeaWiFs data. The best match-up data sets analyzed to date are from Bermuda, Bahrain, and Kaashidoo. Comparing Bermuda and Kaashidoo, both island sites, the aerosol optical thickness as measured by both AERONET and satellite suggests that the aerosol optical thickness is generally higher at Kaashidoo, which lies in the Indian Ocean, and it tends to be more variable than at Bermuda. In general, more data tend to pass the SeaWiFs quality control algorithms at Kaashidoo, which may reflect less cloudiness more than any other single factor. The data suggests that the comparison between the SeaWiFS and AERONET is somewhat better at Bermuda than at Kaashidoo. The reason for the less favorable comparison data at Kaashidoo is under investigation, but some evidence suggests that the AERONET sunphotometer calibration may have impacted this result. Before this analysis is complete, however, the wind vector must be considered in match-up pixel selection. If the wind speed is greater than a few meters per second, the current two-hour sunphotometer data averaging period suggests that pixels outside the scene area may need to be considered for an appropriate comparison. Conversely, the sunphotometer averaging window could be reduced, although it is likely that this problem is not a factor in many of the analyses.

The largest amount of match-up data available is from the Dry Tortugas. After extensive analysis of the Dry Tortugas data, there appear to be some problems with data quality, most likely the result of AERONET sunphotometer calibration or filter decay. This problem may be corrected in the latest match-up data set. In general, data from Bermuda suggest that the aerosol optical thicknesses measured by AERONET and SeaWiFs are highly compatible. In contrast, match-up data from Kaashidoo suggest potential problems with either the AERONET or SeaWiFS aerosol optical thickness measurements, or perhaps both. It is reasonable to conclude on the basis of these results that the atmospheric correction algorithm is highly suspect in the vicinity of Kaashidoo. Data from other match-up locations are being analyzed and preliminary results suggest that SeaWiFS tends to measure a higher aerosol optical thickness at almost all locations than the AERONET. Additional ship and satellite aerosol optical thickness comparisons await a more extensive match up data base, which should be in place by the end of this year.

23.3 WORK PLANNED

There are still some issues to be addressed in the design of the MFRSSR. Controlled experiments need to be conducted on a motion simulator. The required equipment for these tests has been assembled and the experiments will be conducted when a second MFRSSR under construction for DOE is complete. In addition, pitch and roll information need to be incorporated into the data processing algorithms used to process MFRSSR, especially when the instrument is deployed on small ships.

Data from the R/V Ron Brown's 7-month cruise for INDOEX and DOE Nauru-99 campaigns will be used to facilitate match-ups with SeaWiFS and submitted to SeaBASS. In addition, two new MFRSSR units will be deployed in support of Nauru-99: one on the Japanese R/V Mirau and the other on the island of Nauru in the Tropical Western Pacific. These data will include over 200 measurement days aboard the R/V Ron Brown and additional 90 measurement days from the Mirai and Nauru. Several quality match-ups are anticipated from a variety of geographic locations and aerosol regimes. At the conclusion of INDOEX and Nauru-99, in August, all three MFRSSR units (the original and the two new units) will be offloaded at Hawaii and taken to Mauna Loa for a three week calibration, along with the microtops used in these experiments. Before shipment back to Brookhaven National Laboratory, one MFRSSR will be used in a collaborative cruise with Dr. John Porter at the University of Hawaii. Hence, over 300 ship-board meas-

urement days are planned this fiscal year and, once these data have been processed, satellite match-ups will be made. The AERONET/SeaWiFS matchup analysis is continuing. Data from all of the match-up sites will be analyzed. Particular emphasis will be placed on interpreting the match-up data from locations, such as Kaashidoo, where the analysis suggests problems with the atmospheric correction algorithm. In addition, attempts will be made to interpret the AERONET- SeaWiFS match-up data in the context of the full set of atmospheric correction parameters as described by Gordon et al. (1980).

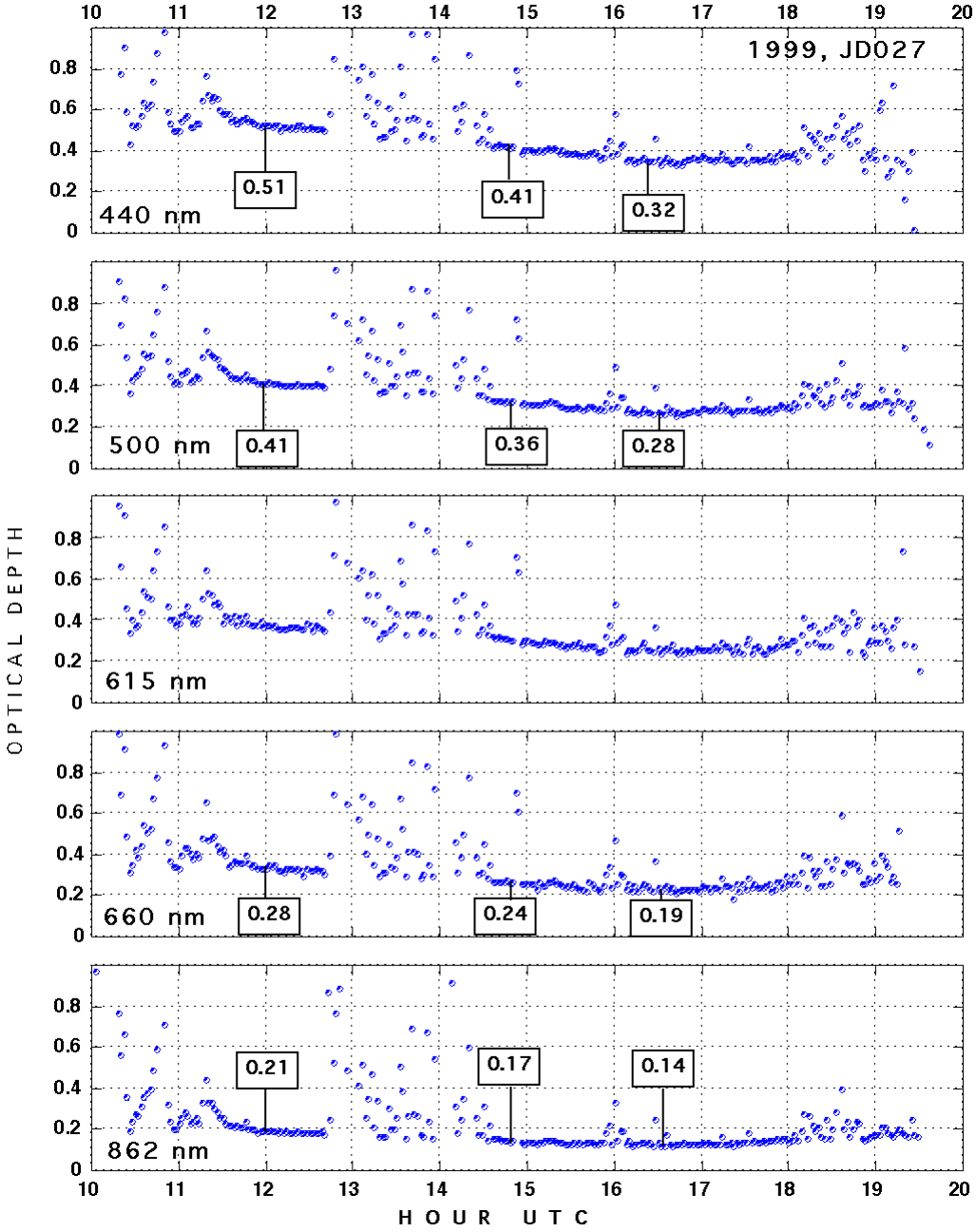

Figure 1. Spectral optical thickness measurements made with the MFRSSR at 415 nm, 500 nm, 610 nm, 660 nm, and 862 nm on January 27, 1999 over the Atlantic Ocean near the equator. Indicated in the boxes are instantaneous hand-held sun photometer measurements at 440 nm, 500 nm, 670 nm, and 870 nm.

Chapter 23

Measurements of Aerosol, Ocean and Sky Properties at the HOT Site in the Central Pacific

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23.1 INTRODUCTION

Monthly cruises have been made to the Hawaii Ocean Time Series (HOT) site (~100 km north of Oahu) since October 1988. The goal of these cruises is to make hydrography, chemistry, and biology observations (PI: Dave Karl and Roger Lucas). Measurements are typically made at a near coastal station (Kahe) on the first day to test the equipment and to obtain coastal shallow water (~1500m) observations. The second and third days are spent at the HOT site. On the morning of the fourth day, measurements are made at the HOT site and noon time measurements are made at the Hale-Aloha station near the mooring before returning to port by early the next morning. The locations of the three stations are:

- Kahe (21.34^o N, 158.27^o W)
- HOT (22.75^o N, 158.0^{o}W)
- Hale-ALOHA buoy (22.43^{o}N, 158.0^{o}W).

The routine HOT measurements are available during the summer following the year of the observations. The 1998 measurements will therefore become available during the summer of 1999. The data sets can be obtained at the National Oceanographic Data Center (NODC) or from the Hawaii HOT web site (www.hahana.soest.hawaii.edu/hot/hot_jgofs.html). Selected parts of this data set will be submitted to the SeaBass archive as the data comes on line.

23.2 RESEARCH ACTIVITIES

Microtops Sun Photometers

Beginning with the HOT89 cruise, aerosol optical depth measurements were made with two Microtops sun photometers. Examples of the data sets collected are shown in Figure 1. Aerosol optical depth measurements were made at 380, 440, 500, 675, 870 and 1020 nm. Column integrated water vapor and ozone concentrations were also derived. These measurements have been submitted to the SeaBass archive. In general we find the aerosol optical depths to be roughly the same (~0.05) at all wavelengths for typical trade wind conditions where sea salt dominates. Asian dust periods also have a flat spectral aerosol optical depth but can have optical depths of 0.1 and higher. Under VOG (volcanic smog) conditions, the shorter wavelengths have larger optical depths such as the case shown in Figure 1 (left panel). Calibration has been a major concern and numerous calibration efforts have been carried out at Mauna Loa and Haleakala. The results of these calibrations are good and they are reported in a technical report submitted to SIMBIOS. The same report goes into detail on calibration problems, measurement problems, and suggested protocols for using the Microtops hand held sun photometers. Comparisons between the ship sun photometer measurements and the SeaWiFS aerosol optical depths at 870 are shown in Figure 2. In general the agreement is about ∀0.04 with the exception of two corrisponding cases which had flat spectral optical depths higher than 0.06, suggesting Asian dust may have been present. For VOG we found a systematic under-prediction of the aerosol optical depth by about 20%.

Marine Shadowband Radiometer

During the past year we have been working on a marine shadowband radiometer which will measure aerosol optical depths and downwelling irradiance at ~20 wavelengths. This system uses a gimbaled cosine response detector and a rotating shadowband arm which shadows the detector. A CVI Laser spectrometer is used to collect the light and a PC104 computer is used to collect the data. The system has been tested on several cruises and the gimbal works well. An algorithm has been written to collect the total and diffuse light and the direct solar component is obtained from the difference. A cloud screening algorithm has also been developed which detects clouds by the variation in the downwelling irradiance just before and after the detector is shadowed. Although we believe we have made significant progress in many areas, we still have not resolved the cosine response problem as we would like near perfect cosine response with the cosine response known to 0.1%. We have tried diffusers made

of teflon, flashed opal, ground glass, spectralon, and integrating spheres. We now believe that the integrating sphere or the spectralon offer the best performance. Several new designs are being machined.

Radiometric Calibration Facility

In the past we have carried out radiance calibration of our systems at the Moby calibration facility (thanks to Dennis Clarke). Now we have purchased a NIST traceable irradiance lamp and integrating sphere from Optronics. These systems were set up in a dark room at the University of Hawaii for optical calibration. Our plans are to maintain this facility with routine checks. Unfortunately, during a SIRREX comparison, we found our calibration was approximately 5.5% too low. We could not understand this difference. Therefore we have purchased a shunt resistor which was recently calibrated by a NIST traceable calibration facility. We will soon use this calibrated resistor to check the current output of our power supply. The Optronics power supply is the first suspect as it had a transistor failure which was replaced prior to our SIRREX comparison. We expect this problem will soon be solved.

In Water Optics Measurements

As part of this SIMBIOS effort, in water PRR (Profiling Reflectance Radiometer) and TSRB (Tethered Spectral Radiometer Buoy) measurements were begun on HOT90 cruise (Dec. 1997). PRR measurements are made by Karl et al. and processed by Ricardo Letalie. Calibration of this instrument was carried out and the coefficients have been submitted to the SeaBASS archive. A description of the data and calibration is available at http://picasso.oce.orst.edu/users/jasmine/ORSOO/.

Aerosol Phase Function Measurements

As part of our initial SIMBIOS proposal, we proposed to develop a polar nephelometer which could measure the aerosol phase function. Throughout the past year we have been developing this system and have recently collected our first measurements from this prototype instrument. Our design follows the system described by Winchester Jr. (in Optical Engineering, 1983, pg. 40). Our first measurements were made at Bellows beach directly downwind of small breaking waves. We have recently purchased a pulsed laser which will allow for phase function measurements at 3 wavelengths (1064, 532, 355 nm). The system is being designed to install in the door of a light aircraft and we expect to hope to make column aerosol phase function measurements in the future.

Sky and Surface Radiometer

We are developing a hand radiometer to sky radiance and above surface upwelling radiance. The sky radiance will be used to derive aerosol size distribution information and the surface radiance will be used to validate satellite measurements and to study the diffuse reflectance problem. This system uses a wide angle camera and a tilt meter to determine the viewing geometry and a spectrometer to measure the sky or the aureole. The scattering angle is derived from the position of the sun in the camera image and a tilt meter. The system will be in a weather proof enclosure using a PC/104 computer to control the two axis motor, the camera, and the spectrometer. We had expected to have a prototype system working by now but delays have pushed it back to Spring 1999.

23.3 WORK PLAN

We have three goals: 1) continue collection of existing measurements on the HOT cruises, 2) finishing the construction of new instruments (shadowband radiometer, polar nephelometer, and sky radiometer), and 3) carry out modeling efforts. The modeling effort will focus on developing new algorithms to derive column aerosol properties from surface measurements and estimating the impact of aerosol on upwelling radiance at the top of the atmosphere.

Chapter 24

Assessment of the Contribution of the Atmosphere to Uncertainties in Normalized Water-Leaving Radiance: a Combined Modelling and Data Analysis Approach

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24.1 INTRODUCTION

Atmospheric correction, i.e. the process of deriving the normalized water-leaving radiances from satellite-measured imagery of the oceans, has been established as one sub-goal of the SIMBIOS program for which the main purpose is to provide routine, long term ocean color data from a variety of international ocean color missions. Our research for the SIMBIOS program is focused on the study of atmospheric correction. The overall objective is to use a sophisticated, state-of-the-art radiative transfer model for the coupled atmosphere-ocean system, with existing and planned algorithms, and in conjunction with data taken by other investigators in the SIMBIOS program, to help quantify the uncertainties in the water-leaving radiance due to inadequacies in atmospheric corrections applicable to OCTS, POLDER, SeaWiFS, MODIS, and other ocean color sensors.

Efficient radiative transfer codes for the atmosphere-ocean system are not generally available, and the popular and intuitively appealing Monte Carlo method (Morel and Gentili, 1991) is too time-consuming to be used in routine retrieval algorithms. To solve the radiative transfer equation for the coupled atmosphere-ocean system, we employ the discrete-ordinate method (Jin and Stamnes, 1994). This model for computing the transfer of radiation in the coupled atmosphere-ocean system is reliable and efficient. It has the accuracy of the Monte Carlo method, but overcomes its computational inefficiency.

24.2 RESEARCH ACTIVITIES

Water-leaving Radiance at NIR Wavelengths

The main goal of this study is to assess the uncertainty or error incurred in atmospheric correction by ignoring the water-leaving radiance caused by scattering from particles in the near-surface water at NIR wavelengths between 660-870 nm. Aerosol multiple scattering is included in the forward modeling to provide realistic simulations of the atmospheric contribution to the TOA radiance. We also employ a bio-optical model of ocean water with ocean particle concentrations of 1.5, 5.0, and 10.0 mg/m^3, respectively, and we employ phase functions for phytoplankton particles (i.e., cyanobacteria and algae, Volten et al., 1998) in the simulations conducted in this study.

Forward modeling is used to simulate or predict radiances that ocean color sensors would measure. From the deviation between the TOA radiances predicted by a model of the coupled atmosphere-ocean system (Jin and Stamnes, 1994) and the same model in which scattering by ocean particles (and hence water-leaving radiances) at NIR wavelengths has been ignored, one can determine under what conditions the water-leaving radiance at NIR wavelengths can be ignored in atmospheric corrections. For each sensor channel we use forward modeling simulations to accurately predict the impact of both atmospheric aerosols and biogenic constituents in the ocean on TOA radiances for any desired sun-satellite geometry, solar zenith angle θ_0, sensor viewing polar angle θ, and relative azimuthal angle ϕ with respect to the sun.

To describe scattering by particles in the ocean we employ the Henyey-Greenstein phase function p_{HG} (Henyey and Greenstein, 1941):

$$p_{HG}(g,\cos\Theta) = \frac{1-g^2}{\left(1+g^2-2g\cos\Theta\right)^{3/2}}$$

This phase function has the desirable feature that it yields complete forward scattering when the asymmetry factor g=1, isotropic scattering when g=0, and complete backward scattering when g=-1. The linear combination

$$p(\cos\Theta) = bp_{HG}(g,\cos\Theta) + (1-b)\,p_{HG}(g',\cos\Theta)$$

is sometimes used to simulate a phase function with both a forward and a backward scattering component (g>0 and g'<0). Here θ is the scattering angle, b is the fraction of forward-scattered light (0<b<1), and g and

g' are usually different. Based on laboratory measurements by Volten et al. (1998), we have used equation (2) with different values of g, g', and b to simulate phase functions corresponding to ocean waters with different types of particles.

The measurements by Volten et al. (1998) were carried out at 633 nm. Lacking better information we assume for our present purpose that they can be used to approximate the phase functions at wavelengths between 630 nm and 870 nm. Previous studies show that far from sources of pollution and/or sources of desert aerosols the aerosol optical depth at 865 nm over the Pacific Ocean lies in the range between 0.08 and 0.11 (Villevalde et al., 1994). In this study we employ a Tropospherical aerosol model with relative humidity of 80% (Shettle and Fenn, 1979) and use a Mie code to calculate the aerosol optical properties. From forward-modeling results based on these synthetic phase functions we conclude that:

- The TOA radiance deviation depends on the scattering phase function of particles in the near-surface water.
- As the aerosol optical depth decreases, the TOA radiance deviation increases. When the aerosol optical depth is large (e.g. τ_a=0.2), TOA radiances, predicted by a model in which water-leaving radiances at NIR wavelengths are ignored, do not deviate significantly from those obtained when including scattering by ocean particles. Thus, at large aerosol optical depths, we may ignore water-leaving radiances at some NIR bands (e.g. 865 nm) without introducing significant errors.
- The TOA radiance deviation increases with increasing ocean particle concentration. When the ocean particle concentration is large and the aerosol optical depth is low, water-leaving radiances at NIR wavelengths contribute substantially to TOA radiances and should not be ignored.
- The TOA radiance deviation that results from neglecting water-leaving radiances depends on the sun-satellite geometry.
- The TOA radiance deviation at λ=765 nm is larger than that at λ =865 nm.
- The TOA radiance deviation at λ =665nm is much larger than that at λ =865nm. Since the 665 nm wavelength has been used in atmospheric correction for CZCS, this deviation can have led to significant uncertainties in ocean color retrievals from the CZCS measurements.

To avoid the uncertainties incurred by ignoring water-leaving radiances at NIR wavelengths retrievals and atmospheric corrections in ocean color imagery should be based on a radiative transfer model for the coupled atmosphere-ocean system (Jin and Stamnes, 1994).

Atmospheric Correction Algorithm

The existing atmospheric correction algorithm is mainly based on the approximate exponential relationship of the single scattering aerosol reflectance over the range 412-865 nm. Two types of lookup tables for *N* selected aerosol models then constitute the main part of the algorithm. The first type of lookup table is for the coefficient ε_{ss} (λ, 865) which relates the single scattering aerosol reflectance at wavelength λ to that at 865 nm. The second type of lookup table is for the coefficient k[λ, $\rho_{as}\lambda$,)] which makes a correction for multiple scattering. For each type of lookup tables, about twelve candidate aerosol models are employed; and table entries are computed for each of these models for solar zenith angles between 0°and 80° in increments of 2.5°, for 33 values viewing zenith angles, and for eight values of the aerosol optical depth between 0.05 and 0.8. The total number of separate solutions to the radiative transfer equation used in the preparation of these lookup tables exceeds 33,000 (Gordon, 1996). Thus, the computational effort involved in the construction of these lookup tables is very large.

Based on a state-of-the-art radiative transfer model for the coupled atmosphere-ocean system, we simulate the process of atmospheric correction. Using four types of aerosol models (Tropospheric, Maritime, Coastal and Urban with RH = 50, 80 and 98 %, θ= 7°) we find that there exists an approximate exponential relationship of the aerosol reflectance over the range 412-865 nm not only in the single scattering case, but also in the multiple scattering case. Thus, a simple and efficient algorithm for atmospheric correction is proposed and discussed by comparing it with the existing algorithm. In our algorithm, the aerosol contribution in the visible in the multiple scattering can be extrapolated directly from that in the near-infrared by use of the approximate exponential relationship. Therefore it is not necessary to construct lookup tables for the coefficient κ[λ, ρ_{as} (λ)]. The new coefficient ε_{ms} (λ, 865), which represents the ratio of the multiple scattering aerosol reflectance at λ to that at 865 nm, is introduced in the new algorithm instead of ε_{ms} (λ, 865) used in the existing algorithm. Future testing of this algorithm will be carried out by use of satellite data and field measurements. The most important conclusion of this study is that one should examine whether or not water-leaving radiances at NIR wavelengths can be ignored when developing algorithms either for the retrieval of atmosphere-ocean parameters or for atmospheric corrections. Otherwise, erroneous results can be obtained if such algorithms are applied to satellite-received data, even for open oceans. A simple and efficient algorithm for atmospheric correction is also proposed and compared with the existing algorithm.

Chapter 25

Validation of the Water-Leaving Radiance Data Product

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25.1 INTRODUCTION

The overall objective of the research is to assess an accuracy of retrieval of the water-leaving radiance from satellite ocean color data. Specific goals include an assessment of accuracy of the atmospheric correction algorithms for variety of meteorological and oceanological conditions, effects of the rough sea surface reflectance and of the small-scale spatial inhomogeneities in the subsurface layer (sub-pixel variability), an accuracy of the water-leaving radiance values obtained from in situ measurements. Combined approach is used which includes direct comparison between the values of water-leaving radiance derived from satellite data and in situ measurements, computer simulation, theoretical analysis.

25.2 RESEARCH ACTIVITIES

Field Methods and Data

The instrumental set constructed in the P.P.Shirshov Institute of Oceanology Russian Academy of Sciences (SIO RAS) for field studies comprises deck and floating spectroradiometers and monitor photometer. The deck spectroradiometer is a modification of the device described before (Goldin et al. 1983); the floating spectroradiometer and the monitor photometer are new instruments (Artemyev et al., 1999). The floating spectroradiometer measures the upwelling radiance and downwelling irradiance in the spectral range 390-700 nm with spectral resolution 2.5 nm; the upwelling radiance is measured just beneath the sea surface and the downwelling irradiance just above the sea surface at a distance about 50 m from ship; thus the difficulties connected with influence of sun glints, correction for light reflected at the sea surface, influence of ship shadow are precluded. The monitor photometer is designed to check calibration of irradiance at 554 nm and measure continuously the surface irradiance at this wavelength during spectral measurements by the spectroradiometers. The radiometric accuracy of the deck and floating spectroradiometers and the monitor photometer is respectively 10%, 5% and 3%. The field testing of the floating spectroradiometer were carried out on the oceanografic platform of the Marine Hydrophysical Institute NASU in Katsiveli, September 1996. They showed an ability of the instrument to work under bad weather conditions (strong wind, cloudiness) when measurements by the deck radiometer are impracticable.

The field studies under satellite ocean color sensors SeaWiFS and MOS-IRS were performed during the scientific cruise of RV *Akvanavt* in the Black and Aegean Seas, October 6-24, 1997 (Artemyev et al., 1999). Along with measurements of spectral upwelling radiance and surface irradiance by the deck and floating radiometers, the studies included measurements of vertical profiles of nadir upwelling radiance and downwelling irradiance by means of the submersible radiometer MER-2040 (these measurements were performed by specialists from the Polish Institute of Oceanology, Sopot); determination of the atmospheric spectral optical thicknesses by means of the sun photometer; measurements of vertical profiles of the seawater beam attenuation coefficient by the submersible transmissometer; sampling and conservation of water samples for determination of phytoplankton pigment concentration. Five drift stations were carried out during the cruise, three in the Black Sea and two in the Aegean Sea. The information on the stations is given in Table 1.

Absolute radiometric calibration of the radiance and irradiance channels was performed before the expedition. During the cruise, intercalibration of the floating spectroradiometer and MER-2040 was carried out; an example of intercalibration is shown in Fig. 1. Discrepancy between values of L_u and E_d measured by these two instruments was mainly in limits of 5%.

In August-September 1998 the field studies in the eastern part of the Barents Sea were carried out during the 13th and 14th scientific cruises of R/V *Akademik Sergey Vavilov*. They included the measurements listed above, excluding measurements by MER-2040, and additionally measurements of the diffuse attenuation coefficient at wavelength 530 nm by the K_d -meter and also determinations of the particulate matter concentration, primary production, dissolved organic carbon concentration, CTD profiles. The information on the stations with optical measurements is given in Table 2.

25.3 RESEARCH RESULTS

The validation cruise of RV Akvanavt in the Black and Aegean Seas

The validation of the SeaWiFS atmospheric correction algorithm was performed with measured data from Station 2 and Station 4 where the measurements were carried out under appropriate weather conditions. Before validation, an agreement of the values of the top-of-the-atmosphere radiance $L_t(l_i)$ measured by SeaWiFS sensor and calculated by a Monte Carlo technique with *in situ* data on $r(l_i)$ and $t_a(l_i)$ was checked. The procedure developed for the Monte Carlo calculation is described elsewhere (Kopelevich et al. 1998; Burenkov et al., 1999). The results of comparison between the measured and calculated values of $L_t(l_i)$ are given in Table 3. As it is seen, the agreement is quite well for Station 2; it should be borne in mind that the observed discrepancies result not only from errors of the measurements but from also some assumption taken for the calculation. The agreement is worse for Station 4; it can be explained by some atmospheric inhomogeneity due to the proximity of the cloud edge to the pixel with this station.

The SeaWiFS atmospheric correction algorithm was validated by comparison of the $L_{WN}(l_i)$ and $t_a(l_i)$ values derived from SeaWiFS data and from *in situ* measurements. The results of comparison are given in Table 4. As it is seen, the agreement is quite satisfactory both for the $L_{WN}(l_i)$ and t_a.

The SeaWiFS algorithm for retrieving chlorophyll concentration and the analytic algorithm developed by the specialists of SIO RAS were validated by comparison of retrieved and measured data. The SeaWiFS algorithm overestimates significantly the chlorophyll concentration for Case-2 waters with predominance of absorption by yellow substance; the analytic algorithm results to reasonable agreement in all cases (Burenkov et al. in press).

The Akademik Sergey Vavilov Cruises in the Barens Sea

The preliminary analysis revealed some cases of incorrect SeaWiFS data products; an example is given in Figure 2. The negative values of $L_{WN}(443)$ are seen over most part of the image (left); the chlorophyll concentration derived from SeaWiFS data agree reasonably with the measured values only in open part of the Barent Sea and differ drastically (by a factor 20 and more) in the Pechora Basin (right image).

The measured spectral dependences of the radiance reflectance exhibit a wide variety of forms (Figure 3): the spectra measured in the north-eastern part of the Barents Sea have the maximum near 420 nm and the ratio $L_{WN}(490)/L_{WN}(555)$ about 3 (St.1209), whereas in the southern part of the Pechora Basin they are respectively near 580 nm and less than 0.5 (St.1095). According to the SeaWiFS data, the chlorophyll concentration varies over a wide range of values: from less than 0.5 $mg \cdot m^{-3}$ in the northern part to more than 20 $mg \cdot m^{-3}$ in the Pechora Basin (Figure 2, right image). The in situ data show much more narrow range of its changes. The further analysis is planned to establish the reasons for the revealed errors resulted from the SeaWiFS algorithms.

Effects of the Sub-pixel Variability

The mathematical simulation of effects of the small-scale inhomogeneities in the subsurface layer (sub-pixel variability) on the retrieval results from satellite data has been performed. The horizontal distribution of chlorophyll concentration with the sharp change was assumed, and the averaged spectral upwelling radiance was calculated. Then the averaged spectra were used to retrieve the values of chlorophyll concentration. Comparison between the obtained and true mean values has shown that discrepancies between them are no more 5 % if the amplitude of change is less 50%, but they increase up to 15% with the twofold change and 45% with the fourfold. Such sharp changes are real in the coastal waters, and potential errors should be taken into account.

25.4 WORK PLAN

- The further analysis of data obtained during the 13th and 14th cruises of R/V *Akademik Sergey Vavilov* in the Barent Sea, August-September 1998.
- Preparation of the scientific equipment for work in the 15-th cruise of R/V *Akademik Sergey Vavilov* in the Norwegian and Greenland Seas.
- The field studies in the 15th cruise of R/V *Akademik Sergey Vavilov* in the Norwegian and Greenland Seas, May-June 1999.
- Analysis of data obtained during the 15th cruise of R/V *Akademik Sergey Vavilov* in the Norwegian and Greenland Seas, May-June 1999.
- Validation of the SeaWiFS algorithm for retrieving the chlorophyll concentration in the Black Sea by comparison of the satellite and available in situ data.

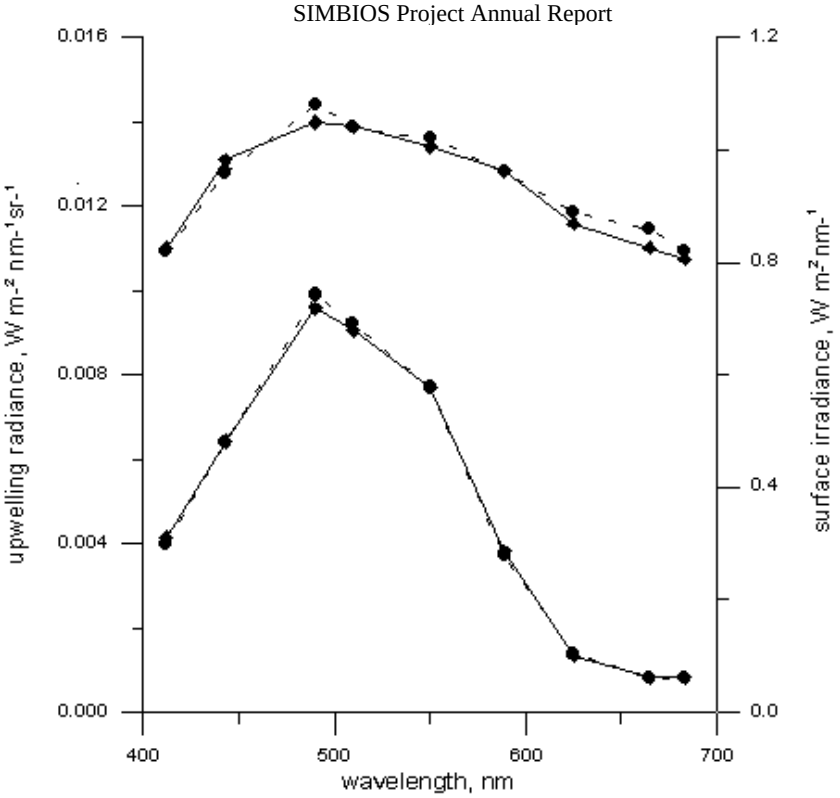

Figure 1. Results of intercalibration between the floating spectroradiometer and MER-2040 at St.2; upper curves - surface irradiance, lower - upwelling radiance; ♦ - floating spectroradiometer, • - MER-2040.

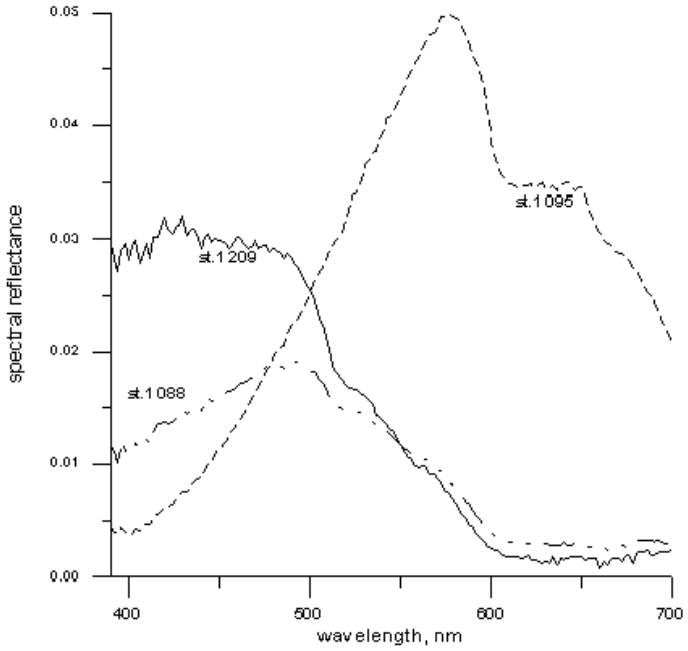

Figure 3. Spectra of the water radiance reflectance measured in different parts of the Barents Sea during the 13-th and 14-th cruises of R/V *Academik Sergey Vavilov*: St.1209 - the north-eastern part of the Barents Sea; St.1088 and St.1095 - the northern and southern parts of the Pechora Basin (see Table 2).

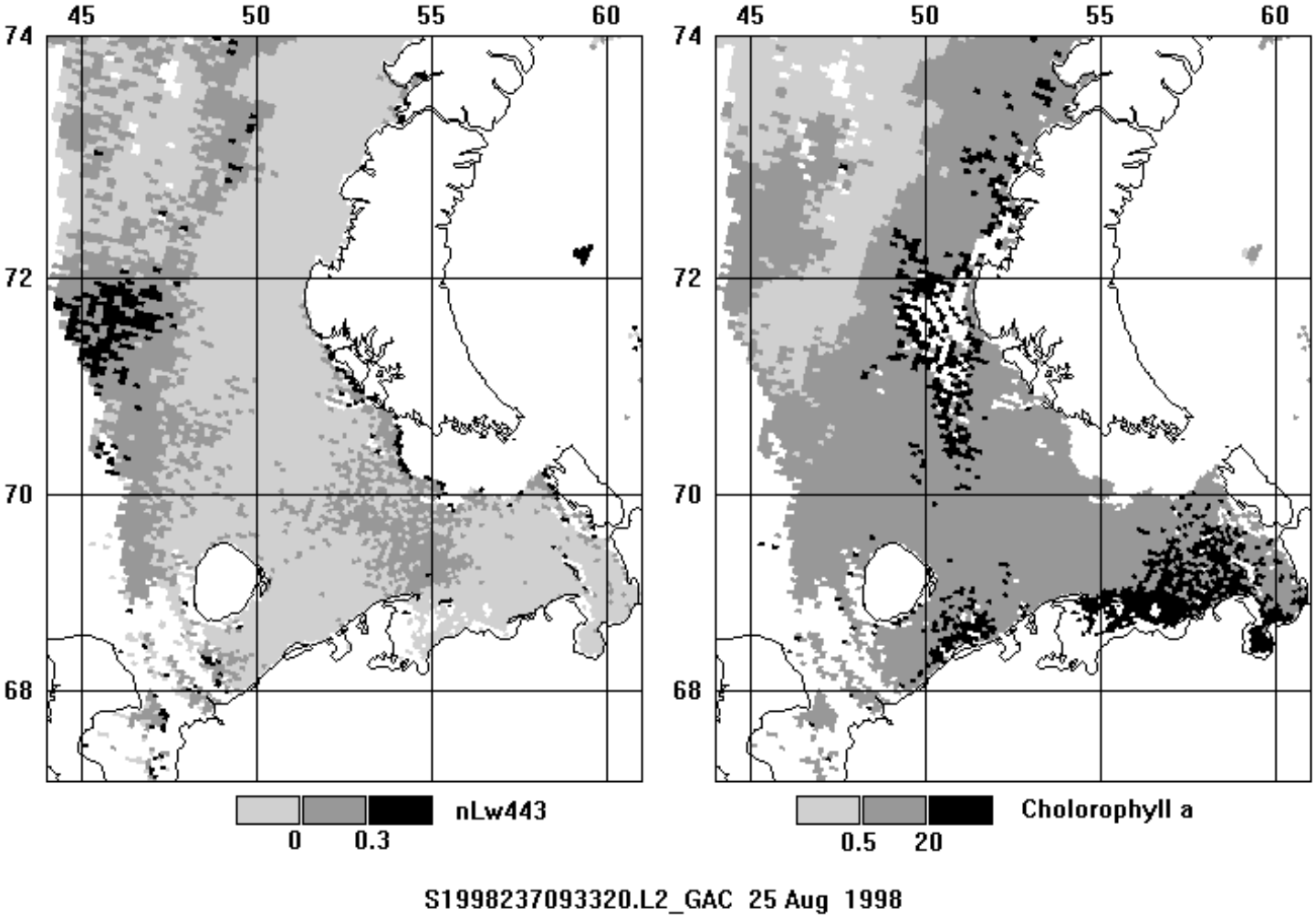

Figure 2. Spatial distributions of values of L_{WN} *(443)* and Chl *a* in the eastern part of the Barents Sea on August 25, 1998

Table 1. The information on the stations of *Akvanavt'97*.

Date	St.	Coordinates (degrees) at the measurement moments	Local time	Difference with GMT, h
10/07/97	1 *	42.5 N, 39.5 E	09:20 - 14:40	+3
10/08/97	2 *,**	43.0 N, 35.6 E	10:05 - 15:40	+3
10/09/97	3	42.9 N, 31.6 E	10:48 - 15:11	+3
10/11/97	4 *, **	39.3 N, 25.1 E	11:30 - 14:55	+3
10/16/97	5 **	39.6 N, 25.8 E	10:19 - 14:58	+3

***** - under SeaWiFS; ** - under MOS-IRS.

Table 2. The information on the stations of R/V "Akademik Sergey Vavilov" 13 and 14 cruises.

Date	St.	Coordinates (degrees) at the measurements moments	Local time	Difference with GMT, h
08/11/98	1088	70.42 N, 47.58 E	10:20 - 14:55	+4
08/12/98	1090*	70.18 N, 52.42 E	13:40 - 15:00	+4
08/14/98	1095	68.97 N, 58.47 E	08:15 - 10:30	+4
08/14/98	1097	69.07 N, 58.42 E	16:20 - 17:30	+4
08/15/98	1099	69.10 N, 58.03 E	09:00 - 10:30	+4
08/19/98	1112*	69.09 N, 58.29 E	11:30 - 12:50	+4
08/19/98	1112*	69.09 N, 58.29 E	13:55 - 14:25	+4
08/23/98	1123	69.06 N, 58.16 E	07:00 - 10:00	+4
08/23/98	1125*	69.50 N, 57.25 E	13:10 - 14:20	+4
08/23/98	1126	69.67 N, 57.24 E	16:25 - 17:30	+4
08/24/98	1131*	69.77 N, 56.28 E	14:10 - 16:00	+4
08/25/98	1133	70.33 N, 55.30 E	10:00 - 14:40	+4
08/29/98	1150	69.33 N, 50.12 E	08:10 - 09:30	+4
08/30/98	1154*	69.62 N, 50.57 E	10:30 - 14:50	+4
08/31/98	1157*	70.54 N, 52.79 E	12:30 - 14:30	+4
09/02/98	1164	68.40 N, 50.70 E	08:20 - 10:20	+4
09/10/98	1174	69.25 N, 41.00 E	08:40 - 10:40	+4
09/11/98	1183	71.50 N, 41.00 E	09:00 - 11:00	+4
09/12/98	1190	73.25 N, 41.00 E	10:00 - 12:00	+4
09/13/98	1196	74.75 N, 41.00 E	09:30 - 11:30	+4
09/15/98	1209	78.00 N, 41.00 E	10:20 - 13:00	+4
09/27/98	1281	76.00 N, 42.27 E	10:20 - 12:40	+4

* - under SeaWiFS

Table 3. Comparison between the SeaWiFS measured and Monte Carlo calculated values of the top-of-the-atmosphere-radiance $L_t(l_i)$; D is the relative discrepancy.

	Station 2			**Station 4**		
λ, nm	L_t SeaWiFS, μW cm^{-2} sr^{-1} nm^{-1}	L_t MC, μW cm^{-2} sr^{-1} nm^{-1}	Δ, %	L_t SeaWiFS, μW cm^{-2} sr^{-1} nm^{-1}	L_t MC, μW cm^{-2} sr^{-1} nm^{-1}	Δ, %
412	7.40	7.42	0.3	8.10	7.89	2.6
443	6.52	6.57	0.7	7.24	6.86	5.0
490	4.84	4.83	0.2	5.35	5.16	3.5
510	4.12	4.08	1.0	4.50	4.21	6.4
555	2.93	2.80	4.4	3.18	2.96	6.9
670	1.25	1.16	7.2	1.55	1.44	7.1
765	0.55	0.59	7.2	0.77	0.73	4.8
865	0.36	0.33	8.3	0.55	0.43	22

Table 4. Comparison between values derived from SeaWiFS and in situ data for the normalized water-leaving radiance $L_{WN}(l_i)$ and the aerosol optical thickness $t_a(865)$; D is the relative discrepancy.

	Station 2			**Station 4**		
λ, nm	L_{WN} SeaWiFS, μW cm^{-2} sr^{-1} nm^{-1}	L_{WN} measured, μW cm^{-2} sr^{-1} nm^{-1}	Δ, %	L_{WN} SeaWiFS, μW cm^{-2} sr^{-1} nm^{-1}	L_{WN} measured, μW cm^{-2} sr^{-1} nm^{-1}	Δ, %
412	0.536	0.492	9	0.770	0.732	5
443	0.752	0.708	6	0.886	0.891	0.6
490	1.036	0.998	4	0.882	0.784	6
510	0.991	0.925	7	0.592	0.537	10
555	0.770	0.772	0.3	0.271	0.272	0.4
$\tau_a(865)$	0.065	0.095	31	0.160	0.142	13

Chapter 26

OCI Data Validation in the Waters Adjacent to Taiwan

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26.1 INTRODUCTION

Taiwan successfully launched her first experimental satellite, ROCSAT-1, on January 27 1999. It is a three-axis stabilized, low-earth orbit satellite with a 35° inclination. ROCSAT-1 is designed to carry out three scientific experiments: ocean color imaging, ionospheric plasma and electrodynamics, and Ka-band communication.

The payload instrument for ocean color imaging on ROCSAT-1 is called Ocean Color Imager (OCI). OCI is a multi-spectral push-broom imager, which is designed to map six reflected spectral radiances from ocean surfaces. The six spectral bands are identical to the six of the eight spectral bands on SeaWiFS. The band characteristic comparison of OCI and SeaWiFS is listed in Table 1.

In order to have successful operation of OCI, there are two scientific groups under the OCI project, the Science Team (ST) and the Science Data Distribution Center (SDDC). The purposes of the ST are to calibrate the sensor, to correct for the atmospheric influence, to develop bio-optical algorithms, and to calibrate and validate OCI data. The SDDC at National Taiwan Ocean University (NTOU) is responsible for processing OCI data and then distributing it to users.

OCI will perform imaging at any time between 9:00 and 15:00 local time. The normal mission operation of OCI is to map ocean surface pigments whenever weather permits.

Ideally, OCI will acquire ocean surface pigment data when cloud coverage is less than 50% of the area along the track. The actual OCI operation will ultimately be decided by the OCI-ST. A preliminary operation priority has been established based on geographic locations, request sequences, weather conditions, and cross calibration and field validation areas.

For calibration and validation purposes, images are schedule to be taken when the OCI tracks overlap with SeaWiFS, or the calibration buoy location or location of the experimental cruises.

26.2 RESEARCH ACTIVITIES

It is believed that the OCI calibration at each wavelength will change in some unpredictable manners as a function of time. Experience with previous sensors, such as Coastal Zone Color Scanner (CZCS), has shown that it is very difficult to determine a sensor's calibration once it has been launched (Mueller and Austin, 1992). Unlike the SeaWiFS instrument, OCI has no on-board solar calibrator. Therefore, a cross-calibration program with SeaWiFS will be performed after OCI is available. To validate OCI and SeaWiFS data, field measurements of optical properties are carried out with a Tethered Spectral Radiometer Buoy (TSRB-II) and a SeaWiFS Profiling Multi-channel Radiometer (SPMR) made by Satlantic Company. TSRB-II is an optical buoy, which can measure the in-water upwelling radiance just beneath the sea surface $L_u(0^-, l)$ and the incident spectral irradiance above the sea surface $E_s(l)$. SPMR is a profiling radiometer that can measure the in-water upwelling radiance $L_u(Z, l)$ and downwelling spectral irradiance $E_d(Z, l)$ with depth *Z*.

To obtain $L_w(l)$ that is measured by the OCI it is necessary to propagate $L_u(0^-, l)$ upward through the sea surface as

$$L_w(l) = L_u(0^-, l)\frac{1 - r(l,q)}{n_w^2(l)} \qquad (1)$$

where $r(l,q)$ and $n_w(l)$ are the Fresnel reflectance at the solar zenith angle and the refractive index for seawater, respectively. In order to remove the influence of view angle, sun angle and the solar irradiance, the water-leaving radiance is generally transferred to normalized water-leaving radiance L_{wn} as

$$L_{wn}(l) = L_w(l)\frac{F_0(l)}{E_s(l)} \qquad (2)$$

where $F_0(l)$ denotes the mean extraterrestrial solar irradiance (Neckel and Labs,1984). For calculating the remote sensing reflectance just above the sea surface $R_{rs}(0^+, l)$ the following equation was used

$$R_{rs}(0^+, l) = 0.54 L_u(0^-, l) / E_s(l) \quad (3)$$

Since the band characteristics of OCI are similar to those of SeaWiFS, some of bio-optical algorithms from the SeaWiFS Bio-optical Algorithms Mini-Workshop (SeaBAM) are evaluated using the data sets that are collected in the water adjacent to Taiwan. The evaluated algorithms are listed in Table 2. We have collected a total of 29 in situ data including optical properties and water samples in order to derive the relationship between optical properties and chlorophyll *a* concentration. All samples, except the surface seawater, were collected by Go-Flo 2.5/5 L sampler which was attached on the rosette multi-sampler. Surface seawater was collected with a bucket. One liter of seawater was immediately filtered by Whatman GF/F (25 mm) filter, under pressure (<0.2 bar). To determine the chlorophyll *a* concentration, the filtered sample was frozen in liquid nitrogen on board, while in the laboratory the N, N-dimethylformamide (DMF) extracting solvent was added in darkness at -20°. Compared with the acetone extracting solvent, DMF has some advantages (Suzuki and Fujita, 1986; Porra et al., 1989; Suzuki and Ishimaru, 1990) and was therefore used in this study. The measurement of chlorophyll *a* was undertaken in the laboratory according to the fluorescence method described by Strickland and Parsons (1972).

26.3 RESEARCH RESULTS

A total of 29 bio-optical data were made in the time period of 1998 in the Kuroshio region near Taiwan for testing the SeaBAM algorithms. The field measurements include $E_s(l)$, $L_u(Z, l)$, $E_d(Z, l)$, and water sample for determining the chlorophyll *a* concentration. The L_{wn} is computed using Eqs. (1), and (2). The R_{rs} is obtained from Eq. (3). Most of the water samples were taken in the Case I water. The range of measured chlorophyll *a* concentration is from 0.08 ug/l to 1.25 ug/l in this data set. The statistical results between calculated chlorophyll *a* concentration using some of SeaBAM algorithms and measured chlorophyll *a* concentration from water samples are listed in Table 3. The results show that R^2 of Aiken-C, CalCOFI 2-band linear, CalCOFI 2-band cubic, Morel 2, and SeaWiFS algorithms are higher than 0.8. The RMS is smaller than 0.015 for these methods. This suggests that the SeaWiFS algorithm is also suitable for the waters adjacent to Taiwan.

26.4 WORK PLAN

In situ measurements of optical properties and chlorophyll *a* concentration will be continuous in the waters adjacent to Taiwan, especially in Taiwan Strait and East China Sea. The schedule for normal operation of OCI is from April 1999. Therefore the inter-comparison between SeaWiFS and OCI will be the most important plan for next period. Some of SeaWiFS project members will also take bio-optical data for validating OCI data. OCI data will be available in April 1999.

ACKNOWLEDGMENTS

Many thanks go to captains and crew of R/V Ocean Researcher II and R/V Ocean Researcher III for shipboard assistance. We appreciate the assistance of the GSFC/DAAC of NASA for providing the SeaWiFS data. This work is supported by the National Space Program Office (NSPO) of Taiwan under grants NSC83-NSPO-A-RDD-019-002, NSC84-NSPO-(A)-OCI-001-02, NSC85-NSPO-(A)-OCI-019-02, NSC86-NSPO-(A)-OCI-019-01, NSC86-NSPO-(A)-OCI-019-02, NSC87-NSPO-(A)-OCI-019-01, NSC87-NSPO-(A)-OCI-019-02, NSC88-NSPO-(A)-OCI-019-01, and NSC88-NSPO-(A)-OCI-019-02.

Table 3. Summary of statistical results of algorithm evaluations.

Method	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
R^2	0.859	0.833	0.816	0.772	0.825	0.769	0.794	0.792	0.848
RMS	0.012	0.014	0.015	0.019	0.015	0.020	0.017	0.018	0.013

Table 1. A Comparison of characteristics between SeaWiFS and OCI.

	SeaWiFS	**OCI**
Inclination	98.25°	35°
Altitude (km)	705	600
Period (min)	98.9	96.6
Orbital repeat time (days)	16	52
Spectral bands (nm)	B1 402-422 B2 433-453 B3 480-500 B4 500-520 B5 545-565 B6 660-680 B7 745-785 B8 845-885	B1 433-453 B2 480-500 B3 500-520 B4 545-565 B5 660-680 B6 845-885 B7 545-565
Nadir pixel (m^2)	1130 x 1130	800 x 800
Swath width (km)	2801	702
Redundancy	No	555 nm
Color sensing	Scanner	push broom
Crossing equator time (local time)	12:00	9:00 ~ 15:00
Bits	10	12
Tilt	-20°, 0°, 20°	No
Launch date (year/month)	1997/8	1999/1

Table 2. Bio-optical algorithms performed for the data taken in the waters adjacent to Taiwan.

Method	**Algorithms**	**Band ratio(R), Coefficient(s)**
1. Aiken-C	C=EXP(a0+a1*ln(R)) C=(R+a2)/(a3+a4*R)	R=Lwn490/Lwn555 a=[0.464,-1.989,-5.29,0.719,-4.23]
2. CalCOFI 2- band Linear	C=10^(a0+a1*R)	R=log(Rrs490/Rrs555) a=[0.444,-2.431]
3. CalCOFI 2- band Cubic	C=10^(a0+a1*R+a2*R^2+a3*R^3)	R=log(Rrs490/Rrs555) a=[0.450,-2.860,0.996,-0.3674]
4. Morel 1	C=10^(a0+a1*R)	R=Log(Rrs443/Rrs555) a=[0.2492,-1.768]
5. Morel 2	C=EXP(a0+a1*R)	R=Ln(Rrs490/Rrs555) a=[1.077835,-2.542605]
6. Morel 3	C=10^(a0+a1*R+a2*R^2+a3*R^3)	R=Log(Rrs443/Rrs555) a=[0.20766,-1.82876,0.75885,-0.73979]
7. Power law model	C=EXP(a0+a1*R)	R=Ln(Lwn443/Lwn555) a=[-0.0177,-1.233]
8. Carder Ratio	Log(C)=a0+(a1+a2*log(R))*log(R)	R=Rrs490/Rrs555 a=[0.0469,-1.0129,-0.7416]
9. SeaWiFS	C=10^(a0-a1*R+a2*R^2+a3*R^3)+a4	R=log(Rrs490/Rrs555) a=[0.2974,-2.2429,0.8358,-0.0077,-0.0929]

GLOSSARY

ACE	Aerosol Characterization Experiment
ADEOS	Advanced Earth Observation Satellite (Japan)
AERONET	Aerosol Robotic Network
AM-1	Not a acronym, used to designate the morning platform of EOS
AOP	Apparent Optical Properties
AOT	Aerosol Optical Thickness
APV	Autonomous Profiling Vehicle
ARGOS	Not an acronym, but the name given to the data collection and location system on the NOAA Operational Satellites.
ASCII	American Standard Code for Information Interchange
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Advanced Visible and Infrared Imaging Spectrometer
BATS	Bermuda Atlantic Time-series Study
BBOP	Bermuda Bio-Optics Profiler
BBSR	Bermuda Biological Station for Research
BNL	Brookhaven National Laboratory
BTM	Bermuda Test Mooring
Cal/Val	Calibration and Validation
CalCOFI	California Cooperative Oceanic Fisheries Investigation
CALVAL	Calibration Validation
CARICO	Carbon Retention in a Colored Ocean
Case-1	Water whose reflectance is determined by absorption.
Case-2	Water whose reflectance is significantly influenced by scattering.
CCD	Charge-Coupled Device
CDOM	Chromophoric Dissolved Organic Matter
CHN	Carbon, Hydrogen and Nitrogen
CHORS	Center for Hydro-Optics and Remote Sensing (San Diego State University)
CICESE	Centro de Investigation Cientifica y de Edcacion Superior de Ensenada (Mexico)
CIMEL	The name of a sun photometer manufacturer
CNES	Centre National d'Edudes Spatialle
CONICIT	Consejo Nacional de Investigaciones Cientifica y Technologicas (Venezuela)
CRAM	Conditional Relaxation Analysis Method
CTD	Conductivity-Temperature-Depth
CZCS	Coastal Zone Color Scanner
DAAC	Distributed Active Archive Center
DLR	Deutshe Forshungsanstalt f r Luft-und Raumfarhrt (German Aerospace Center)
DMF	Dimethylformamide
DOC	Dissolved Organic Carbon
DoD	Department of Defense
DOE	Department of Energy
ECOHAB	Ecology of Harmful Algal Blooms
EEZ	Exclusive Economic Zone
EORC	Earth Observation Research Center
EOS	Earth Observing System
FFP	Firm-Fixed Price
FOV	Field of View
ftp	File transfer protocol
FWHM	Full Width Half Maximum
GAC	Global Area Coverage, coarse resolution satellite data with a nominal ground resolution at nadir of approximately 4 Km
GB	Gigabyte, or about one billion bytes
GF/F	Not an acronym, but a specific type of glass fiber manufactured by Whatman.
GLI	Global Imager
GoCal	Gulf of California
GPS	Global Positioning System

GSFC	Goddard Space Flight Center
HIVE	High-Latitude Intercomparison and Validation Experiment
HOBI	Hydro-Optics, Biology and Instrumentation
HOT	Hawaii Ocean Time series
HPLC	High Performance Liquid Chromatography
HQ	Headquarters
HRPT	High Resolution Picture Transmission
ICESS	Institute for Computational Earth Science System
IDL	Interactive Data Language
INDOEX	Indian Ocean Experiment
IOCCG	International Ocean Color Coordinating Group
IOP	Inherent Optical Properties
IR	Infrared
IRS	Indian Remote Sensing Satellite
ISCCP	International Satellite Cloud Climatology Project
ISPO	Interim SIMBIOS Project Office
JGOFS	Joint Global Ocean Flux Study
JPL	Jet Propulsion Laboratory
LAC	Local Area Coverage, fine resolution satellite data with a nominal ground resolution at nadir of approximately 1Km
LIDAR	Light Detection and Ranging Instrument
LED	Light Emitting Dicode
LOA	Laboratorie d'Optique Atmospherique
MARMAP	Marine Resources Monitoring, Assessment and Prediction
MBARI	Monterey Bay Aquarium Research Institute
MB	Megabyte, or about one million bytes
MER	Multispectral Environmental Radiometer
MERIS	Medium Resolution Imaging Spectrometer
MFRSSR	Marine Fast Rotating Shadow-band Spectral Radiometer
MISR	Multi-angle Imaging SpectroRadiometer
MOBY	Marine Optical Buoy
MODAPS	Modular Ocean Data and Power System
MODIS	Moderate Resolution Imaging Spectroradiometer
MOS	Modular Optoelectronic Scanner
MSl12	Multi-Sensor level-1B to level-2 code
MTPE	Mission to Planet Earth
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NAVOCEANO	Naval Oceanographic Office
NDBC	National Data Buoy Center
NIMBUS	Not an acronym, but a series of NASA experimental weather satellites containing a wide variety of atmosphere, ice, and ocean sensors.
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NODC	National Oceanographic Data Center
NOPP	NIMBUS Observation Processing System
NRA	NASA Research Announcement
NSF	National Science Foundation
NSPO	National Space Program Office
NTOU	National Taiwan Ocean University
OCI	Ocean Color Imager
OCTS	Ocean Color and Temperature Sensor
ONR	Office of Naval Research
ORCA	Optical Research Consortium

	of the Arctic
OSC	Orbital Sciences Corporation
OSU	Oregon State University
PAR	Photosynthetically Available Radiation
PHILLS	Hyperspectral Imager for Low Light Spectroscopy
PI	Principal Investigator
PM-1	Not a acronym, used to designate the afternoon platform of EOS
POLDER	Polarization Detecting Environmental Radiometer (France)
PRR	Profiling Reflectance Radiometer
R&D	Research and Development
R/V	Research Vessel
ROCSAT	Republic of China (Taiwan) Satellite platform for the OCI sensor.
RR	Round-Robin
SAB	South Atlantic Bight
SBE	Sea-Bird Electronics
SCOR	Scientific Committee on Oceanic Research
SDDC	Science Data Distribution Center
SeaOPS	SeaWiFS Optical Profiling System
SeaBAM	SeaWiFS Bio-optical Algorithms Mini-workshop
SeaBASS	SeaWiFS Bio-optical Archive and Storage System
SeaDAS	SeaWiFs Data Analysis System
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SIMBAD	The name of a sun photometer
SIMBIOS	Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies
SIO	Scripps Institution of Oceanography
SGI	Silicon Graphics, Inc.
SIRREX	SeaWiFS Intercalibration Round-Robin Experiment
SLOWDROP	Slow Descendent Rate Optical Profiler
SMSR	SeaWiFS Multispectral Surface Reference
SOOP	Ship of Opportunity Program
SOW	Statement of Work
SPMR	SeaWiFS Profiling Multi-channel Radiometer
SQM	SeaWiFS Quality Monitor
ST	Science Team
TB	Terabytes
TOA	Top of the Atmosphere
TOMS	Total Ozone Mapping Spectrometer
TOTO	Tongue of the Ocean
TSM	Total Suspended Matter
TSRB-II	Tethered Spectral Radiometer Buoy - II
XBT	Expendable Bathythermograph

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