Final Report

Performance Period 8/18/97 - 11/30/00

Bio-Optical measurement and modeling of the California Current and Polar Oceans

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Contract number: NAS5-97130

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Overview

This report summarizes our 3-year effort for our NASA SIMBIOS Contract:

Bio-Optical measurement and modeling of the California Current and Polar Oceans NAS5-97130

The principal goals of our 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 advanced algorithm development. To achieve our goals requires continued efforts to execute complex field programs globally, as well as development of advanced ocean optical measurement protocols. We completed a comprehensive set of ocean optical observations in the California Current, Southern Ocean, Indian Ocean requiring a large commitment to instrument calibration, measurement protocols, data processing and data merger. We augmented separately funded projects of our own, as well as others, to acquire *in situ* data sets we have collected on various global cruises supported by separate grants or contracts. In collaboration with major oceanographic ship-based observation programs funded by various agencies (CalCOFI, US JGOFS, NOAA AMLR, INDOEX and Japan/East Sea) our SIMBIOS effort has resulted in data from diverse bio-optical provinces. For these global deployments we generate a high-quality, methodologically consistent, data set encompassing a wide-range of oceanic conditions. Global data collected in recent years have been integrated with our on-going CalCOFI database and have been used to evaluate SeaWiFS algorithms and to carry out validation studies. The combined database we have assembled now comprises more than 700 stations and includes observations for the clearest oligotrophic waters, highly eutrophic blooms, red-tides and coastal case 2 conditions. The data has been used to validate water-leaving radiance estimated with SeaWiFS as well as bio-optical algorithms for chlorophyll pigments. The comprehensive data is utilized for development of experimental algorithms (e.g. high-low latitude pigment transition, phytoplankton absorption, and cDOM). During this period we completed 9 peer-reviewed publications in high quality journals, and presented aspects of our work at more than 10 scientific conferences.

Year End Technical Memorandum 2000

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Introduction

This SIMBIOS project contract supports *in situ* ocean optical observations in the California Current, Southern Ocean, Indian Ocean as well as merger of other *in situ* data sets we have collected on various global cruises supported by separate grants or contracts. The principal goals of our 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 advanced algorithm development.

In collaboration with major oceanographic ship-based observation programs funded by various agencies (CalCOFI, US JGOFS, NOAA AMLR, INDOEX and Japan/East Sea) our SIMBIOS effort has resulted in data from diverse bio-optical provinces. For these global deployments we generate a high-quality, methodologically consistent, data set encompassing a wide-range of oceanic conditions. Global data collected in recent years have been integrated with our on-going CalCOFI database and have been used to evaluate SeaWiFS algorithms and to carry out validation studies. The combined database we have assembled now comprises more than 700 stations and includes observations for the clearest oligotrophic waters, highly eutrophic blooms, red-tides and coastal case 2 conditions. The data has been used to validate water-leaving radiance estimated with SeaWiFS as well as bio-optical algorithms for chlorophyll pigments. The comprehensive data is utilized for development of experimental algorithms (e.g. high-low latitude pigment transition, phytoplankton absorption, and cDOM).

Research Activities: Field methods and data

A key element of our program includes on-going deployment on CalCOFI cruises to the California Current System (CCS) for which we have a 7-year time-series. This region experiences a large dynamic range of coastal and open ocean trophic structure and has experienced strong interannual forcing associated with the El Niño – La Niña cycle from 1997-2000 (Kahru and Mitchell, 2000; Kahru and Mitchell, in press). CalCOFI data provides an excellent reference for evaluating our other global data sets.

During the third year of our contract, we participated in 3 CalCOFI cruises, one cruise in collaboration with NOAA AMLR to the Southern Ocean, three cruises in East Asian marginal seas, and one cruise off the west coast of Mexico with colleagues from CICESE in Ensenada, Mexico. The global distribution of our present data set is shown in Figure 1. 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 procedures, 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 conjunction 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 fluorometrically and with HPLC. Spectral absorption coefficients (300-800 nm) of particulate material were estimated by scanning particles concentrated onto Whatman GF/F filters (Mitchell 1990) in a dual-beam spectrophotometer (Varian Cary 1). Absorption of soluble material was measured in 10 cm cuvettes after filtering seawater samples through 0.2 µm pore size polycarbonate filters. Absorption methods are described in more detail in Mitchell et al. (2000). We have also been collecting detailed measurements of other optical and phytoplankton properties including phycoerythrin pigment, size distribution using flow cytometry and a Coulter Multisizer, photosynthesis, and particulate organic matter (carbon and nitrogen).

Research Results

Our normalized water leaving radiances (L_{wn}) at SeaWiFS bands for the global data set are plotted against surface chl-*a* in Figure 2. Our original CalCOFI data represented approximately 30% of the data used by O'Reilly et al. (1998) for development of the SeaWiFS OC2v2 and approximately 25% of the updated OC 4 algorithm (O'Reilly et al., 2000). Previously we used SeaDAS v3.0 to evaluate OC2v2 estimates of chl-*a* compared to a CalCOFI-specific regional algorithm (CAL-P6) using match-ups collected during CalCOFI cruises (Kahru and Mitchell, 1999). Here we compare retrievals for SeaDAS v4.0, which has updated atmospheric and bio-optical algorithms (Figures 3 and 4). Whereas OC2v2 in SeaDAS 3.0 tended to overestimate *in situ* chl-*a* at high values and underestimate at low values (Kahru and Mitchell, 1999), we find that OC4 in SeaDAS 4.0 tends to underestimate chl-*a* at high values, but is very good at low chlorophyll (Figure 3). Even after processing with the new atmospheric algorithm that eliminates the assumption that L_{wn} in the near infrared is zero (Siegel et al., 2000), SeaDAS v4.0 still has significant underestimates of L_{wn} at 412 for all our match-ups (chl-a range 0.1-10.0) with worse performance at high chl-*a* (Figure 4). Even L_{wn} 443 tends to be underestimated over most the range, but not as severely as L_{wn} 412. Continued effort is still required to improve the accuracy of L_{wn} if we are to be able to apply multi-wavelength bio-optical retrieval algorithms that require accurate estimates of L_{wn} at 412 and 443 (e.g. Garver and Siegel, 1997; Carder et al., 1999).

For the Southern Ocean data (red crosses in Figure 2), there is a strong deviation from our other global data sets, and much greater variance in the scatter plots. This region has been shown to have bio-optical algorithms that are different than low latitude regions such as CalCOFI (Mitchell and Holm-Hansen, 1991; Mitchell, 1992). The large variance in the L_{wn}-chl-a scatter plots may be attributable in part to very different community types (e.g. prymnesiophytes, diatoms, cryptophytes as discussed in Arrigo et al., 1998). Our results underscore the need for more data to serve as a basis for regional algorithms to improve estimates of chl-*a* from ocean color remote sensing. Regional algorithms will require procedures to allow transition from low latitude to high latitude without introducing errors at the lower latitudes. More data and advanced models are required to resolve issues regarding Southern Ocean bio-optical algorithms, and the causes of observed differentiation within the region as well as differences between the Southern Ocean and lower latitudes. For a better understanding, it is essential to determine not only reflectance and chlorophyll, but also inherent optical properties including absorption and backscattering as reported by Reynolds et al. (In press). Generally, there are few observations in the Southern Ocean, and even fewer with detailed observations including inherent optical properties. We lack combined pigment and optical observations in the extremely low chlorophyll regions that can be observed in the SeaWiFS images for the southern Pacific Ocean sector west of the Drake Passage, and the southern Indian Ocean sector west of Kerguelan

Island. These two regions represent very low satellite-derived chlorophyll, which never exceed values of 0.2 mg chl-*a* m^{-3}.

A significant issue that has arisen within the SIMBIOS community is the fidelity of chl-a estimates using either HPLC or fluorometric methods. We have completed analysis and quality control for more than 800 samples taken from the same water sampling bottles during CalCOFI cruises (Figure 5). The fluorometric method is described in Venrick, et al., (1984) and the HPLC method is described in Goericke and Repeta (1993). We find that there is excellent overall agreement with a nearly 1:1 relationship, however individual samples routinely differ by up to30-40%. For the JGOFS Southern Ocean Polar Front cruises, the discrepancies were much larger and are still unresolved. A high priority for SIMBIOS should be to ensure the highest possible quality of pigment estimates, which will require consistent implementation of rigorous protocols. As a contribution to this effort, we participated in the SIMBIOS pigment round robin experiment during the past year.

Future Plans

With renewal of our SIMBIOS contract, we will continue our approach of acquiring detailed, high quality data sets at the global scale. We will continue to participate in CalCOFI cruises. In 2001 we will also participate in the NOAA AMLR cruise to the Southern Ocean and the NOAA ACE-Asia cruise to the western sub-tropical Pacific, East China Sea, and Yellow Sea. A detailed set of spectral reflectance, absorption, backscattering, pigment, and particle size structure will be determined on most cruises. A new free-fall radiometer will be acquired with 19 channels (310-700 nm) for determining both downwelling and upwelling irradiance, and upwelling radiance for all spectral bands. We have shown that measuring these three radiometric geometries with our MER 2048 allowed us to retrieve backscatter and absorption coefficients (Stramska et al., 2000). We will continue our modeling efforts to improve our understanding of regional bio-optical properties and their relationship to biogeochemical parameters (e.g. Reynolds et al, in press; Loisel et al., submitted). Our goal is to develop appropriate regional parameterizations for semi-analytical inversion models for the retrieval of inherent optical properties as well as biogeochemical properties besides chl-*a* in addition to continuing our validation work for standard ocean color satellite algorithms.

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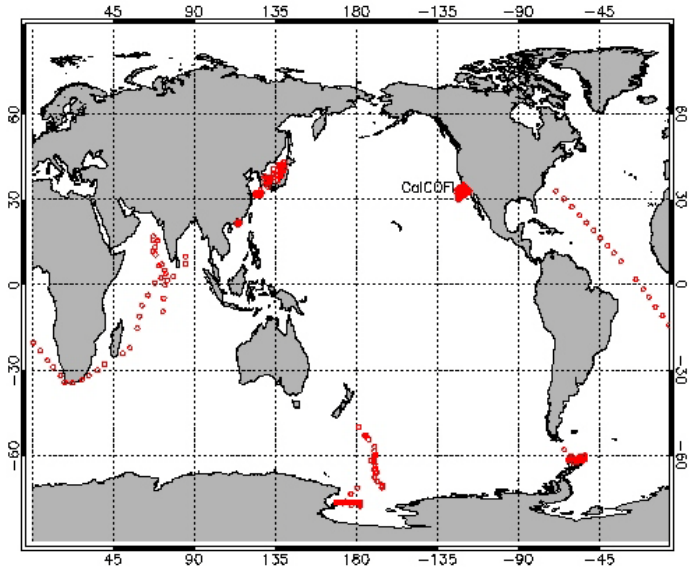

Figure 1. Distribution of *in situ* optical stations available for algorithm development.

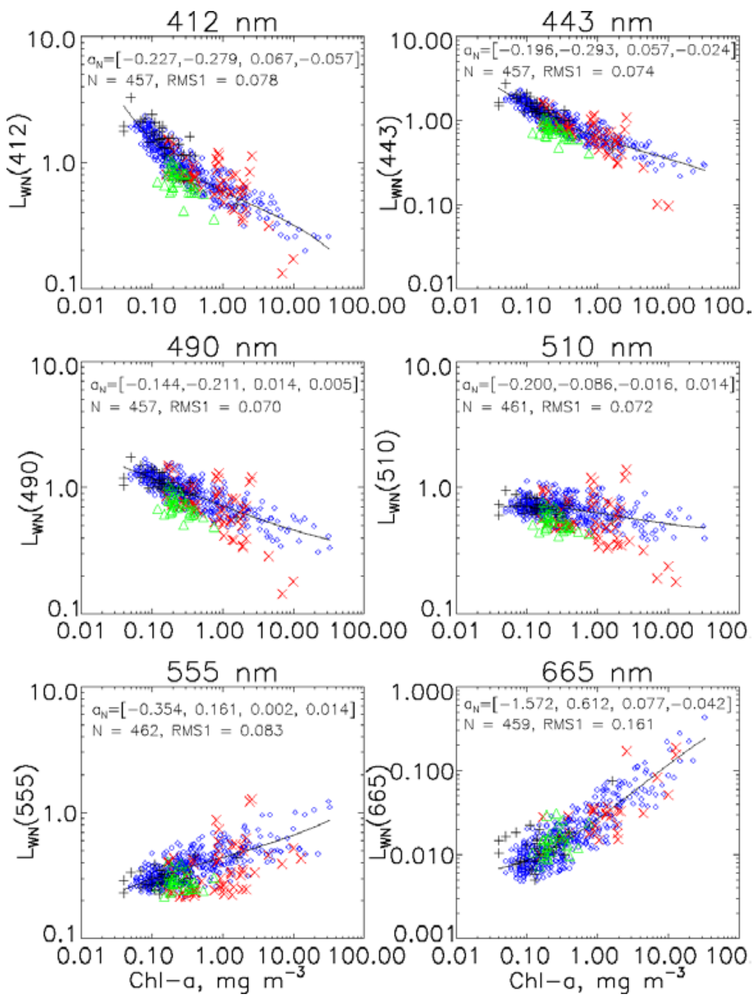

Figure 2. Normalized water leaving radiance at SeaWiFS bands plotted against chlorophyll for our global data set. Blue = CalCOFI, Green = Japan/East Sea; Black = INDOEX; Red = JGOFS Southern Ocean.

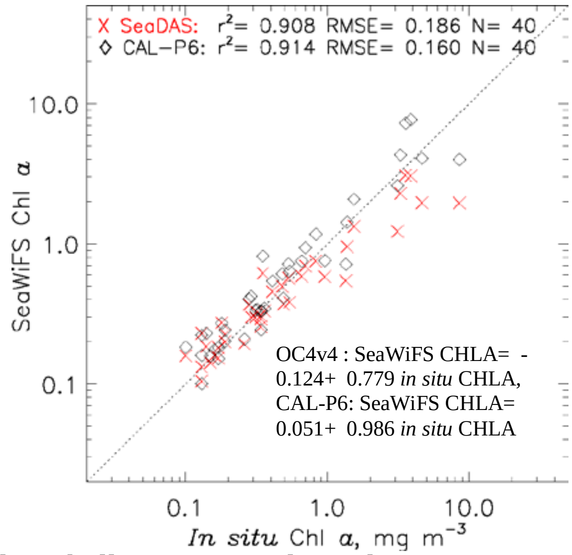

Figure 3. Chlorophyll-*a* estimates derived using SeaWiFS SeaDAS version 4.0 compared to in situ estimates of chlorophyll-*a* for NASA's global processing version 3.0 OC4 algorithm, and our CAL-P6 algorithm.

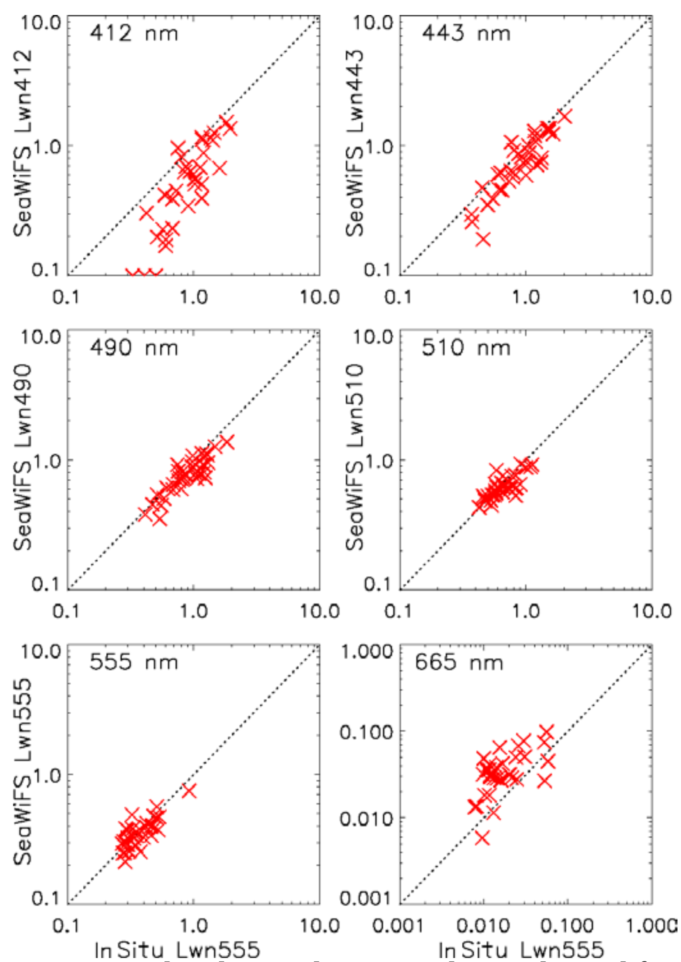

Figure 4. Normalized water leaving radiance derived from SeaWiFS SeaDAS version 4.0 processing compared to *in situ* measurements at the 6 visible bands of SeaWiFS.

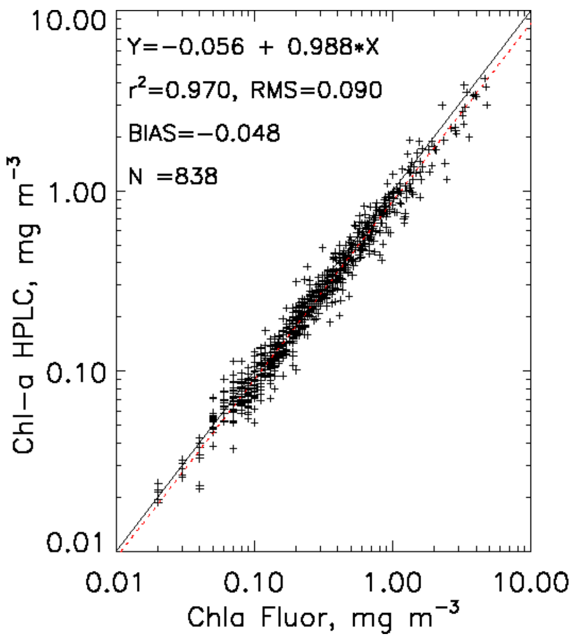

Figure 5. CalCOFI HPLC total chlorophyll-*a* (mono-vinyl and di-vinyl chl-*a*, and closely related derivates) plotted against fluorometric chlorophyll-*a*. The 1:1 and regression fits are indicated by the solid and dashed lines, respectively.

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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.

In collaboration with the CalCOFI and US JGOFS programs, our sampling efforts have been focused primarily on the California Current and Antarctic waters, with the purpose of generating a high-quality, methodologically consistent data set encompassing a wide-range of oceanic conditions. In the past year we have collaborated with other SIMBIOS PIs to collect data in the Atlantic and Indian Oceans and we are merging our ONR-sponsored Sea of Japan data set to the SIMBIOS database. The combined data base we have assembled 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, inherent optical properties 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, and cDOM).

Research Activities: Field methods and data

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 second year of our contract, we participated in 3 CalCOFI 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 been under-represented in the databases (e.g. SeaBAM) used to formulate and test modern ocean color algorithms. During the past year, we have analyzed detailed observations collected in year 1 of our SIMBIOS project and have published novel algorithms for retrieval of particulate organic carbon (Stramski et al., 1999) and have submitted a detailed optical model for Southern Ocean waters (Reynolds et al., submitted).

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 conjunction 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 fluorometrically 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 10 cm cuvettes after filtering seawater samples through 0.2 um pore size polycarbonate filters. We have also been collecting detailed measurements of other optical and phytoplankton properties including phycoerythrin pigment, size distribution using a Coulter Multisizer, photosynthesis, and particulate organic matter (carbon and nitrogen).

Research Results

A. Chl algorithms - CalCOFI data represents approximately 30% of the data used by O'Reilly et al. (1998) for development of the operational SeaWiFS Ocean Color 2 version 2 algorithm (OC2v2). We have evaluated this algorithm compared to a CalCOFI-specific regional algorithm (CAL-P6) using match-ups collected during CalCOFI cruises (Kahru and Mitchell, in press). At this time the atmospheric correction or calibration errors in the retrieval of L_{WN} create larger errors in chl-*a* retrieval than differences between OC2v2 and CAL-P6. For the Southern Ocean, however, there is a significant bias in the OC2v2 algorithm, which warrants a focused effort – at low chl-*a* OC2v2 underestimates chl-*a*, and it overestimates at high chl-*a*. Figure 1 illustrates the $L_{WN}(490)/L_{WN}(555)$ ratio plotted against chl-*a* for our combined RACER and JGOFS Southern Ocean data sets. This region has been shown to have bio-optical algorithms that are different than low latitude regions such as CalCOFI (Mitchell and Holm-Hansen, 1991; Mitchell, 1992; Arrigo et al., 1998). Our results underscore the eventual need for specific regional algorithms to obtain more accurate estimates of chl-*a* and primary production from ocean color remote sensing. Regional algorithms will require procedures to allow transition from low latitude to high latitude without introducing errors at the lower latitudes. Unfortunately, there is relatively little data in the polar front region; we have less than 20 observations from JGOFS, and there are no reports of other data in this region. Also lacking in the polar Southern Ocean data sets are combined pigment and optical observations in the extremely low chlorophyll regions that can be observed in the SeaWiFS imager for the southern Pacific Ocean sector west of the Drake Passage, and the southern Indian Ocean sector west of Kerguelan Island. These two regions represent very low satellite-derived chlorophyll which never exceed values of 0.2 mg chl-*a* m^{-3}.

L_{WN} match-ups

In situ instrument intercomparison - During INDOEX, we deployed our Biospherical Instruments MER-2048 and the SIMBIOS pool Satlantic SPMR radiometer at the same stations. The MER-2048 was deployed from the ship's stern A-frame, with potential contamination by ship's shadow, and the SPMR was deployed in free-fall mode, which would have no ship shadow artifacts. Figure 2A is a scatter plot for SeaWiFS channels of L_{WN} derived from the two systems. Overall, the correspondence is excellent with no bias relative to the 1:1 relationship. Figure 2B is a plot of MER-2048 and SPMR derived spectral L_{WN} compared to SeaWiFS derived L_{WN} for a clear sky match-up. The issues of poor L_{WN} retrieval reviewed by Kahru and Mitchell (in press) and Mitchell and Flatau, 1998 are evident.

Evaluation of atmospheric correction schemes - The SIMBIOS Project has defined a need to evaluate the atmospheric correction algorithms for SeaWiFS, and convened a workshop which led to the proposal of 6 separate atmospheric correction schemes. We evaluated all 6 schemes with our match-up data (25 match-ups, 17 of which are from CalCOFI). Evaluation of satellite-retrieved normalized water-leaving radiances (L_{WN}) was done by comparing SeaWiFS HRPT images with *in situ* data collected concurrently (± 4 hours). HRPT data were processed to L_{WN} using SeaDAS 3.3 software (Fu et al. 1998; update 004 released 9/1/99). The level 2 generation atmospheric correction module of this version of SeaDAS was modified by the SIMBIOS project with 6 candidate codes to be evaluated. Satellite values were derived as averages over 3 x 3 pixel areas centered at the *in situ* measurement. In summary, these comparisons reveal under-estimation of the SeaWiFS-retrieved L_{WN} using the "baseline" algorithm compared to *in situ* measurements; the discrepancies were larger for pooled data greater than 1 mg chl m^{-3}. An example of the SeaWiFS retrieved problem is illustrated in Figure 2B. The differences were generally smallest in the 555 nm band, and largest at shorter wavelengths. Some of the proposed atmospheric correction revisions improved the underestimation, but none of the candidate algorithms was capable of retrieving accurate L_{WN} for SeaWiFS bands 1 and 2. Part of the problem at short wavelengths may be attributed to calibration errors rather than issues related to the zero water leaving radiance assumptions or aerosol models of the base line processing.

Work plan for next period

Our participation in the quarterly CalCOFI cruises in the California Current will continue throughout the next period. We also hope to carry out at least 1 cruise to the Southern Ocean as well as additional cruises in Korean waters. We will continue data processing from previous cruises, including CalCOFI, JGOFS, INDOEX and Japan/East Sea. Specific attention will be placed on developing routine processing schemes for our AC9 and Hydroscat data. We will continue our modeling efforts to improve our understanding of regional bio-optical properties and their relationship to biogeochemical parameters (e.g. Reynolds et al, submitted). Our goal is to develop appropriate regional parameterizations for semi-analytical inversion models for the retrieval of inherent optical properties as well as biogeochemical properties besides chl-*a* from satellite ocean color data.

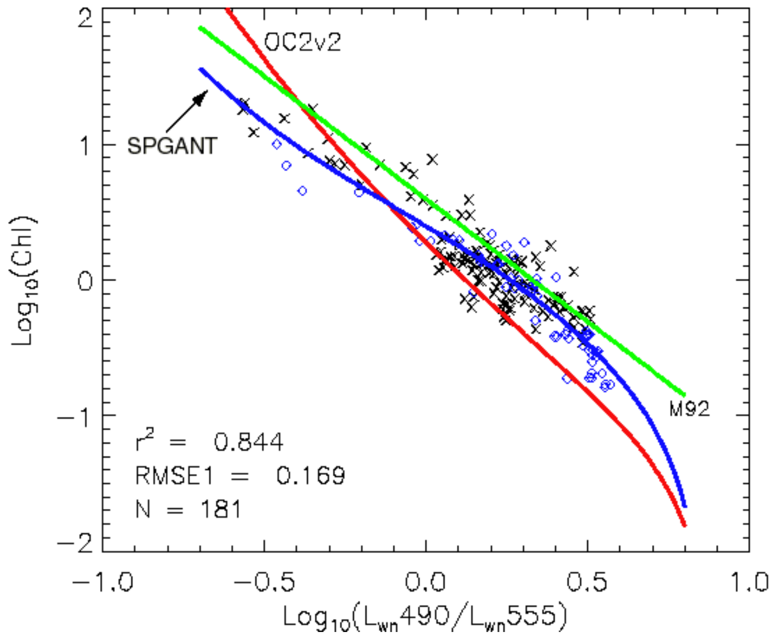

Figure 1. The relationship between log transformed values of $L_{WN}(490)/L_{WN}(555)$ versus chlorophyll *a* for Southern Ocean data. Curves represent the SeaWiFS OC2v2, Mitchell 1992, and our latest Southern Ocean algorithm SPGANT.

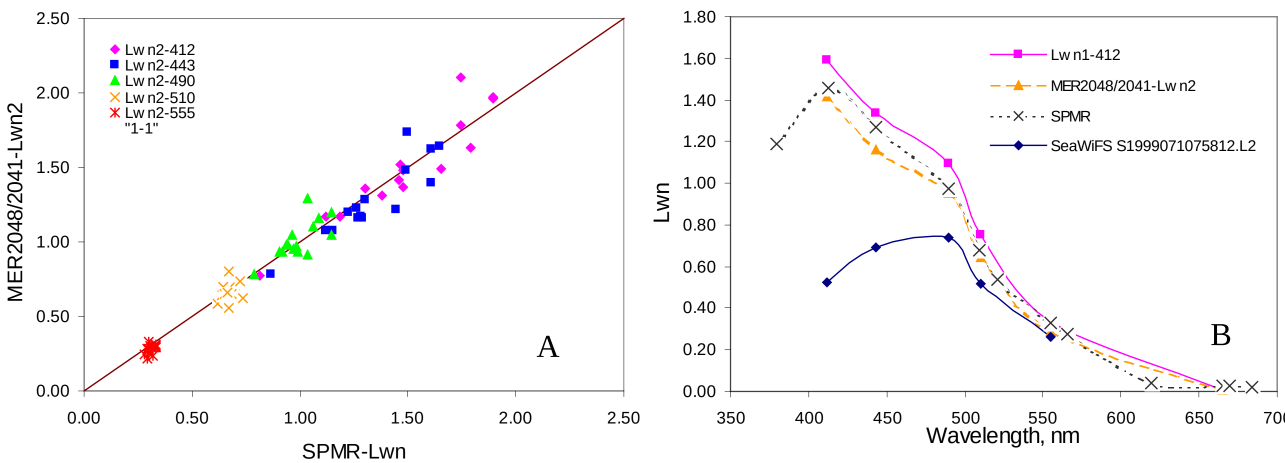

Figure 2. A. Scatter plot of L_{WN} estimates for several stations during INDOEX derived from data using our Biospherical Instruments MER 2048 and the SIMBIOS pool Satlantic SPMR. **B.** Spectral plot of L_{WN} derived from SeaWiFS and from two different in water profilers.

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Bio-Optical measurement and modeling of the California Current and Polar Oceans

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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.

Research Activities: Field methods and data

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 2 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.

Research Results

L_{WN} matchups- 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 (Figure 1). The differences were generally smallest in the 555 nm band, and largest at shorter wavelengths. The magnitude of under-estimation in the shorter wavelength bands increases at high Chl concentration.

Chl algorithms- 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 2 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, submitted).

Work plan for next period

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.

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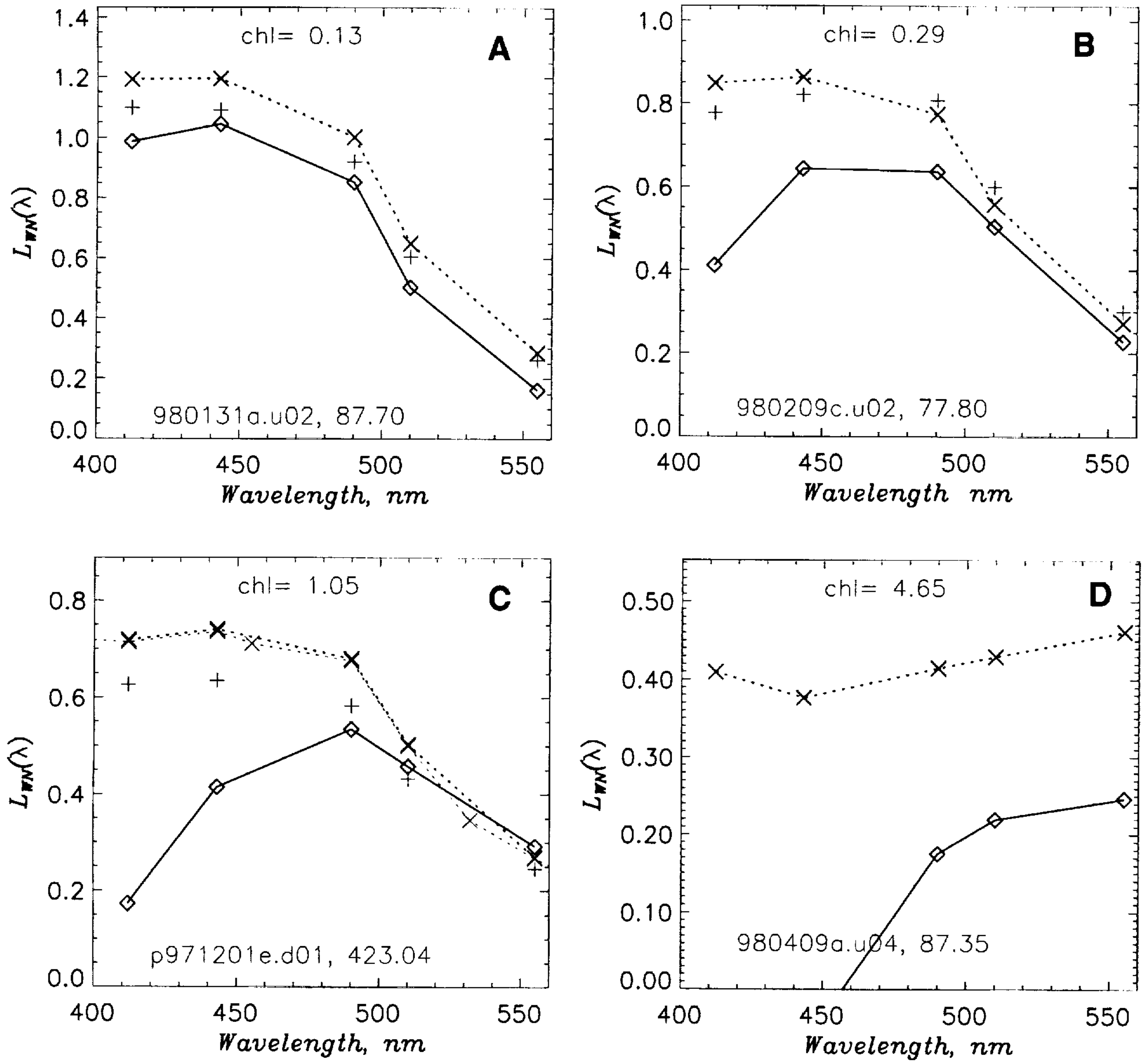

Figure 1. Examples comparing SeaWiFS-derived normalized water-leaving spectral radiances (o, solid lines) with *in situ* measurements from CalCOFI (panels A, B, D) and the Southern Ocean (panel C). *In situ* values were calculated using in-water spectral measurements of E_d and L_u (×, dashed lines) or using above surface measurements of E_d (+). Surface chlorophyll a concentration at each station is also indicated.

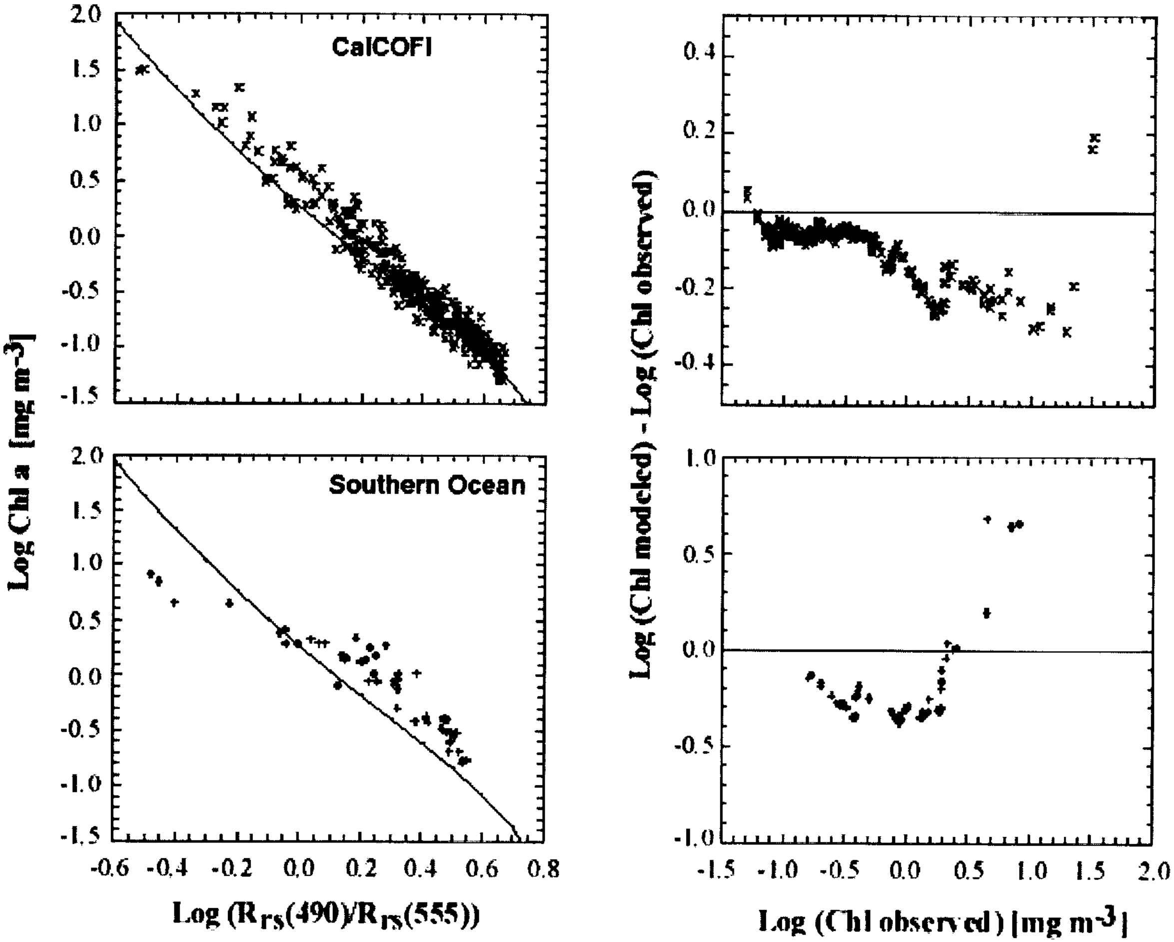

Figure 2. A comparison of the OC2-v2 algorithm (solid line in left panels) with *in situ* measurements of chlorophyll a from CalCOFI and the Southern Ocean. The right panels illustrate quantile-quantile plots of the differences between modeled and measured chlorophyll a.

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