OCEAN OPTICS IN THE CALIFORNIA CURRENT: OBSERVATIONS AND THEORY

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ABSTRACT

We present a combined analysis of apparent optical properties and inherent optical properties of the California Current based on multi-instrument bio-optical measurements during the California Cooperative Oceanic Fisheries Investigation (CalCOFI) cruises. Detailed radiative transfer modeling is employed and radiance and irradiances for the model are derived and compared to measured values. Bio-optical parameterizations for the California Current are developed and compared to existing parameterizations for Case 1 waters. Discrepancies between absorption parameterizations are discussed.

Key words: CalCOFI, optics, absorption, remote sensing, California Current

1 INTRODUCTION

Apparent optical properties (AOP) in the ocean (e.g. diffuse attenuation coefficients, reflectance) depend on variations in inherent optical properties (IOP) including the absorption and scattering due to phytoplankton, and other particles, colored dissolved organic matter (cDOM) and on the boundary conditions of radiometric forcing, including atmospheric conditions, solar zenith angle, the underwater radiance distribution and bottom reflection. An adequate description of ocean optics and the goal of optical closure require detailed measurement complemented by radiative transfer modeling. This paper presents a combined analysis of AOP and IOP of the

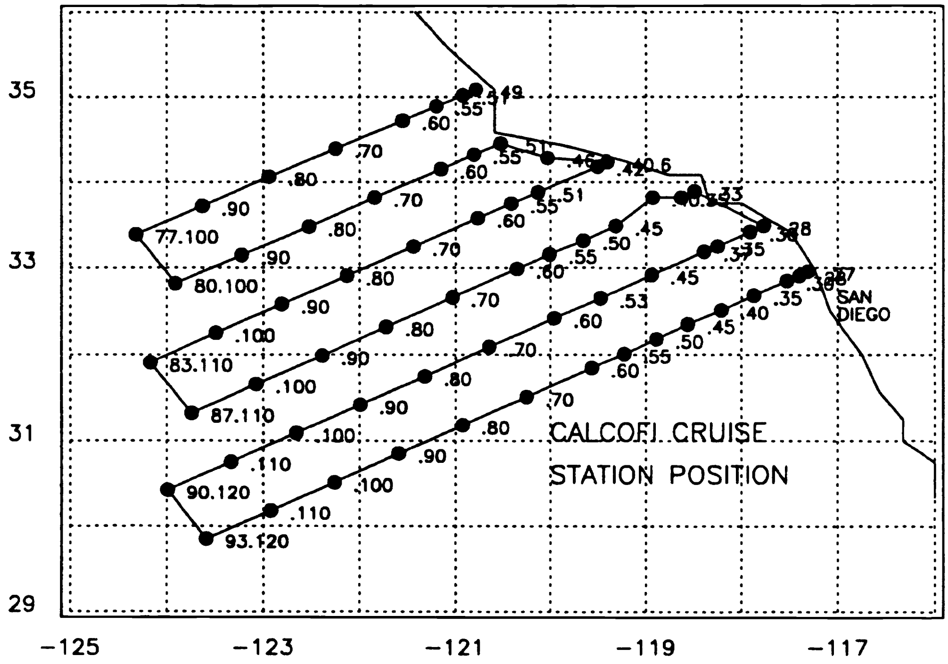

Figure 1: Station positions along the CalCOFI grid from line 77 north of Point Conception to line 93 off San Diego.

California Current based on multi-instrument bio-optical measurements during CalCOFI cruises and a detailed modeling study.

1.1 CalCOFI and Bio-optical Properties of the California Current

The California Cooperative Oceanic Fisheries Investigations (CalCOFI) region (Fig. 1) encompasses the full dynamic range of temperate coastal and open ocean trophic structure. CalCOFI Reports provide information on the biological and physical status of the region. For example Hayward et al[9] report on a transient state of the California current in 1994-1995. Mantyla et al[13] report on primary production and chlorophyll relationships, derived from ten years of CalCOFI measurements. Mean transport of mass, heat, salt and nutrients has been studied[25] for the volume defined by the modern (1984-1987) CalCOFI surveys (Fig. 1). Phytoplankton distributions in the North Pacific Ocean including the California Coastal Current have been reported by Ondrusek et al.[22]

The California Current region has been studied extensively with respect to its bio-optical properties[28] and almost half of the observations for NASA's CZCS Global Processing algorithm were collected in the Pacific off Baja California or the Gulf of California. Pioneering work on scattering phase functions[24] diffuse attenuation, and reflectance[1] have been carried out in this region. Several studies have focused on the details of the absorption coefficients[15,30] and one of the first experiments on "optical closure" was carried out in waters off San Diego.[20] Mueller and Lange[21] discuss a provisional analysis of satellite ocean color imagery and profiles of spectral irradiance and Chl-a fluorescence of the Northeast Pacific Ocean including the California Current system. The large historical background of optical measurements in the region, and the large dynamic range of pigment and particle concentrations, make this an ideal location to study the optical properties of Case 1 waters in detail. We have implemented a detailed optical sampling program as part of the quarterly CalCOFI cruises which occupy the stations shown in Figure 1.

During 3 years of sampling we have completed more than 300 optical stations and particpated in 12 cruises. Surface chlorophyll values range four orders of magnitude ($0.05 - 500 \mathrm{mg/m}^3$) for the stations we have occupied. The focus of the work has been to acquire spectral irradiance and radiance profiles and to support the in-water measurements with detailed analyses of pigments, and measurements of the absorption coefficients for particulate and soluble fractions.

1.2 Radiative transfer models - matching IOP with AOP

For the special condition of large optical depth of a homogeneous layer it is possible to derive an expression for the rate at which the diffuse attenuation coefficient for vector irradiance approaches its asymptotic value. Thus, it is possible to define the relationship between single scattering properties and irradiances.[33,6,31] For example, it can be shown that the asymptotic diffuse coefficient K_d and ω are related

$$K_{\infty}/c = 1 - 0.52\omega - 0.44\omega^2 \tag{1}$$

This theoretical expression can be inverted to show that, in principle, the vertical structure of the absorption, scattering, attenuation, and backscattering coefficients can be derived from the vertical structure of the scalar and vector irradiances and the nadir radiance.[33] The approach has great merit as it offers semi-analytical insight to the inverse problem. However, the assumptions of a diffuse regime and a homogeneous water layer limit this approach.

We have therefore used a computationally intensive approach by employing a plane parallel multistream radiative transfer model[16] to match IOP with AOP. This approach gives us the capability to define arbitrary vertical distributions of single scattering properties (IOP) and also to derive absolute values of the radiance field or directional water-leaving reflectance.

2 METHODS

2.1 Basic relationships

Among the AOP of most interest to ocean scientists are the spectral diffuse attenuation coefficient, the irradiance reflectance, and the remote sensing reflectance (K, R, and R_{rs}, respectively). Numerous prior studies have shown how K, R, and R_{rs} depend on the IOP. In particular, for Case 1 waters, absorption coefficients are a dominant terms. The spectral absorption properties of dissolved and particulate matter may be partitioned into several components:

$$a(\lambda) = a_w(\lambda) + a_p(\lambda) + a_s(\lambda) \tag{2}$$

$$a_p(\lambda) = a_{ph}(\lambda) + a_d(\lambda) + a_i(\lambda) \tag{3}$$

where the subscripts w, p, ph, d, s and i denote water, particulates, phytoplankton, detrital particulates, soluble (gelbstoff) and inorganic particulates, respectively. An analogous set of equalities may be written for the beam attenuation (extinction) and total scattering coefficients, c and b. For oceanic water types with little terrestrial influence (Case I), the phytoplankton and detrital particulates are key variables (Smith and Baker, 1978) and the water coefficients are constant and suspended inorganic particles are negligible. The sum $a_p = a_{ph} + a_d$ or $a_{ph}(\lambda)$ are often normalized for convenience by pigment concentration (e.g. chl + phaeo or chl-a) to give the pigment specific absorption coefficients:

$$a_p(\lambda) = a_p^*(\lambda)[\mathrm{chl} + \mathrm{phaeo}] \tag{4}$$

$$a_{ph}(\lambda) = a_{ph}^*(\lambda)[\mathrm{chl} - \mathrm{a}] \tag{5}$$

2.2 In situ data collection and water sampling

Our data set includes measurements from two WetLabs AC9s, a Biospherical Instruments MER 2040, beam c(660) with a Seatech transmissometer, and discrete measurements of spectral absorption at 1 nm resolution for particulate (a_p) and soluble (a_s) material. The AC-9 absorption and attenuation meter concurrently determines the spectral transmittance and spectral absorption of water for nine channels in the range 410-850 nm with a bandpass at 10 nm per channel. The MER2040 measures downwelling irradiance and upwelling radiance covering 340-700 nm for 13 channels with 10 nm bandpass. Conductivity and temperature sensors (SeaBird), the Seatech transmissometer, and a Wetlabs fluorometer are integrated to the MER2040 data stream. A Wetlabs Modular Data and Power System (MODAPS) provides power and data acquisition for all instruments on the profiling package. Water samples were collected from a General Oceanics rosette consisting of 24 ten liter bottles, a CTD, transmissometer, and fluorometer. Samples from the water bottles were taken for determination of a_p, a_s, and chlorophyll.

2.3 Spectral measurements of absorption

Estimates of the absorption of particles (a_p) were made by concentrating the particles on Whatman GF/F filters under low vacuum pressure. The samples were scanned 300-800 nm in a dual beam spectrophotometer (Varian Cary 1) using a blank filter saturated with filtered sea water as the reference. Procedures for sample preparation, data acquisition, and data processing followed the Quantitative Filter Technique of Mitchell.[14] Absorption of soluble material (a_s) was determined by filtering the seawater through 0.2μm pore size polycarbonate filters. The filters were first rinsed several times with MilliQ (Millipore Corporation) water to minimize contamination by the filters. The samples were run on the Cary 1 spectrophotometer in 10 cm quartz cuvettes from 300-800 nm with MilliQ water as the reference. We attempted to maintain the reference and sample cells at room temperature using a temperature controlled circulating bath interfaced to circulating flow cuvette holders. Residual temperature artifacts are often noted from 650-750 nm,[23] so the value at 600 nm was used as a null point.

2.4 Chlorophyll determination

Samples were collected on GF/F filters, extracted in 90% acetone for 24 hours at 4C in the dark, and chlorophyll concentrations were determined by the fluorometric method[10] using a Turner Designs fluorometer. Procedures followed the standard CalCOFI protocols.[32]

2.5 Hydrolight model

The numerical radiative transfer model used in this study is a slightly modified version of Hydrolight 3.0 code.[16] We have found that sky radiance boundary conditions, including specifications of clouds, are important for proper in-water irradiance modeling. Therefore, we investigated the model of Brunger and Hopper[4] for the average anisotropic sky radiance (or intensity) as a function of the position of the Sun, the diffuse fraction k, and the atmospheric clearness index k_t. The complete range of sky conditions from clear to turbid to overcast is covered. We have tested (not reported here) sensitivity of in-water fluxes to choice of k and k_t. We have found that zenith position and cloud cover play an important role in modeling results. A simple spectral solar irradiance model for cloudless maritime was employed,[8] complemented by a cloudy sky model.[12] A separate user-supplied function `chlz(z)` estimated the chlorophyll concentration at geometric depth z using a spline interpolation and CalCOFI measurements. Then the bio-optical models of Morel (1991)[18] and Gordon and Morel (1983)[7] were used to convert the chlorophyll concentration into a and b values. Pure sea water absorption and scattering coefficients are determined from the data of Smith and Baker (1981).[29] Twelve model wavebands were specified 335 – 345, 375 – 385, 390 – 400, 407 – 417, 438 – 448, 450 – 460, 485 – 495, 505 – 515, 527 – 537, 550 – 560, 565 – 575, 660 – 670 to correspond with MER channels.

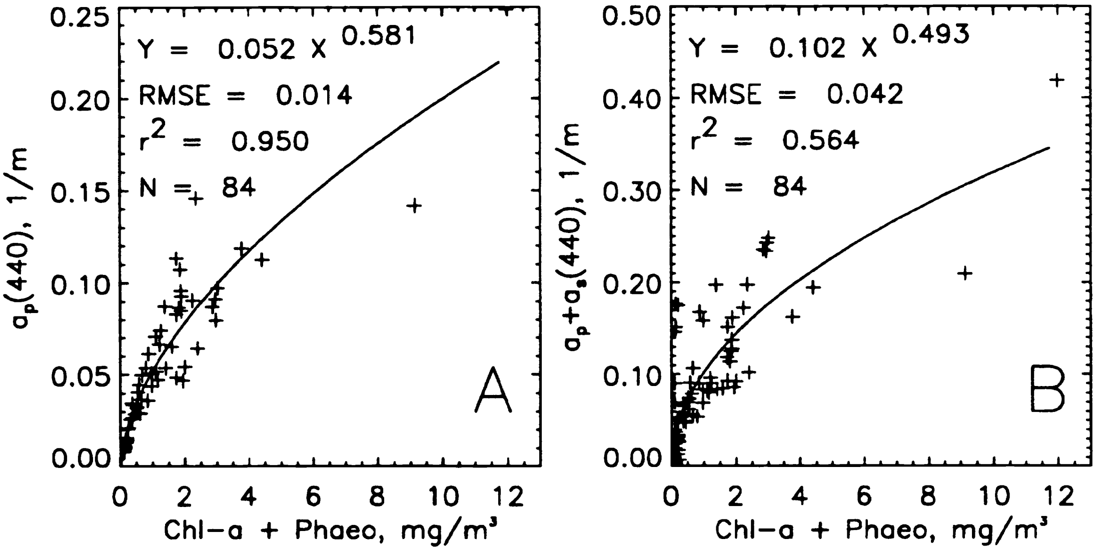

Figure 2: (A) Correlation between pigment (chl-a+phaeo) and the particle absorption at 440 nm. (B) Correlation between pigment (chl-a +phaeo) and the sum of particle and soluble absorption at 440 nm.

3 RESULTS

3.1 Bio-optical models of California Current Case 1 waters

We have developed a version of the bio-optical model for Case 1 water based on measured chlorophyll and published parameterizations.[27,17,2] Also, we have developed absorption parameterizations based on *in situ* chlorophyll, a_p and a_s measurements (c.f. Figure 2). These models have been used in numerical sensitivity studies and will be reported in an extended publication.

3.2 Modeling results

Data collected for latitude 29.51.4N, longitude 123.35.6W at station 93.120 was modeled using Hydrolight.[16] The station was occupied commencing at 1838 UTC with up and downcasts separated by about 10 minutes. The winds were southerly with wind speed of 5 kn. The atmospheric pressure was 1018.9 hPa and the Secchi depth was 41m. Thin clouds were observed. *In situ* water was collected at 2, 27, 54, 110, and 154 meters. Comparison of the model results to observation is given in Figure 3. While we observe reasonable agreement between observations and model output of E_d and L_u, there are notable issues which must be considered. Rarely does one have ideal sky conditions when operating at sea, and the 30% high cirrus cloud condition observed at this station is a typical good situation. The consequence for this station is that the downcast had about 20% lower irradiance than the upcast but this was not modeled explicitly. Also there was a cloud anomaly at about 12 m depth on the upcast. Surface illumination forcing, together with possible near surface effects from the ship shadow, bubbles, foam, wave focusing, etc. may be responsible for some anomalies in the example. These are realistic issues which challenge accurate retrieval of R_{rs} and L_u from measurements alone. There are remaining inconsistencies due to the bio-optical model which has highly parameterized particulate and cDOM absorption components based on the Morel model for Case 1 waters. Figure 3B shows that our measurement of the non-water absorption $(a_p + a_s)$ is in good agreement with the Morel model from 350-450 nm but diverges significantly at longer wavelengths where the Morel model over estimates $a_p + a_s$. We believe the high estimates of the Morel model are physically impossible at the red absorption peak where a_s is negligible and a_p is extremely well correlated to chlorophyll.[30,15,2] Errors in the Morel absorption model, when it is applied to total water attenuation coefficients, are relatively unimportant at wavelengths longer than 600 nm since water absorption greatly dominates $a_p + a_s$. However, as indicated in our example for 440 and 555 nm (Figure 2A), the excess absorption per unit pigment of the Morel model may result in stronger attenuation of the Hydrolight modeled E_d and L_u fields (e.g. larger slope of the $\ln(L_u)$ or $\ln(E_d)$ vs depth).

4 DISCUSSION

Absorption by dissolved material has been considered less significant for Case 1 waters[11,3] but this is not a reasonable assumption.[26,5] Figure 2 shows $a_p(440)$ is much better correlated to chl+phaeo than is the sum $a_p(440)+a_s(440)$. The good correlation between a_p and pigment concentration is the basis for most bio-optical parameterizations. However, a_s is not well correlated with total particulate absorption, or pigment, and will thus pose a challenge for ocean color algorithms and bio-optical parameterizations.

The parameterizations of a_p and a_s as a function of chlorophyll for the Hydrolight model were chosen to be based on Morel.[19] Thus, the a_p shape function is dependent on the Prieur et al parameterization derived from a fitting to spectral K, R and chlorophyll data. Measurement of a_s was generally not done for most cruises, so the parameterizations for a_s also are not based on a concurrent data set with the K and R data. The laboratory determinations that we perform for a_p and a_s also have a set of issues that must be considered. Our correction for the pathlength amplification factor for the a_p measurements on GF/F filters is largest in weakly absorbing regions, and the instrument noise is also largest in this domain, so the errors of the method are largest from 575-650 nm. Furthermore, we have chosen to normalize our raw a_s at 600 nm, which may lead to underestimates of the true values. The issues of methodology, treatment of blanks, null value normalization, pathlength amplification, and storage of preparations for determinations of a_p and a_s are still unresolved within the community and require more focused attention before a

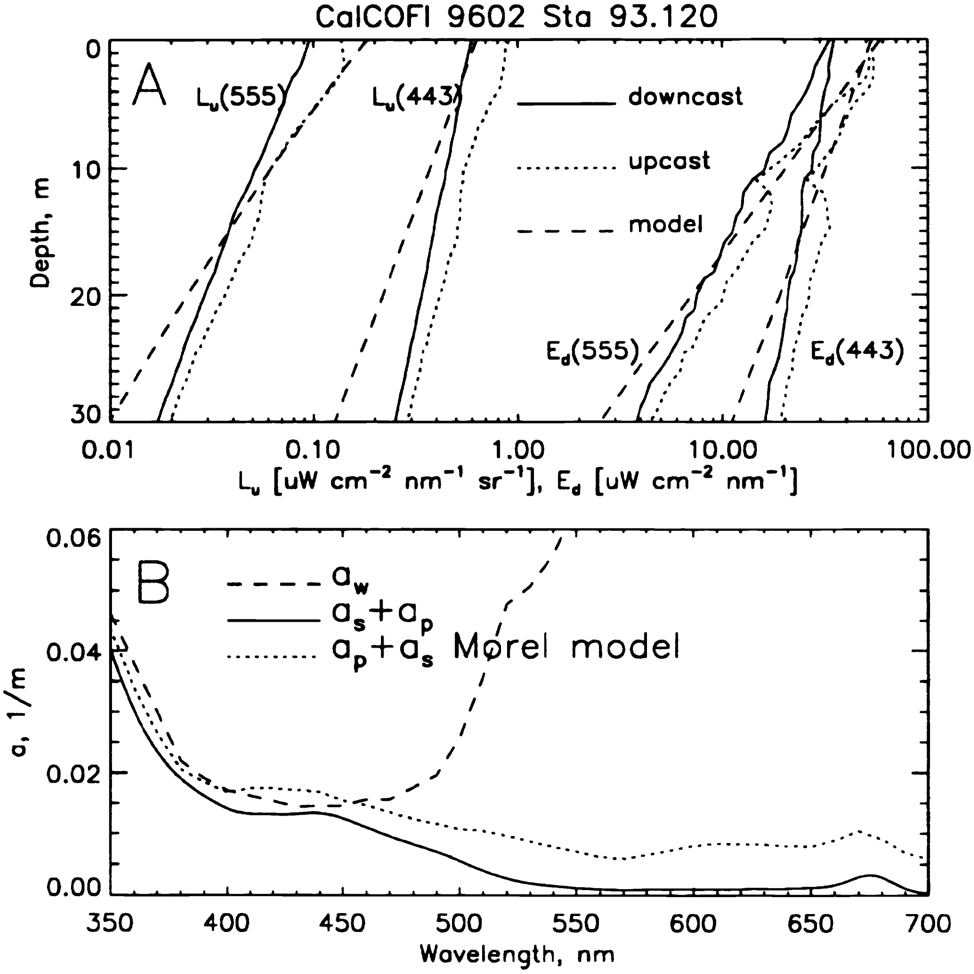

Figure 3: (A) Comparison of measurement at CalCOFI 9602 station 93.120 with radiative transfer calculations based on the Hydrolight code for 2 wavelengths (443 and 555 nm). The left half of the panel depicts nadir upwelling radiance, while the right half depicts downwelling irradiance. R_{rs} can be calculated from these measurements. Dashed lines are model data; solid lines are the downcast; dotted lines are the upcast. (B) Comparison of the Morel[19] bio-optical model for $a_s + a_p$ (based on our measured chl-a+phaeo), and our direct laboratory estimates of $a_s + a_p$ for the mixed layer at the same station. Absorption by pure water is shown for comparison. The value of chl was 0.08 mgm^{-3}.

consensus will be attained. What we do see, quite clearly in Figure 3B, is that direct methods for estimating $a_p + a_s$ are not in agreement with one of the leading parameterizations. When the Hydrolight model is run, discrepancies that are dependent on parameterizations should be expected, and the discrepancies we note in Figure 3A between measured and model output are consistent with overestimates of the $a_p + a_s$ when the Morel[19] parameterization is used.

5 Acknowledgments

Greg Mitchell has been supported in part by ONR N000014-91-J-1186 and NASA (NAGW-3665) grants. P. J. Flatau is supported in part by the Office of Naval Research Young Investigator Program and DuPont Corporate Educational Assistance. The existence and high quality of the CalCOFI data is made possible by the efforts of many members of the Marine Life Research Group (MLRG).

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